Analyzing the spatial variation of environmental impacts from sugarcane land use and expansion in Sao Paulo state, Brazil.

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Abstract

In this study, the spatial variation of environmental impacts from sugarcane production was quantitatively assessed for Sao Paulo state, Brazil. The study analyzed the time step from 2004-2015. More specifically, the study objective was to analyze spatially the environmental impacts generated from the sugarcane use and expansion. The spatial variation analysis is a relevant component to understand the spatial sustainability from the sugarcane industry in the state. The Land Use Change (LUC) dynamics from the state were evaluated on yearly basis for the entire time step (2004-2015) with a geographical information system (GIS) and were the reference point for the environmental impacts assessments. 4 different environmental impacts were assessed on yearly basis for the entire time step (2004-2015). CO_2 emissions from sugarcane land use and LUC were quantified with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, water shortage was evaluated with a water balance approach, biodiversity with the Mean Species Abundance indicator, and soil erosion with the RUSLE equation. Furthermore, the environmental impacts were integrated and classified between negative, positive and no change impacts to obtain a complete image of the sustainability (spatially) of the sugarcane production in the state. The spatial variation in the environmental impacts and integration section was also assessed with GIS. On a general basis, there were more negative than positive impacts from the sugarcane production and expansion (depending on harvest year). Furthermore, areas with sugarcane expansion are generating more negative impacts than the constant sugarcane areas. The environmental impacts integration showed that there were several tradeoffs between impacts and the Northwest area of the state is the one with the most negative scores. Nevertheless, the scores vary from year to year with some years performing worse than others. The geographical variation from environmental impacts is mostly determined by previous land use (with the exception of the water indicator). Furthermore, inter-annual variations between impacts are relative low and mostly determined by different factors for each environmental impact. This study provides a basis and framework to identify possible areas more suitable for sugarcane expansion that could generate more positive than negative impacts and also key parameters that could be improved to enhance the sustainability of the sector.

1. Introduction

Since the beginning of the modern age, society has been driven by its dependence on fossil fuels. CO_2 emissions from fossil fuels have been identified as the main contributor to climate change (Friedlingstein et al., 2010). Despite knowledge of climate change induced impacts such as biodiversity loss, sea level rise, temperature rise and negative effects on crop yield (IPCC, 2014), CO_2 emissions have continuously increased (The World Bank, 2016a). Emissions have tripled in the last 50 years, intensifying climate change (The World Bank, 2016a). Furthermore, societal dependence on fossil fuel energy is extensive and entrenched, as more than 80% of the world energy consumption is derived from fossil fuels and the trend has remained stable for the last 30 years (The World Bank, 2016b). In order to reduce this dependence on fossil fuels and mitigate the impacts of climate change a switch to a renewable energy system with low associated greenhouse gas (GHG) emissions is required (Cornelissen et al., 2012).

In the upcoming years, energy demand is expected to continue increasing, driven mainly by population growth (IEA, 2010) (Petrecca, 2014). Renewable Energy (RE) defined by the IPCC as "any form of energy that is replenished by natural processes at a rate that equals or exceeds its rate of use, obtained from the continuing or repetitive flows of energy occurring in the natural environment," is already playing a key role in supplying energy services in a sustainable manner as a function of climate change mitigation (Arvizu et al., 2011). In 2008, the RE share of energy sources from the global total primary energy supply corresponded to 12.9% (Bioenergy accounting for 10.3%) (IEA, 2010). This share has improved over the last years (Chum et al., 2011) and several projections (under different scenarios) forecast an increase of RE supply for 2030 and 2050 (Chum et al., 2011; WWF, Ecofys and OMA, 2011; GEA, 2012).

Bioenergy (Energy obtained from animal and vegetable derived material) accounts for the largest share of RE (Chum et al., 2011); as a result it demands special attention. Bioenergy is mainly derived from Animal By-Products (ABP), Agricultural By-Products (AGBP) and Energy Crops (EC) (Chum et al., 2011). The vast majority of EC is composed of Sugar, Starch and Oilcrops (Luque et al., 2008), and at the present these EC are one of the main feedstocks for Biofuels production (Koizumi, 2015). Biofuels are commonly defined as "any sort of fuel that is made from organic matter (Biomass)" (Luque et al., 2008), and are produced to enhance energy security, reduce GHG emissions, and strengthen agricultural/rural development (Koizumi, 2015). Biofuel production has increased over the last years and the trend is expected to continue into the future (Licht FO, 2014a) (Licht FO, 2014b).

Bioethanol accounts for the largest share of biofuels production, with Brazil positioned as the world's second largest producer (Koizumi, 2015). Brazil is the leading country in sugar cane production and has been a pioneer in the use of it to produce bioethanol (Altieri, 2012). Brazil's biofuels industry has replaced more than half of the country's gasoline needs (Altieri, 2012), reducing GHG emissions (Walter et al., 2011). Furthermore, it has enhanced the country's economy and has generated more than 845,000 direct and indirect jobs (Renewables Global Status Report, 2015). However, sugarcane cultivation is not only intended for bioethanol production, it is also processed into sugar. Brazil is the leading sugar producing country in the world (USDA, 2016), and has constructed a prevailing model for producing sugar and ethanol in an integrated way (de Souza Dias et al., 2015). The sugar and bioethanol industry have expanded over the last decades and has induced Land Use Change (LUC) derived from sugarcane expansion, and within a 5 year period (2005-2010) 4 million hectares of sugarcane have expanded in the central-south region of Brazil (Adami et al., 2012).

LUC has become one of the main issues regarding the sustainability of bioethanol production (Walter et al., 2011). Particularly in Brazil, there are high concerns regarding the relationship between sugarcane production and deforestation or food crops displacement (Walter et al., 2011). Furthermore, there is a risk of LUC generating a cascade effect leading to habitat loss, ecosystem function loss and even affecting regional hydrological cycles (Goldemberg et al., 2008). In addition, it is recognized that significant GHG emissions can result from LUC (Fargione et al., 2008), and the net CO_2 emissions from the sugarcane industry are still debated (Cerri et al., 2009). Impacts on soil generated from LUC are largely dependable on agronomic and agro-processing practices (Zuurbier and Van de Vooren, 2008). In Brazil, soil erosion and compaction are considered problems in sugarcane fields (especially the ones under intense mechanization during cultivation and harvesting) (Martinelli and Filoso, 2008). LUC dynamics have been identified as one of the fundamental components related to environmental and societal problems (Turner et al., 2007). Furthermore, the study of these dynamics is considered an essential element for understanding global sustainability and environmental change (Turner et al., 2007).

Different studies performed in Brazil, especially from an environmental perspective, have contributed to an understanding of the sustainability of the ethanol and sugar industry (Goldemberg et al., 2008; Walter et al., 2011). Sustainability of the bioenergy sector has been an important research objective and several sustainable criteria sets such as the one developed by Sao Paulo state (laws) have been developed in the last years (Aguiar et al., 2011). Numerous studies mainly from a Life Cycle Assessment (LCA) and energy balance approach, suggest that the production and use of bioethanol, reduces GHG emissions when compared to gasoline (de Carvalho Macedo, 1992; de Carvalho Macedo, 1998; Goldemberg et al., 2008; Macedo et al., 2008; Luo et al., 2009; Seabra et al., 2011). Nevertheless, none of these studies have addressed the impacts from direct LUC. Few studies have considered the GHG emissions from sugar cane cultivation and expansion. However, a study from de Oliveira Bordonal (2015) assessed direct LUC (by the means of satellite images) derived from sugarcane expansion from 2006–2011 in central-south Brazil and suggested that direct LUC had a favorable impact on C fixation (C sink behavior). Nonetheless, avoided emissions could differ drastically when considering the effect of LUC and even account for higher emissions compared to the gasoline life cycle (Walter et al., 2011).

Other sustainability criteria such as biodiversity have been studied by different authors. Rodrigues et al. (2011) studied the effects on biodiversity from LUC for different land covers (Forest, Cropland, etc.) from different sugarcane farms and Filoso et al. (2015) suggested an ecological restoration with native species to prevent habitat fragmentation induced by LUC.

Sugarcane crops also affect soils; Silva et al. (2007) suggested that sugarcane cultivation leads to soil compaction. Additionally, Martinelli and Filoso (2008) recommended measures to prevent soil degradation and erosion from sugarcane cultivation. Filoso et al. (2015) also suggested that soil compaction is a problematic issue in Brazil agriculture, especially in sugar cane, leading to the loss of topsoil with important nutrients and carbon (Chavez-Rodriguez and Nebra 2010). Cabral et al. (2012) and da Silva et al. (2013) concluded that rain water is enough for the sugarcane production, resulting in no irrigation needed; and sugarcane productivity increases with water level. Meanwhile, Chavez-Rodriguez et al. (2013) calculated water usage for the bioethanol production and suggested means to reduce it. Hernandes et al. (2014) calculated water footprint for Brazil Biofuels concluding that more data is needed to assess if the sugarcane expansion can lead to water scarcity.

Filoso et al (2015) have highlighted the importance of measuring additional sustainability criteria (GHG, water, biodiversity, etc) in order to understand the sustainability of the sugarcane production industry in Brazil. Furthermore, none of the mentioned studies have analyzed spatially the sustainability of the sector. Sustainable criteria and the elements that determine it may vary strongly within the same region and might be influenced by different environmental and socio-economical contexts (even within the same region). A regional assessment without spatial differentiation from relevant factors that determine sustainable criteria might lead to inadequate conclusions. Therefore, a spatial differentiation approach is more suitable for analyzing the linkage between sugarcane LUC dynamics and sustainable criteria (CO_2 emissions, water stress, soil erosion and biodiversity impacts) that influence the sustainability of the sugarcane production industry. In addition, the spatial assessment will help identify areas that are more or less sustainable for different environmental criteria.

Taking into account that Sao Paulo state produces more than 60% of Brazil’s sugarcane (Altieri, 2012) and that it has experienced the largest sugarcane expansion in the country (Rudorff et al., 2010), the main objective of the study is to analyze spatially the sustainability of the sugarcane production in Sao Paulo state (Brazil) from 2004-2015. The sustainability of the sugarcane land use and expansion areas was assessed through an environmental impacts assessment focused on CO_2 emissions from LUC and land use, biodiversity, soil and water. It must be highlighted that indirect land use change goes beyond the scope of the study and therefore is not included. The spatial and chronological analysis (evaluation of the sustainability on yearly basis) will provide a complete reference to understand the dynamics (regarding environmental impacts) generated spatially and temporally from sugarcane expansion and current sugarcane use areas in Sao Paulo state. Following the same order of ideas, the study will investigate the following question and sub questions:

- What is the spatial variation in environmental impacts from sugarcane expansion for Sao Paulo state?

  - What are the land use change dynamics in Sao Paulo state from sugarcane production?

  - What are the areas in Sao Paulo state with a better sustainability performance?

2. Methods

The research followed a systematic approach to assess on yearly and spatially explicit basis, the Environmental Impacts (EI's) in Sao Paulo state generated from LUC (areas where sugarcane is expanding). Nevertheless, the impacts were also assessed for the current sugarcane land use areas (areas where sugarcane is already cultivated). The current sugarcane land use areas extension ranges between 16-21% (depending on harvest year) of the total state area. The magnitude of the current sugarcane land use area is extensive to the level that it was considered important to assess the EI's of these zones (EI's from current land use might be more significant given the vast area used for sugarcane production). The EI's addressed in the study were CO_2 emissions from land use and LUC, water shortage, soil erosion and biodiversity. Each environmental impact was quantified spatially explicitly on a yearly basis (from 2004 to 2015) and the unit of analysis for each impact is addressed in the correspondent subsection. The analysis was conducted for each harvest year (2004-2005, 2005-2006 and so on) to obtain a complete chronological description of the sugarcane production performance for the studied time step (2004-2015). Important dynamics could have been left out of the evaluation if the EI's assessment was performed without a chronological order.

In order to obtain the impacts from sugarcane expansion and land use, the methods were applied for all land cover categories for the first reference year from the harvest year and for the sugarcane category for the last reference year of the harvest year. E.g. for the 2005-2006 harvest year, the methods are applied for all land cover categories for 2005, but for 2006 only for the sugarcane land cover category (further information is explained on each section and this was done for each harvest year). In addition, the EI's were integrated on a yearly basis to obtain a complete picture of the sustainability of the state sugarcane production. The results from each EI were evaluated (given the difference of each EI units) into positive and negative impacts. The integration of the EI's is explained in the EI's integration section

The study addressed direct impacts from the sugarcane expansion and current sugarcane land use. Indirect impacts such as indirect land use change (ILUC) go beyond the scope of the study. As mentioned before, the EI's assessment is dependable on the LUC dynamics and processes from the state. For this reason, the LUC dynamics were also analyzed on yearly basis for the whole state. However, he LUC dynamics section does not only analyze the sugarcane expansion, but also the sugarcane contraction area (only for this section). It must be highlighted that the LUC analysis is not part from the EI's but they are highly entrenched with each other. Furthermore, this was done order to contribute to a better understanding of the EI's and LUC dynamics in the state. Analyzing spatially each environmental impact demanded specific spatial data from different components such as climate, soil types and (particularly important) land cover. The input data was processed and modeled with ArcMap 10.2.2. A sensitivity analysis was performed in order to get a clear picture of how the uncertainty in different components from the input data was affecting the results. The following section discusses the methods used for quantifying each environmental impact with a special subsection for the study area and land cover data.

2.1. Study Area

The case study area consists of Sao Paulo state, which is located in the Southeast region and is one of the 26 states that form Brazil. The Southeast region has experienced the largest sugarcane expansion (Martinelli and Filoso, 2008). This expansion has been driven mainly by the expanding domestic ethanol market and exports to other countries (Goldemberg et al., 2008). Sao Paulo state alone has more than 50% of the country's sugarcane land cover and is responsible for more than 60% of Brazilian sugarcane production (Martinelli and Filoso, 2008) (Altieri, 2012). Furthermore, the state produces approximately 62% of Brazil's ethanol (Goldemberg et al., 2008).

Sao Paulo is the most populated state in the country with over 41 million people and an area of 248,209.4 square kilometers (IBGE, 2015). The state has a subtropical climate with an annual precipitation of 1250-1850 mm and a mean annual temperature of 18-26 °C (INMET, 2015). Sao Paulo state borders in the north with Minas Gerais state, in the South with Parana state, in the west with Mato Grosso do Sul and in the east with the Atlantic Ocean. The exact location of Sao Paulo state in Brazil is shown in Fig.1.

Fig. 1 Sao Paulo state location in Brazil, case study area

2.2. Land cover data

The study was based on the land cover data developed by Delft University of Technology (TUD) as part of the Improved space-based remote sensing for land use mapping; towards a sustainable expansion of the bioethanol sector in Brazil project. The land cover data set includes yearly land cover data from Sao Paulo state (2004-2015) with accuracies ranging from 70% to 90% for all land cover classes in standard conditions. The land cover data (maps) is on geographic coordinates (GCS WGS 1984) with a 0.000250 ° resolution and it is divided into the following categories (TUD, 2016):

- Urban area: Includes built in area such as roads.
- Water: Including wetlands.
- Forest: correspond to dense foliage/high biomass species with high crown cover, native forest being the most occurring case.
- Low vegetation: corresponds to unmanaged grassland, but also includes rangeland with predominant grassland cover, managed pastureland and abandoned cropland.
- Medium vegetation: corresponds to dense shrubland and woodland with low crown cover. Additionally, it also includes dense foliage rangeland and fruit crops such as citrus.
- Eucalyptus: includes the eucalyptus species and planted eucalyptus which can be distinguished from forest due to its harvest events.
- Annual crops: Crops that complete their harvest cycle annually such as beans
- Sugarcane: correspond to sugarcane plantations regardless of harvest stage (Plant cane, ratoon or land under renovation).

Projection and resolution

The study dealt with different data coordinate systems and resolutions. Aggregating all this data into the same scale could lead to different data values and interferences (Jelinski and Wu, 1996). In order to establish a scale and coordinate system adequate for the study, several aspects were taken into account. First, one of the most important input data (soil types and climate) is on projected coordinate system (South America Albers Equal Conic Area), for this reason and to process all the input data in the same coordinate system (this will give no distortion of areas between input data), the other input data was projected to South America Albers Equal Conic Area. Second, the resolution was chosen taking into account that it had to be small enough to show the land use changes (sugarcane expansion) over time and big enough to spend reasonable time on running the models given that it had to be repeated for each year (High resolution may lead to long periods of modelling time). On average, the total area of a sugarcane plantation in Sao Paulo state was 8,000 ha (80 km^2) in 1970 and currently (2014) is around 12,000 ha (120 km^2) (Gasparatos and Stromberg, P. (2012). A resolution of 1 km^2 was considered enough to satisfy both requirements (land use change from sugarcane plantations and modelling time); subsequently all the input data resolution was resampled into 1 km^2.

2.3. CO_2 emissions

2.3.1. CO_2 emissions from LUC

CO2 emissions from LUC result from carbon stock changes in biomass, dead organic matter, litter, harvested wood products and soils (IPCC, 2006). These carbon stock changes are driven mainly by the conversion from one land use to another, resulting in either carbon accumulation or carbon decrease in a specific stock (IPCC, 2006). In order to establish the CO_2 emissions or carbon sequestration from the sugarcane expansion and current land use, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC guidelines) were used. This study analyzed the direct land use change plus current use from sugarcane and calculated the relevant carbon pools for the land cover classes present in the land cover data: Biomass (above ground biomass and below ground biomass) and soils (Soil Organic Carbon (SOC)).The measurement unit for this section was t CO_2-eq/ha year. The stock difference method with a tier1 (procedures) and tier 2 (given some specific data) combination was applied to assess carbon stock changes in different points in time and is represented by equation 1. According to tier 1, dead organic matter net stock and litter net stock changes are assumed to be 0 given that the average transfer rate into both stock is equal to the average transfer rate out (IPCC,2006). Harvester wood products carbon stock was also not calculated given that it goes beyond the scope of the study. Furthermore, several input data were used to establish spatially explicit carbon content (for each land cover category) for the relevant pools and it is explained on each land cover category.

Equation 1

$$\Delta C = \frac{(C_{t2} - C_{t1})}{(t_2 - t_1)}$$

Where:

ΔC = annual carbon stock change in the pool, tons of C/year
C_{t1} = Carbon stock in the pool at time $_{t1}$, tons of C
C_{t2} = Carbon stock in the pool at time $_{t2}$, tons of C

As mentioned before, the ΔC was calculated for the two relevant carbon pools and integrated to obtain the total change. According to 2006 IPCC guidelines procedures, both carbon pools have different emission time lines. While the biomass carbon pool represents the yearly changes, the soils one is computed under the assumption that it would take 20 years for them to reach stability. This means that the emission or sequestration results from the soil carbon pool are calculated for 20 year time spam. Even with the time lines difference, the 2006 IPCC guidelines integrates the results as a whole. For this reason (and the complications to track soils changes for each individual cell on yearly basis during the whole studied period 2004-2015), it was assumed soil stable conditions for each year[1].

2.3.1.1. Above and below ground Biomass:

The biomass carbon content was quantified for each year (2004-2015) for above and below ground biomass. The 2006 IPCC guidelines were used as reference and detailed methods were applied to obtain specific cell values (spatial biomass carbon content distribution). The detailed methods are explained in the next section for each land cover category. Equation 2 was applied to obtain carbon content in above and below ground biomass for each category.

Equation 2

$$C_{Bi} = \left((B_{above} * DM) + \left((B_{above} * DM) * R\right)\right) * CF$$

Where:

C_{Bi} = Biomass carbon content for land cover category i, tons of carbon dry matter/ha
B_{above} = Above ground biomass production, ton/ha
DM= Dry matter content of above ground biomass, %
R = ratio of below-ground biomass to above-ground biomass
CF = carbon fraction of dry matter, tons of C

In the following subsections, additional steps for determining Equation 2 parameters are described for each land cover category. It must be highlighted that the additional steps are taken in order to establish spatially explicit results.

Sugarcane:

FAO sugarcane suitability map (FAO, 2012a) was used to obtain spatial variation (biomass dry matter content) within sugarcane land cover category. This approach was selected given that there is no spatially explicit sugarcane map of sugarcane yield for the studied time step. Suitability maps are based on soil, terrain conditions, water input, agricultural inputs and climatic conditions (FAO, 2012a). An intermediate agricultural input level was assumed (given that high input levels assume full mechanization), rain fed as water input (Sao Paulo sugarcane industry has no irrigation (Goldemberg et al., 2008)) and climatic baseline conditions. Furthermore, sugarcane yield values for Sao Paulo sugarcane production from 2004-2015 were retrieved from the Brazilian Institute of Geography and Statistics (IBGE for the Portuguese acronyms) (IBGE, 2015). Successively, a mean suitability value was calculated for the state (taking into account only sugarcane area). The mean suitability value was paired with the sugarcane yield for each specific year. A cross multiplication was applied to obtain sugarcane yield values for each cell from each correspondent suitability value. This process was done in order to establish spatial difference production between sugarcane plantations in the state.

Equation 2 was used for each cell (taking into account sugarcane dry content values, carbon fraction and yield data) and carbon content from above and below ground biomass was

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[1] Further information is for this topic is present on the soil subsection.

obtained[2]. This process was repeated for every year. It must be highlighted that the yield values and the mean suitability values (dependable on sugarcane area) were different for every year, correspondent yearly values were used.

Forest:

The forest land cover category was divided within Sao Paulo climatic zones[3] according to 2006 IPCC guidelines procedures (R values are dependable on climatic zones). Next, the improved pan-tropical map of aboveground woody biomass (in tons of dry matter/ha) at 1 km resolution (Avitabile et al., 2016) was implemented to obtain above ground biomass. Crossing the forest land cover with the pan-tropical map resulted in above ground dry biomass content for each cell in the forest category. Equation 2 was applied using 2006 IPCC guidelines default values for R and CF (Table 1). This process was repeated for every year (with the forest area variating on a yearly basis). Additionally, the cross layer from the forest land cover category with the pan-tropical map was checked on a yearly basis to assure proper overlapping areas.

Low vegetation:

Given that this category includes a wide definition, it was assumed that this vegetation corresponds to grassland, managed planted pastures and rangeland. Planted pastures (including rangeland) in Brazil are used for livestock production (Carvalho, 2006). Furthermore, Alfalfa grass is one of the most important forage crops in Brazil and the world (Lacefield et al., 2009).

The procedure for low vegetation category followed the same approach applied for sugarcane category. The FAO Alfalfa suitability map (FAO, 2012b) was used as a proxy indicator to establish the suitability value for each cell with low vegetation (no spatially explicit alfalfa yield maps were available). The mean suitability value for low vegetation was calculated and paired with default average values for above ground biomass (in tons of dry matter/ha) from the grassland category in the 2006 IPCC guidelines (stable yields over time). A cross multiplication was used to obtain aboveground biomass values from each correspondent suitability value. It must be highlighted that root to shoot (R) values vary depending on climatic zones (Table 1). Equation 2 was applied for each cell and default CF for herbaceous grassland from the 2006 IPCC guidelines was applied (Table 1). The mean pair process was repeated for every year changing the mean suitability values for each climatic zone (depending on low vegetation area and given that the other variables remain stable). It must be highlighted that the mean suitability value depends on the yearly LUC from this category.

Medium vegetation:

Just as low vegetation, medium vegetation has a wide definition. Medium vegetation not only includes shrubland and woodland but also citrus crops. For the purpose of this theme, it was

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[2] Equation 2 parameters for sugarcane are displayed on Table 1

[3] IPCC 2006 has a world climatic zones classification, the ones that cover Sao Paulo extent are: warm moist, tropical moist, tropical wet and tropical montane.

assumed that this category was mainly composed of shrubland. The procedure followed was similar to the one in the low vegetation category. Taking into account that there are not shrubland suitability or biomass spatially explicit maps for the studied time step, alfalfa suitability map was used as a proxy indicator for shrubland suitability. The mean suitability value was also calculated and paired with the tropical above ground biomass average value for shrubland from the 2006 IPCC guidelines (in tons of dry matter/ha). A cross multiplication was used to obtain aboveground biomass values from each cell from the correspondent suitability value. Equation 2 was applied with R and CF default values for shrubland category in the 2006 IPCC guidelines (Table 1). This process was repeated for every year changing the mean suitability value (this values depends on the yearly LUC from this category).

Eucalyptus:

The approach for Eucalyptus category was more simplistic than the other land cover categories. Considering that there were no spatially explicit biomass maps, suitability maps or a coherent proxy indicator suitability map for eucalyptus (no suitability maps from similar trees species were available). This category was classified within Sao Paulo state climatic zones and default values for above ground biomass were given (climatic zone dependable) for Americas Eucalyptus from the 2006 IPCC guidelines (Table 1). Equation 2 was used with R and CF default values for Americas Eucalyptus (Table 1). This process was repeated for every year (given that the land cover category area changes but the other variables remain constant).

Annual cropland:

Given the lifecycle of annual crops, there is no change in biomass carbon content for annual crops (IPCC, 2006). The carbon from biomass that has grown during the year is harvested at the end of it (giving a net balance of 0) (IPCC, 2006). Additionally, annual cropland area transformed to sugarcane is cleared before cultivation. For these reasons the biomass content of this category was assumed as zero.

Water and Urban:

For the last two land cover categories it is assumed no presence of biomass. Therefore, the carbon content of these categories in relation to biomass is 0.

2.3.1.2 CO_2 emission from sugarcane expansion (biomass):

Integrating spatially the carbon content from each land cover category resulted in a spatially explicit Sao Paulo state total carbon content map (for each specific year). The carbon stock map from the state was used in equation 1 as C_{t1}. For C_{t2} in equation 1 only sugarcane carbon content was used (from the next consecutive correspondent year, and was calculated for each year). This was made with the purpose of calculating only the carbon content difference from the expansion of sugarcane plantations and sugarcane plantations already in use. Equation 1 was applied to establish the change in the biomass carbon pool for each subsequent years (2004-2005, 2005-2006 and so on). Each sugarcane C_{t2} cell was subtracted from the corresponding cell (spatially) in $C_{t1.}$ Finally, the ΔC was multiplied by the CO_2 emission factor (– 44/12) to obtain t CO_2 emissions/ha year from LUC towards sugarcane (IPCC,2006).

Table 1. Input data to calculate above and below round biomass and carbon content for each land use category

Land cover	**Climatic zone**	**Dry matter content (% of fresh weight)**	**Average above ground biomass (ton of dry matter/ha)**	**R**	**CF**
Sugarcane	All	28^A	N.A.	0.18^A	0.43^B
Forest	Pan tropical	N.A.	Spatially-specific values^C	$(0.20^{for<125ton/ha})^D$ $(0.24^{for>125ton/ha})^D$	0.47^D
Low vegetation	Warm moist	N.A.	1.6^D	2.8^D	0.47^D
	Tropical moist and wet		6.2^D	1.6^D	
Medium vegetation	Tropical	N.A.	80^D	0.40^D	0.50^D
Eucalyptus	Tropical wet	N.A.	200^D	0.24^D	0.47^D
	Tropical moist		90^D	0.20^D	
	Tropical mountain system		75^D	0.20^D	
Annual cropland	N/A		N/A	N/A	Assumed to be 0^D

^{A} *(Herrera, 1999);* ^{B}*(Ripoli et al., 1991);* ^{C}*(Avitabile et al., 2016);* ^{D}*(IPCC, 2006)*

Sensitivity analysis

A sensitivity analysis was performed with the relevant land cover categories and parameters to analyze how these influence the results. It must be highlighted that the analysis was performed for only one harvest year (2012-2011). Sugarcane, medium and low vegetation are the relevant land cover categories for this section. The sugarcane expansion is mostly occurring on the low vegetation land cover category and in less degree on medium vegetation (it is also occurring on the annual cropland but the biomass for this category is assumed to be 0). Furthermore, the sugarcane land cover category is the one most correlated with the CO_2 emissions (especially the yield parameter). The analysis was conducted by shifting the relevant parameter from each land cover category to the maximum or minimum value present in the IPCC 2006 guidelines while leaving the other categories unchanged. Table 2 summarizes the input data used for the sensitivity analysis from the biomass section.

Table 2 Parameters used for the sensitivity analysis for the CO_2 emissions from the biomass section

Land cover	Year	Climatic zone	Average above ground biomass (ton of dry matter/ha)	Yield	Max	Min
Sugarcane	2012	-	-	78.86^{B}	85.54^{BC}	72.10^{BC}
	2013	-	-	80.39^{B}		
Low vegetation	All	Warm moist	1.6^{A}	-	2.8^{A}	0.4^{A}
		Tropical moist and wet	6.2^{A}	-	10.85^{A}	1.55^{A}
Medium vegetation	All	Tropical	80^{A}	-	90^{A}	40^{A}

[A](IPCC, 2006) [B](IBGE, 2015) [C](The max and min values for sugarcane were the maximum and minimum yield values from the studies time)

2.3.1.3. CO_2 emissions from Soil Organic Carbon (SOC)

Given that land use and land management have a large impact on organic C, the 2006 IPCC guidelines focus on methods estimating SOC (IPCC, 2006). There is a large difference on how the land use and management practices affect SOC in mineral versus organic soil types (IPCC, 2006). SOC is one of the most important components of soil; it determines the plants grow capacity, is the main source of energy and nutrients for microorganism and it also has an important role in nutrient retention, water holding capacity and soil structure (Paul, 2014).

Following IPCC 2006 guidelines procedures in combination with FAO soil types (FAO, 2015c) map and FAO climate regimes map (FAO, 2015d), Sao Paulo state was classified according to 2006 IPCC guidelines climate and soil type categorization. After the categorization, there was no presence of organic soils and the carbon stock change in soils was conducted for mineral soils. It was assumed that soils were in equilibrium for each reference year and default soil organic carbon stock values for mineral soils (ton of C/ ha in 0-30 cm depth) were assigned to each land cover category (IPCC, 2006). For urban areas, it was assumed that all was built in and that there was no SOC storage in the first 30 cm depth. The same assumption was made for water. Following equation 3, as there was no presence of organic soils and the inorganic soil net flux is 0 for tier 1 and 2 (IPCC,2006). The unit of measurement for this section is t CO_2-eq/ha year

In order to obtain the SOC (in tonnes of carbon per hectare in the first 30 cm soil depth) for each land cover category, the reference carbon content from each land cover category was multiplied by the correspondent soil stock change factors (Equation 4). Similar to the biomass carbon pool, the land cover categories were integrated into a Sao Paulo state SOC map (used as SOC_1 in Equation 3). Equation 3 was applied to establish the difference in SOC for each subsequent year (2004-2005, 2005-2006 and so on, t_1 correspond to the first year and t_2 to the second consecutive year). It must be highlighted that for SOC_{t2} only sugarcane SOC was used. This was made with the purpose of focusing on the SOC change from the expansion of sugarcane plantations and the ones already in sugarcane use. Each sugarcane SOC_{t2} cell was subtracted from the corresponding cell in $SOC_{t1.}$ $\Delta\, C_{Mineral}$.was multiplied with the CO_2 emission factor (– 44/12) to obtain t CO_2 emissions/ha from SOC changes towards sugarcane expansion and current use

Equation 3

$$\Delta\, C_{Mineral} = \frac{(SOC_{t2} - SOC_{t1})}{D}$$

$$SOC = SOC * F_{LU} * F_{MG} * F_I * \mathrm{A}$$

Δ $C_{Mineral}$ = annual change in carbon stocks in mineral soils, tons of C/year
SOC_{t1} = soil organic carbon at time $_{t1}$, tons of C/ha
SOC_{t2} = soil organic carbon at time $_{t2}$, tons of C/ha
SOC = soil organic carbon stock, tons of C/ha
D = time dependence of stock change factors, if using default values D = 20 years to reach equilibrium
A = 1 hectare is the area measure for this study.
F_{LU} = stock change factor for land use system or subsystem for a particular land use, dimensionless
F_{MG} = stock change factor for management regime, dimensionless
F_I = stock change factor for input of organic matter, dimensionless

Default values for SOC are dependable on soil type and climate, the variation between SOC in land covers is driven mainly by the soil stock change factors. Each land cover was classified according to the most adequate stock change factor value. Following IPCC procedures, the study assumes that carbon stock from areas without changes (no LUC) remain stable (for the SOC section). Table 3 displays the stock change factors used for each land cover (climatic zone dependable). The following section explains for each land cover category how the stock change factors were selected. Additionally, Table 5 presents the geographical input data used to calculate the CO_2 emission from LUC.

Sugarcane:

In 2007, Sao Paulo state authorities with the help of sugarcane associations signed a protocol (Green protocol) in order to change the traditional sugarcane harvesting (which applies fire) to what is known today as green harvesting (Franca et al., 2014). The protocol focused mainly on changing the pre-harvest burn practice (traditional method) to mechanical harvest (collects the stalks and leaves the residues on the field) practices for 2014 in mechanized areas and 2017 in non-mechanized areas (Galdos et al., 2009). It is expected that management practice changes occurring in sugarcane areas will contribute deeply to the sustainability of the sector (Panosso et al., 2009). F_{LU} values were selected assuming long term cultivated areas. F_{MG} factor refers mainly to till practices, given that sugarcane plantations have reduced till practices due its perennial lifecycle and 6 year harvest cycle (Macedo et al., 2008); F_{MG} values were selected for reduced till. F_I values are related to input level and returned residues.

For the first time period (2004-2014) low F_I values were selected given that pre-burn practice is implemented and residues are burned. Taking into account the prohibition of the pre-burn harvest from 2014 (Franca et al., 2014) and that mechanical harvest leaves high amounts of residues on the plantation area (De Figueiredo and La Scala, 2011), high input F_I values were selected for the (2014-2015) time period.

Forest:

For the forest category, all the stock change factors have a default value of 1 (IPCC, 2006).

Low vegetation:

As mentioned before, the low vegetation category has a broad definition and includes rangeland, managed and planted pastures and grasslands. Stock change factors were selected separately for the mentioned lands (IPCC, 2006) and mean values were calculated and assigned to the low vegetation category (the mean approach was used given the lack of data to calculate stock change factors as a weighted average). Several components such as moderate degraded grasslands (in Sao Paulo state affected by grazing for cattle production (Carvalho, 2006)), permanent grasslands values and medium input values were taken into account to select the correspondent default stock change factor.

Medium vegetation:

The procedure for this category was similar to the one implemented with the low vegetation category. Medium vegetation includes shrubland, rangeland and even tree fruit cropland. Stock change factors were selected separately for the mentioned lands following 2006 IPCC procedures. Then, mean values were calculated and assigned to the medium vegetation category. Stock change factors for shrubland have a default value of 1 (IPCC, 2006). For rangeland, F_{LU} values were selected assuming long term rangelands. The management factor was assumed for moderate degraded grasslands (Carvalho, 2006) and the input stock change factor has a default value of 1 (IPCC, 2006). Regarding citrus, F_{LU} values were selected assuming long term citrus plantations. The other stock change factors were assumed as no tillage and low input level (Coltro et al., 2009)

Eucalyptus:

Stock change factors for this category were assigned taking into account the agricultural process from the Americas Eucalyptus. In Brazil, the eucalyptus has a 7 year rotation process with soil tillage before harvesting (Manavakun, 2014). No soil tillage was assigned for management practice. Other stock change factors values are default values of 1 for Agroforestry (IPCC, 2006)

Annual cropland:

Annual cropland stock change factors were selected taking into account the yearly harvest cycle (from germination to the production of seed in one year). Close to 50% of Brazil's annual cropland is harvested with no tillage practices (de Freitas and Landers, 2014), the reduced tillage value was assigned for F_{MG} (IPCC,2006). F_{LU} values were selected assuming long term cultivated areas with annual cropland. It is almost impossible to determine the numerous different annual croplands in this category which could lead to different input levels; it was assumed a medium input level value.

Table 3. SOC stock change factors employed for each land cover category

Land cover	Climatic zone	F_{LU} [A]	F_{MG} [A]	F_I [A]
Sugarcane 2004-2014	Warm moist	0.69	1.08	0.92
	Tropical moist/wet	0.48	1.15	0.92
	Tropical montane	0.64	1.09	0.94
Sugarcane 2014-2015	Warm moist	0.69	1.08	1
	Tropical moist/wet	0.48	1.15	1
	Tropical montane	0.64	1.09	1
Forest	All	1	1	1
Low vegetation	Warm moist	0.896	1.016	1
	Tropical moist/wet	0.826	1.053	1
	Tropical montane	0.88	1.026	1
Medium vegetation	Warm moist	1	1.016	0.973
	Tropical moist/wet	1	1.053	0.973
	Tropical montane	1	1.026	0.98
Eucalyptus	Warm moist	1	1.15	1
	Tropical moist/wet	1	1.22	1
	Tropical montane	1	1.16	1
Annual cropland	Warm moist	0.69	1.08	1
	Tropical moist/wet	0.48	1.15	1
	Tropical montane	0.64	1.09	1

[A] *(IPCC, 2006)*

Sensitivity analysis

Different from the CO_2 emissions from the biomass section, the emissions from the SOC parameter depend exclusively from the LUC. As mentioned before, the methodology assumes that there are no SOC changes in sugarcane maintaining areas. Furthermore, each soil type has a carbon stock reference value regardless of the land cover type. The spatial difference between land cover categories carbon stock is manly ruled by the stock change factors (F_{LU} , F_{MG}, F_I). A sensitivity analysis was also conducted for this section (for the 2004-2005 harvest year) with the relevant land cover categories. Low vegetation, medium vegetation and annual croplands are the relevant land cover categories given that sugarcane is expanding the most in those land cover categories. Stock change factors were shifted to their maximum and minimum correspondent values while leaving the other parameters unchanged. Additionally, sugarcane stock change factors were also analyzed. Table 4 summarizes the input data used for the sensitivity analysis from the SOC section.

Table 4 Parameters used for the sensitivity analysis for the CO_2 emissions from the SOC section

Land cover	Climatic zone	F_{LU} [A]		F_{MG} [A]		F_I [A]	
		Max	Min	Max	Min	Max	Min
Low vegetation	Warm moist	0.924	0.869	1.116	0.919	N/A	N/A
	Tropical moist/wet	0.9	0.74	1.153	0.954	N/A	N/A
	Tropical montane	0.986	0.773	1.476	0.577	N/A	N/A
Medium vegetation	Warm moist	1.16	0.83	1.14	0.919	1.016	0.93
	Tropical moist/wet	1.16	0.83	1.152	0.953	1.016	0.93
	Tropical montane	1.16	0.83	1.476	0.577	1.136	0.823
Sugarcane	Warm moist	0.773	0.607	1.134	1.026	1.048	0.791
	Tropical moist/wet	0.7	0.26	1.234	1.058	1.048	0.791
	Tropical montane	0.96	0.32	1.635	0.545	1.41	0.47
Annual cropland	Warm moist	0.773	0.607	1.134	1.026	N/A	N/A
	Tropical moist/wet	0.7	0.26	1.234	1.058	N/A	N/A
	Tropical montane	0.96	0.32	1.635	0.545	N/A	N/A

[A] *(IPCC, 2006)*

Table 5 Geographical input data used to calculate CO_2 emissions

Input data	Reference
Brazil land cover data set (2004:2015)	(TUD, 2016)
Crop suitability index for sugarcane	(FAO, 2012a)
Crop suitability index for alfalfa	(FAO, 2012b)
Biomass forest map	(Avitabile et al., 2016)
Thermal regimes: thermal climates	(FAO, 2012c)
Soil types	(FAO, 2012d)

2.4 Biodiversity

Land use change has been identified as one of the main drivers of global biodiversity loss (De Baan et al., 2013). Furthermore, agricultural expansion is seen as one of the major threats to biodiversity loss (Dirzo and Raven, 2003). Several methodologies have been developed to measure biodiversity impacts from land use changes that vary in great extent from each other. Traditional methods such as species richness or species inventories mostly include direct measurements on the field (Pereira et al., 2013). Nevertheless, field samples are expensive and time consuming to process for a whole state as Sao Paulo. Other studies have used landscape indicators as proxy indicators to determine the biodiversity status of an area (McGarigal and Cushman, 2002; Fahrig, 2003). Furthermore, different models such as the GLOBIO model have been developed to estimate the impact on biodiversity from different drivers such as LUC. Other types of models such as statistical models are used to determine biodiversity distribution and possible impacts in those areas (Ferrier and Guisan, 2006). However, these types of models demand high amounts of specific input data. In this study, the impact of land use change induced from sugarcane on biodiversity was measured by 3 different approaches. These approaches were selected based on the available input data (LUC being the most important) and model knowledge needed for the processing. Each approach is explained in the correspondent sub-section. The Mean Species Abundance (MSA) indicator was the only one used for the results integration section and for the sensitivity analysis for this section.

2.4.1 Protected areas

The status of Protected Area (PA) is given to a region due to its ecological, social and economic importance (Watson et al, 2014). These areas are at the core of efforts towards conserving nature and the services they provide to people (IUCN, 2013). In addition to the crucial objective of conserving biodiversity (Le Saout et al, 2013), well-managed protected areas can provide crucial ecosystem services and now PA's are also seen as crucial components of global climate change mitigation efforts (Watson et al, 2014). Conversely, land use change is one of the most important factors leading to biodiversity and habitat loss (Falcucci et al, 2007). It is well known that changes in land cover are mostly caused by deforestation, agriculture and urban expansion (Ellis and Porter-Bolland, 2008). Consequently, PA's are seen as one of the most important tools in conserving biodiversity with in their limits from possible land use change dynamics (Le Saout et al, 2013).

The land use change within protected areas induced from sugarcane expansion (sugarcane expanding within PA's) was used as a proxy indicator to determine biodiversity impacts. Brazil's protected areas are categorized within two major groups (strict PA's and sustainable use PA's). Strict PA's are focused mainly on ecosystem protection, scientific research and education (Rylands and Brandon, 2005). Activities such as agriculture are forbidden in these areas. Different from strict PA's, sustainable use PA's can be exploited for natural resources in a sustainable way (that includes agriculture and other practices that may affect biodiversity dynamics) (Rylands and Brandon, 2005). Taking into account that biodiversity might be affected in sustainable use PA's given anthropogenic activities and that strict PA's are focused mainly on ecosystem protection (Rylands and Brandon, 2005), only strict PA's were assessed in this study (it is assumed that they are better proxy indicator than sustainable use PA's). Strict PA's are subdivided into: National park, Biological reserve, Ecological station, Wildlife refuge and Natural monument. The strict PA's data[4] was clipped into Sao Paulo state extent (Filtered to assess PA's located only in Sao Paulo state) and then intersected with the land cover data. The process was repeated for each year in order to obtain the yearly dynamics from sugarcane plantations expansion (if present) inside PA's. More than 20 strictly PA's were found in Sao Paulo state. Some PA's extent trespass Sao Paulo state limits (for this the area of PA's only located in Sao Paulo state were quantified). All the PA's area was added and normalized [5].

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[4] Obtained from the Brazilian biodiversity conservation institute Chico Mendes(ICMBio, 2016)

[5] Getting the all PA's area values into a common scale, % of total PA's area

2.4.2 Land cover change dynamics (forest category)

Land cover change dynamics have become an essential mechanism in evaluating the consequence of anthropogenic activity in the environment and landscape (Dunn, 2004). It is recognized that land cover changes have major consequences in all biodiversity levels (Tallmon et al., 2003). Furthermore, these changes may lead to alteration in biotic diversity, and primary productivity (Flamenco-Sandoval et al., 2007). Several studies have used changes in land cover classes (especially forest land cover) as proxy indicators to reveal changes in habitats and biodiversity in different regions (Flamenco-Sandoval et al., 2007; Texeira et al., 2009; Abdullah and Nakagoshi 2007). Changes in forest land cover category can also be used as a proxy indicator (Farhtig, 2003). Therefore, measuring land use changes in forest land cover category can be used as a proxy indicator for biodiversity status in an area.

Land cover change is a dynamic process and just as cover loss (forest cover), regeneration processes also occur. The net balance analysis (difference between cover loss and regeneration) has become a crucial part of the land cover change dynamics analysis (Flamenco-Sandoval et al., 2007). Deforestation dynamics from sugarcane expansion for the whole Sao Paulo state were analyzed for each year of the studied time step (2004-2015). The analysis was conducted mainly for the forest category (total forest area) taking into account deforestation areas, regeneration area and net balance analysis. Additionally, 3 landscapes indicators (number of patches, percentage of landscape and patch density) were measured and analyzed spatially for the forest category from the land use change from sugarcane expansion. Number of patches in the forest category was assumed as the number of cells that change from forest to sugarcane. Each patch was defined as the number of neighboring cells (or just one cell) from the same category that were transformed, otherwise, the patch size is 1 km^2 (given the maps resolution). Percentage of landscape is the area that is deforested in relation to the total forest category area from sugarcane expansion. Patch density was calculated as the number of patches in 100 ha of forest area.

2.4.3 Mean species abundance (MSA)

MSA is a biodiversity indicator defined as “the remaining mean species abundance of original species, relative to their abundance in pristine or primary vegetation, which are assumed to be not disturbed by human activities for a prolonged period” (Alkemade et al., 2009). MSA is normally measured by the GLOBIO model with input data from the Integrated Model to Assess the Global Environment (IMAGE). The model works without any biodiversity distribution information; instead it uses a causal-effect relationship between environmental drivers and biodiversity impacts (Alkemade et al., 2009). Land use change, atmospheric nitrogen deposition, infrastructure, fragmentation and climate change are the drivers included in the model (Alkemade et al., 2009). For the purpose of this study (taking into account that land use change is the main axis from this study), land use change is the only environmental driver that was taken into account. However, the MSA indicator is restricted for terrestrial ecosystems (water land cover category was not evaluated) (Alkemade et al., 2009).

The MSA indicator varies from 0-1; being 1 a pristine original ecosystem with species abundance not affected by human activities and 0 the opposite. Each land cover category has a different MSA land use value (depending on description). Alkemade et al., (2009) assigned MSA values to different land cover categories based on literature review. The land cover categories from this study were related to the ones from Alkemade et al., (2009) and MSA values were assigned (Table 6). Subsequently, the MSA per cell was calculated for each harvest year (2004-2005, 2005-2006 and so on) taking into account sugarcane land cover area dynamics. The yearly change was classified into 5 categories depending on the land cover that was transformed into sugarcane. Positive change is defined as areas where the MSA land use value increases due to sugarcane expansion in 0-0.3 MSA land use score. No change areas are the ones that stay constant with the same MSA land use value (sugarcane remaining sugarcane). Negative change areas are the ones with a negative change (reduction of MSA score) from 0-0.3 MSA land use. Negative change - areas are the ones with a reduction between 0.3-0.6 MSA score. Negative change - - areas are the ones with bigger change than 0.6 MSA land use score.

Table 6 MSA land use value assigned to this study land cover categories

Land cover category	**MSA land use score**
Urban	0.05[A]
Water	N.A.
Forest	1[B]
Eucalyptus	0.5[C]
Low vegetation	0.6[D]
Medium vegetation	0.75[E]
Sugarcane	0.3[F]
Annual cropland	0.1[G]

[A] *Value from artificial land cover category (Alkemade et al., 2009);* [B] *Values from forest land cover category primary vegetation (Alkemade et al., 2009);* [C] *Value from secondary forest land cover category (Alkemade et al., 2009);* [D] *Mean value from grass or shrubland, livestock grazing and man-made pastures land cover categories (Alkemade et al., 2009);* [E] *Mean value from grass or shrubland and agroforestry land cover categories (Alkemade et al., 2009);* [F] *Value from Low-input agriculture land cover category and perianal bioenergy crop (Alkemade et al., 2009) (van Rooij, 2008) ;* [G] *Value from intensive agriculture land cover category (Alkemade et al., 2009).*

Sensitivity analysis

Following the same approach from the biomass and SOC section, the sensitivity analysis for the MSA was conducted for the relevant land cover categories. Low vegetation, medium vegetation, annual cropland and sugarcane were the relevant land cover categories given that LUC dynamics for sugar expansion in Sao Paulo state occur mainly between them. MSA land use parameter was changed to the maximum or minimum score (depending on land cover) while leaving the other land cover categories unchanged. The 2007-2006 harvest year was used for the analysis and sugarcane maintaining values were not accounted (no change score). It must be highlighted that the standard error from the land cover categories regarding the MSA score is low, different from some parameters in the IPCC 2006 guidelines used in the other sections. For the analysis only the LUC result (reference value) was taken into account

(The value for sugarcane maintaining areas stay constant) Table 7 summarizes the input data used for the analysis from the MSA section.

Table 7 Parameters used for the sensitivity analysis for the Biodiversity section

Land cover category	**MSA land use score**	
	Max	**Min**
Low vegetation	0.62^D^	0.58 ^D^
Medium vegetation	0.77^E^	0.73 ^E^
Sugarcane	0.34^F^	0.26 ^F^
Annual cropland	0.11^G^	0.09 ^G^

DMean value from grass or shrubland, livestock grazing and man-made pastures land cover categories (Alkemade et al., 2009); E*Mean value from grass or shrubland and agroforestry land cover categories (Alkemade et al., 2009); FValue from Low-input agriculture land cover category and perianal bioenergy crop (Alkemade et al., 2009) (van Rooij, 2008) ;* G*Value from intensive agriculture land cover category (Alkemade et al., 2009).*

2.5 Water quantity

Water availability is strongly linked with LUC dynamics; these dynamics directly affect fresh water supplies (especially with agricultural expansion) and may trigger water stress in different areas (Foley et al., 2005). Furthermore LUC dynamics can disturb the water balance and affect regional hydrological water cycles (Goldemberg et al., 2008). Studies have highlighted how changing the land use to other purposes (especially agriculture) may cause changes in precipitation, evapotranspiration, runoff, and groundwater flow (Foley et al., 2005; Tong et al., 2012; Baker and Miller, 2013). Evapotranspiration is one of the major components of the water balance and it is crop dependent (Allen et al., 1998). Furthermore, this component also depends on several other variables such as growing stage of the crop, climatic conditions and soil type and quality (Allen et al., 1998). Different methodologies such as the L-THIA/NPS GIS model have been developed to analyze potential water depletion from LUC (Bhaduri et al., 2000). Nevertheless, applying these methods demand a high degree of knowledge in modelling and specific regional and temporal data. Just as for all the other EI's, the calculations were completed not only for sugarcane expansion area but also for the existing areas of sugarcane use.

A water balance approach has been used in several other studies addressing the potential water shortage from LUC due to bioenergy crops (van Dam et al., 2009; van der Hilst et al., 2012). This study followed the same approach by comparing sugarcane evapotranspiration to the effective precipitation of the region. This process was done spatially and temporal explicit and completed for each of the correspondent harvest years. This was done with the purpose to identify if the current sugarcane plantations areas were undergoing water shortage. Equation 4 describes the water depletion in reference to bioenergy crops production (van Dam et al., 2009).

Equation 4

$$WS_i = ((ET_{0i} * K_{ci}) - EP_i)$$

Where:

WS = Total water shortage in month i, mm/month
ET_i = Reference evapotranspiration of month i, mm/month
Kc_i = Crop evapotranspiration coefficient for specific growth stage in month i, dimensionless
EP_i = Effective precipitation in month i, mm/month
i= Month January to December

Sugarcane in Brazil has a semi-perennial ratoon cycle and it grows approximately for 12 (year sugarcane) or 18 months (year-and-half sugarcane) depending on sugarcane variety (Rudorff et al., 2010). In the south-central region, where Sao Paulo state is located, sugarcane harvesting extends from April to December (Rudorff et al., 2010). Sugarcane growing stages (number of days) differ from sugarcane virgin to sugar cane ratoon (Allen et al., 1998). Given the impossibility to identify spatially between virgin sugarcane and sugarcane ratoon, each growing stage length (number of days) was calculated as an average from virgin sugarcane and sugarcane ratoon. Table 8 illustrates sugarcane growing stages with their correspondent Kc values (the total number of days is more than a year given the extended growing time of the virgin sugarcane). Taking into account harvest season in Sao Paulo state, it was assumed that all sugarcane cycle is completed in 12 months (year sugarcane) and harvested in April. Considering the time frame of the sugarcane growing stage, the initial season was assumed for the month of April, the Mid-season from May to December and the late season from January to March[6]. In order to obtain specific sugarcane evapotranspiration values, the Kc values were multiplied with ET_0 as shown in equation 4

Table 8 Kc values assigned to each corresponded sugarcane growing stage

Growing stage (number of days)[A]	Kc values (dimensionless)[A]
Initial (40 days)	0.45
Mid-season (260 days)	1.25
Late season (100 days)	0.75

[A]*(Allen et al., 1998)*

Effective precipitation (EP) is the amount of precipitation that is actually added and stored in the soil (Brouwer and Heibloem, 1986). EP is calculated from actual precipitation, and for this study, the United States Department of Agriculture (USDA) formula (equation 5) present in the CROPWAT 8.0 model was used. Actual precipitation data was extracted from the Brazilian National Meteorological institute (INMET Portuguese acronym). Long term monthly precipitation averages from 1961-1990 data were retrieved from the conventional meteorological stations located in Sao Paulo Minas Gerais, Parana, Rio de Janeiro and Mato Grosso do sul states[7]. Precipitation averages were retrieved from Sao Paulo and neighboring states in order to interpolate and obtain precipitation values for the whole Sao Paulo state extension. The data was accessed through the INMET network (http://www.inmet.gov.br/portal/index.) (INMET, 2016), this network only allows access to conventional stations (Automatic stations data was not available). Each station location was

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[6] ET_0 and EP average reference maps were calculated with the same time frame from each different sugarcane growing stage (in order for time frames of all variables to match)

[7] Long term averages were used given the lack of data for other climatic parameters such as temperature for the studied time step (2004-2005)

processed through ArcGIS in Sao Paulo state map (and neighboring states). Effective precipitation was calculated (with equation 5) for each station on a monthly basis and then interpolated with the Inverse Distance Weighted (IDW) method from the ArcGIS toolbox (based on stations location) to obtain a spatially explicit effective precipitation reference map for each month in Sao Paulo state. Taking into account sugarcane grow stages and harvest time defined by the Kc values, 3 different EP reference maps were developed. This was made with the intention to evaluate if there was any water deficit in the different growing stages of Brazilian sugarcane. Each EP reference map is based on monthly averages of different consecutive months. The first map considers the time step from January to March, the second one corresponds to April and the third one from May to December.

Equation 5

$$EP_i = \left(P_i * \left(\frac{125 - *0.2P_i}{125}\right)\right)$$

Where:

EP_i = Effective precipitation in month i, mm/month
P_i = precipitation in month i, mm/month

The evapotranspiration rate from a reference surface is called the reference crop evapotranspiration or reference evapotranspiration (ET0) (Allen et al., 1998) This values is calculated assuming hypothetical grass reference and as mentioned before, multiplying this value with crop specific Kc values results in specific crop evapotranspiration rate (depending on growing stage). The study applied the Penman–Monteith methodology (equation 6) which is the most widely method applied for calculating ET_0 (van der Hilst et al., 2012). Solar radiation, air temperature, air humidity and wind speed are the meteorological factors that determine $ET_{0.}$ Long term monthly averages were used for maximum temperature, minimum temperature, mean temperature and relative humidity. It was not possible to establish long term monthly averages for wind speed and actual number of hours of solar duration; for these two elements a mean monthly value was calculated from 2004-2015 time step. The required data was accessed through the INMET network (http://www.inmet.gov.br/portal/index.) for the same stations as in the EP section (INMET, 2016). ET_0 was calculated for each station (equation 6) and then interpolated with the Inverse Distance Weighted (IDW) method from the ArcGIS toolbox to obtain a ET_0 reference map for Sao Paulo state. ET_0 reference maps were developed with the same monthly averages division as in the EP section. In consequence, 3 different ET_0 reference maps were developed and used in equation 4. It must be highlighted that ET_0 and EP reference maps (with the monthly division) are the same for each harvest year.

Equation 6

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

ET_{0i} = Reference evapotranspiration of month i, mm/month
R_n = net radiation at the crop surface, MJ/m^2 month,
G = soil heat flux density, MJ/m^2
T = air temperature,°C
u_2 = wind speed, m/s
e_s = saturation vapour pressure, kPa
e_a = actual vapour pressure, kPa
e_s - e_a = saturation vapour pressure deficit, kPa
Δ = slope vapour pressure curve, kPa/°C
γ = psychrometric constant kPa °C

Sensitivity analysis

The sensitivity analysis for this section is different from the other indicators. Given that this category is more dependable on biophysical characteristics such as crop evapotranspiration coefficients, the sensitivity analysis was conducted for each sugarcane growing stage. The Kc sugarcane parameter for each growing stage was changed to the maximum and minimum score while leaving the other variables constant (effective precipitation). The 2014-2015 harvest was used for the analysis and table 9 summarizes the input data used for this section analysis.

Table 9 Kc values assigned to each corresponded sugarcane growing stage for the sensitivity analysis

Growing stage (number of days)[A]	**Kc values (dimensionless)**[A]	
	Max	**Min**
Initial (40 days)	0.6	0.4
Mid-season (260 days)	1.3	1
Late season (100 days)	1.05	0.6

[A] *(Allen et al., 1998)*

2.6 Soil erosion

Soil erosion is a natural process driven by water and wind; nevertheless human activities have enhanced this process through land cover alterations (Yang et al., 2003). In the last years, soil degradation has been identified as one of the most important environmental threats to the sustainability and productive capacity of agriculture (Yang et al., 2003; Pimentel, 2006). LUC not only enhances soil erosion directly (mainly through agricultural processes and deforestation), it also disturbs it indirectly through the disruption of natural cycles (water cycle, carbon cycle, etc) (Yang et al., 2003). In Brazil, soil degradation as a consequence of erosion is one of the major issues linked to sugarcane cultivation (Martinelli and Filoso, 2008). Soil erosion in sugarcane cultivation areas (due to management practices) tends to be high in comparison to other land covers such as pasture lands and forest (Politano and Pissarra, 2005). A large number of methodologies to measure soil erosion such as soil erosion measure by plots have been used in the past years (Boix-Fayos et al., 2006). However, applying these techniques demands extensive field work. Alternatively, numerous soil erosion models have been developed (European soil erosion model, Limburg soil erosion model, Water and tillage erosion model, etc.) by different organizations (Soil erosion site, 2016). Nonetheless, the Revised Universal Soil Loss Equation (RUSLE) is the most frequently used and accepted equation to estimate soil erosion (Laflen and Moldenhauer, 2003)

The RUSLE equation is an empirical based model derived from the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). RUSLE enables the calculation of annual rate of soil erosion spatially and it is driven by five major factors (rainfall pattern, soil type, topography, crop system, and management practices) (Renard et al., 1997). RUSLE is commonly applied into GIS environments and the calculations are performed for each cell from the grid/raster (Fu et al., 2006). Equation 7 describes the annual rate of soil erosion driven by the 5 major factors (Renard et al., 1997). The calculations were done on a yearly basis and take into account sugarcane land cover current use (2004 base map) and sugarcane cultivation expansion. This was made with the purpose to obtain soil erosion from sugarcane cultivation and expansion. It must be highlighted that this study focused only on soil erosion cause by the action of water.

Equation 7

$$A = R * K * LS * C * P$$

Where:

A = Soil loss, t/ ha year
R = Rainfall-runoff erosivity factor MJ mm/ha h year
K = Soil erodibility factor t ha h/ha MJ mm
L = Slope-length factor, dimensionless
S = Slope steepness factor, dimensionless
C = Cover management factor, dimensionless
P = Conservation support practice factor, dimensionless

Rain-runoff erosivity factor (R)

Rainfall erosivity is defined as the aggressiveness of the rain to cause erosion and the original R factor for any given period is obtained by summing for each rainstorm, the product of total storm energy (E) and the maximum 30-min intensity (I30) (Wischmeier and Smith 1978). Nevertheless, pluviometry data with that level of detail was not available for Sao Paulo state. Numerous authors have estimated the R value by using monthly and annual precipitation averages by the means of the Fournier index equation 8 (Bertoni and Lombardi, 1985; Neto and Moldenhauer, 1992; Renard and Freimund, 1994; da Silva, 2004; Kouli et al. 2009). Furthermore numerous authors have found strong relationships between the Fournier index and annual values of R (Bertoni and Lombardi Neto, 1985). These relationships (equations) between R and Fournier index are ideally computed with over 20 year rainfall data and depend on local conditions (Bertoni and Lombardi Neto, 1985). In Brazil, these relations (equations) have been calculated for different regions finding a strong relationship with linear or exponential equations (da Silva, 2004). Neto and Modenhauer (1992) defined an equation for a municipality in Sao Paulo state with more than 20 year of precipitation data. Following the same approach as da silva (2004), this study used Neto and Modenhauer (1992) equation to relate Fournier index values to calculate R values for the Sao Paulo state region (equation 8).

Equation 8

$$Cc_i = \frac{M_i^2}{P}$$

$$R = \sum_{i=1}^{12} 68.730 * Cc_i^{0.841}$$

Where:

CC = Fournier index for month i, dimensionless
M = Monthly value of precipitation for month i, mm
P = Annual precipitation, mm
R = Rainfall-runoff erosivity factor MJ mm/ha h year

Precipitation monthly data was retrieved from the conventional meteorological stations located in Sao Paulo Minas Gerais, Parana, Rio de Janeiro and Mato Grosso do sul states for the 2004-2015 time step. The data was accessed through the INMET network data (INMET, 2016), this network allows only to access conventional stations. 7 out of the 21 station were missing monthly values for some years (1 or 2 monthly values missing), these missing values were replaced with the long term precipitation averages 1961-1990 for the specific missing month from correspondent meteorological station. R values were calculated for each station and interpolated to obtain spatially explicit and temporally (year basis) R maps for Sao Paulo state.

Soil erodibility factor (K)

The K factor is an empirical measure of soil erodibility affected by soil properties (Fu et al. 2006). The main soil properties affecting K are soil texture, organic matter, structure, and permeability of the soil profile (Fu et al. 2006). K values calculations demand detailed field data of soil types such as soil silt %, clay % organic matter %, etc. (Wischmeier and Smith 1978). Other authors have calculated K values by estimating soil variables with high detailed soil type description (Kouli et al. 2009). Given the impossibility of field work and lack of explicitly detailed soil type properties, this study followed the approach from Silva et al., (2005) and Beskow et al., (2009). Based on a literature review, Silva et al., (2005) created a data base of K values for the soil types present in Sao Paulo state (it must be highlighted that the K values in the data base were calculated based on field work). The Brazilian updated soil classes' map was downloaded from IGBE data base (ftp://geoftp.ibge.gov.br) (IBGE,

2006) and clipped into Sao Paulo extent. Based on Silva et al., (2005), K values were assigned to each type of soil to obtain a K spatial map from Sao Paulo state. Different from R values maps; K values map is constant for the entire time step (2004-2015).

Slope-length (L) and slope steepness (S) factors

The slope length factor (L) represents the effect of slope length on erosion, and the slope steepness factor (S) reflects the influence of slope gradient on erosion (Wischmeier and Smith 1978). Originally these values are measured on field taking into account slope length and slope angle (Wischmeier and Smith 1978). Nevertheless, several authors calculate the LS factor by the means of digital elevation models (DEM) (Fu et al., 2006; Kouli et al. 2009; Prasannakumar et al., 2012). Sao Paulo state DEM was downloaded from the Federal University from Rio Grande do Sul data base (http://www.ecologia.ufrgs.br/labgeo), this data base provides the official reference DEM's for all Brazilian states (Weber et al., 2004). There are many formulas capable of calculating LS factors (Kouli et al. 2009). Nevertheless, the LS factor was calculated following the equation from Bizuwerk et al., (2003). Equation 9 describes how the LS factor was calculated.

Equation 9

$$LS = (Flow\ accumulation * \frac{Cell\ size}{22.13})^{m} * (0.065 + 0.045\, s + 0.0065\, s^{2})$$

Where:

LS = combined slope length and slope steepness factor for each cell, dimensionless
Flow accumulation = accumulated upslope contributing area for a given cell, dimensionless
Cell size = size of grid cell, meters
m= value m is a constant varying from 0.2-0.5, dimensionless
S = slope gradient, %

Flow accumulation and slope values are required to estimate LS factor. The flow accumulation and slope gradient were computed from the Sao Paulo state DEM using ArcGIS Spatial analyst plus with arc hydro extension toolbox for flow accumulation and slope gradient. The cell resolution from the Sao Paulo state DEM is 30 m. For practical reasons and to avoid less incongruence the LS was calculated with the original cell resolution and then resampled to the same resolution of the other environmental impacts (this had to be done for the integration of EI). m values are given depending of the slope, for slope values bigger than 5% a m value of 0.5 is given, for slopes values between 3-5% a m value of 0.4 is given, for slope values between 1-3 a m value of 0.3 is given and for slope values below 1% a m value of 0.2 is assigned (Wischmeier and Smith, 1978). Just as the k values map, LS map remains constant for the entire time step (2004-2015).

Cover management factor (C)

C factor is defined as the ratio of soil loss from land cropped under specific conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier and Smith, 1978). This value is normally calculated using satellite images and the Normalized Difference Vegetation Index (NDVI) (Prasannakumar et al. 2012) or by empirical equations based on the measurements of variables related to ground covers collected in sample plots (LU et al., 2004). Nevertheless, values for C factor depending on land cover are available in literature. Studies performed in Brazil and Sao Paulo state have calculated different C values for several land cover categories (Hilu, 2003; Ruhoff et al., 2006; Silva et al., 2007; Galdino et al., 2015). It must be highlighted that C values are time dependable (growing stage) and land cover dependable, this study assumed that these values were constant for each land cover (not changing in time) for the entire studied time step (2004-20015). Additionally, the values were assigned based on a literature review from studies performed in Sao Paulo state or Brazil.

C values were assigned following the same approach of Silva et al., (2007). C values were assigned based on literature review for the Sao Paulo state scenario (Silva et al., 2007). Land cover categories were compared with the ones from Silva et al., (2007) and several assumptions were done. Low vegetation category has a wide definition in this study, nevertheless it can be associated with pastureland land cover category (Low vegetation C factor is from pastureland land cover category). Mid vegetation land cover category includes Shrubland, Pastureland and Citrus crops, for this category a mean value was calculated between citrus crops and pastureland from Silva et al., (2007) land cover categories. It must be highlighted that there was no comparable category for shrubland. Given the lack of data for the forest category in Sao Paulo state, this C factor value was adopted from another study performed in Brazil (Ruhoff et al., 2006). The eucalyptus category was assigned the same C factor as the forest one[8]. Similar to R values maps, C values map were also assigned spatially explicit on a yearly basis. However these values are not variating within each land cover category. Table 10 shows the C values assigned to each land cover category.

Table 10 C factors for different land cover categories in Sao Paulo state

Land cover	C factor	Reference
Urban	0.12	(da Silva, 1999)
Water	N.A.	N.A.
Forest	0.01	(Ruhoff et al., 2006)
Eucalyptus	0.01	(Ruhoff et al., 2006)
Mid vegetation	0.2	(Silva et al., 2007)
Low vegetation	0.16	(Silva et al., 2007)
Sugarcane	0.17	(Mitchell and Bubenzer, 1980; Silva et al., 2007)
Annual cropland	0.29	(Ruhoff et al., 2006)

Conservation support practice factor (P)

The support practice factor (P) represents erosion prevention practices, such as strip-cropping and terracing and varies from 0-1 (being 1 not prevention at all) (Kim et al., 2005). These

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[8] This approach is not the most recommendable, nevertheless given the land use dynamics from Sao Paulo state sugarcane expansion never occurs on eucalyptus land cover. In consequence this assumption is not affecting the results for this or any section.

values are assigned depending on the soil prevention practices adopted locally for each land cover. Nevertheless, most of the studies assign a value of 1 given the lack of significant erosion prevention strategies (Kim et al., 2005; Fu et al., 2006; Kouli et al., 2009; Prasannakumar et al., 2012). The P factor values were assigned following the same approach at in the C values section. The same assumptions were made and values were assigned based on literature review from Silva et al., (2007) methodology. P values maps were also calculated spatially explicit on yearly basis and Table 11 illustrates the P values assigned to each land cover category.

Table 11 P factors for different land cover categories in Sao Paulo state

Land cover	P factor	Reference
Urban	1	(da Silva, 1999)
Water	N.A.	N.A.
Forest	0.1	(Ruhoff et al., 2006)
Eucalyptus	0.1	(Ruhoff et al., 2006)
Mid vegetation	0.6	(Silva et al., 2007)
Low vegetation	0.7	(Silva et al., 2007)
Sugarcane	0.7	(Mitchell and Bubenzer, 1980; Silva et al., 2007)
Annual cropland	0.5	(Bertoni and Lombardi Neto, 1990; Mitchell and Bubenzer, 1980; da Silva, 1999).

Sensitivity analysis

The soil erosion indicator is the only that lacks of a sensitivity analysis. There is no standard error % to change the values from P or C factors. Furthermore, the only variable that is changing each year is the R factor. Given this assumption, the results would be correlated to this parameter and would vary depending on the change of the R factor. No sensitivity analysis was considered necessary with the available data.

2.7 Environmental impacts integration

In order to establish spatially the sustainability of the sugarcane production, the EI maps were integrated. The integration was done for each harvest year. Given that the EI are measured in different units, merging them requires certain degree of standardization. Normally, the integration method depends on the study objective (Abaza et al., 2004). A simple reclassification was done and values of 0, 1 or -1 were assigned to each EI. -1 corresponds to a negative impact, 1 to a positive impact and 0 to no impact. This reclassification will help to identify the spatial difference between sustainable (positive values) or unsustainable (negative values) sugarcane production and sugarcane expansion areas.

Regarding CO_2 emissions, it is considered a negative impact if the area is emitting CO_2 and if it is acting as a sink it is considered a positive impact. As to biodiversity, only the MSA indicator was taken into account. If the MSA value is positive, then it is considered a positive

EI and if the value is negative it is considered a negative EI. Regarding to water shortage, positive EI’s are assumed when there is a water surplus from sugarcane plantations and negative EI’s take place when sugarcane is submitted to water shortage. With regard to soil erosion, negative values are assumed when soil loss is generated and when there is no presence of soil loss no change is assumed. The soil loss parameter lacks a positive effect (given the methodology applied, there is no soil accumulation). Then, each EI’s values (with the new reclassification) were summed up and a scale between -4 and 4 was obtained. A score of 4 translates into an area with only positive EI’s for all the categories, meanwhile a score of -4 is the opposite. Nevertheless the maximum positive score is 3 given the assumption from the soil parameter. It was assumed that all EI’s are equally important.

3. Results

The results section is distributed between each EI and Sao Paulo state land use dynamics. Land use dynamics are highly important given that they are closely related to each EI (main driver). The sensitivity analysis results are also included in each EI section.

3.1 Land use change

Fig. 2 displays the yearly changes in sugarcane plantation area (ha) that are occurring in Sao Paulo state. The sugarcane plantations have increased from 4.17 million hectares in 2004 to 4.95 million hectares in 2015 (Fig .2 (F)). However, in intermediate years the sugarcane area goes as high as 5.38 million hectares in 2012. Sugarcane area was also analyzed without projecting the input data to 1 km^2 (Using high resolution original maps) and the same magnitude variation was found. Other studies using Landsat type remotely sensed data reported an increase of 2.57 million ha in 2003 to 4.45 million ha in 2008 (Rudorff et al., 2010). Meanwhile, the CANASAT (2016) project has reported a total sugarcane cultivated area of 3.13 million hectares in 2004 to 5.7 million hectares in 2014[9]. The sugarcane expansion dynamics show an expansion, reaching a peak and then decreasing trend (Fig. 2 (A)), this trend is repeated two times in the studied time step. Even if the total area results differ in magnitude from other studies (Uriarte et al., 2009), the sugar expansion trend goes in line with other publications (Adami et al., 2012) (CANASAT, 2016).

Sugarcane plantations have been expanding yearly with a peak value in 2007-2008 harvest season. The sugarcane phenomenon is not only characterized by sugarcane expansion, sugarcane plantations are also shifting into other land cover categories (Fig 2. (B)) almost as the same rate as the sugarcane expansion. Given that the study is only addressing direct land use change and the state is considered a closed system, the real change[10] (Fig. 2 (D)) was in average 0.82 million hectares for the entire time step. This value completely contrasts with other studies sugarcane expansion values[11] (Rudorff et al., 2010) (Adami et al., 2012) (CANASAT, 2016) (Nassar et al., 2008). The sugarcane expansion and area transformed to other land cover category in comparison to the remaining area (F), is only a small percentage of it, as reported in other studies (CANASAT, 2016) (Adami et al., 2012). Even if there is a clear expansion, it seems the total sugarcane area tends toward stabilization (Fig 2. (B)).

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[9] Sugarcane land cover definition (including area under renovation) was taken into account for results comparison between all studies.

[10] Difference between sugarcane area expansion and sugarcane change to other land cover categories.

[11] Other studies only take into account the sugarcane area expansion and not the one that changes from sugarcane

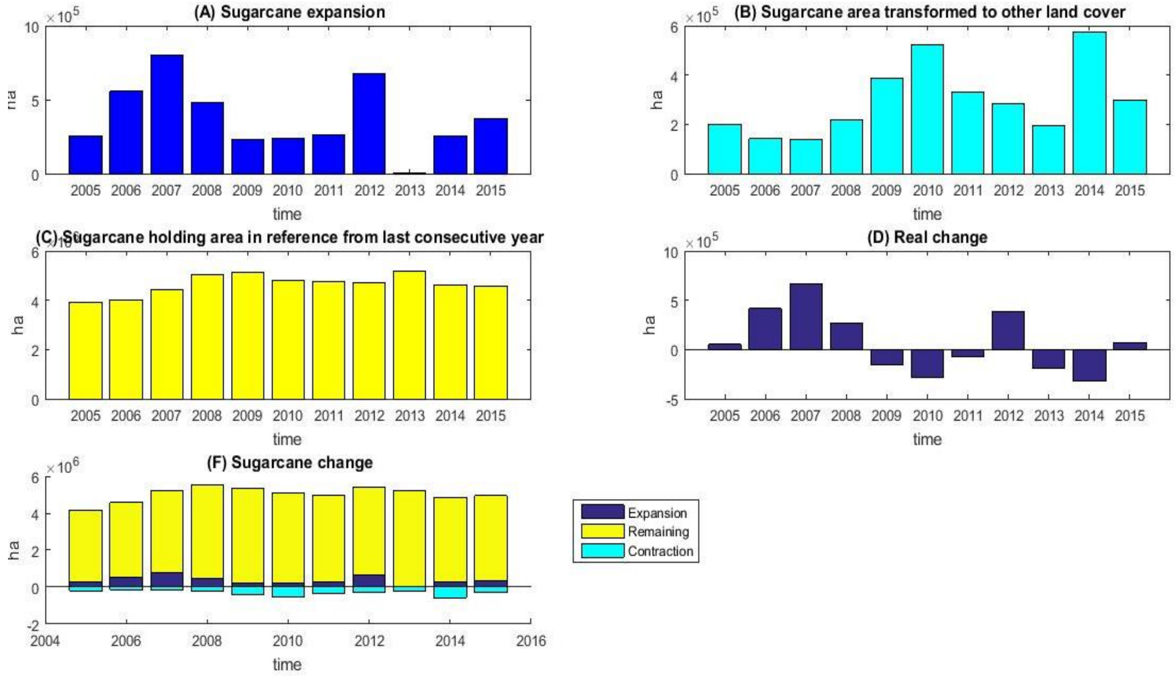

Fig. 2 Area change from sugarcane land cover in Sao Paulo state

In spatial terms, the sugarcane expansion is occurring mainly in the North and North-West areas of Sao Paulo state for all harvest years[12]. The results are relatively similar to the ones reported in other studies with an exception for 2012-2013 harvest season (given the low sugarcane expansion value compared to other studies) (CANASAT, 2016). From the 2014-2013 harvest season and onwards sugarcane is also expanding in the South-West region of the state (annexes A). Fig 3. Sugarcane land cover change, illustrates spatially the sugarcane change in Sao Paulo state for 2007-2008 harvest year. The 2007-2008 harvest years follow the same tendency as all harvest years (annexes A) and most of the sugarcane yearly new plantations are taking place in the North and North-West part of the state. Opposite from sugarcane expansion, the land use change from sugarcane to other land cover category is not following a clear pattern. The transformation for all the harvest years is dispersed along the map taking place where sugarcane is more concentrated. Sugarcane yearly expansion seems to be in line with other studies with some exceptions such as 2012-2013 harvest year (CANASAT, 2016). It must be highlighted that the analysis was done only by visual inspection (lack of data for processing from other studies) and that resulted in a superficial analysis. Two years seem to differ more than others (2012 and 2013) from similar studies (annexes A).

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[12] All the yearly sugarcane change maps are in the annexes

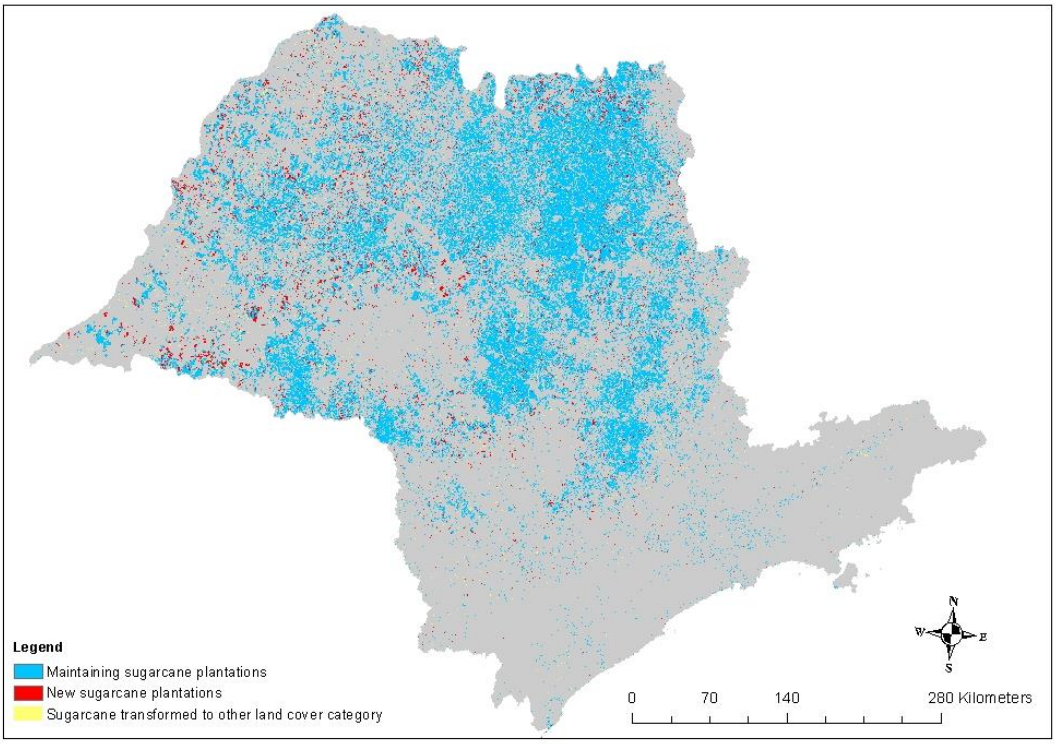

Fig. 3 Sugarcane land cover change in Sao Paulo state from 2007-2008

Fig. 4 land cover transformation represents the results from the land use change dynamics observed in Sao Paulo state for the studied time step. The majority of the direct land use change induced from sugarcane expansion (more than 60%) is occurring on the low vegetation category and in less quantity from annual cropland. Other studies have described similar dynamics, reporting sugarcane expansion taking place mainly from pasture land (comparable low vegetation category) and cropland (Nassar et al., 2008) (Adami et al., 2012). Furthermore, in a survey performed by CONAB (Brazilian Supply Company), they also observed similar dynamics with 66% of sugarcane expansion taking place on pasture land and 29% in cropland for the 2007/2008 harvest year (CONAB, 2008). Even in less quantity, all the other land cover categories were transformed into sugar cane plantations with the exception of Eucalyptus. Expansion in Urban and water land cover categories is not common (IPCC, 2006). Nevertheless, sugarcane is also transforming (low quantity) from and into these two other land cover categories in the studied time step. The yearly sugarcane expansion into the forest category is less than 1% for all the years with an exception of 2013, which corresponds to 30% of the entire sugarcane expansion (the value is high given the drastically low sugarcane expansion when compared to other years). Similar studies reported less than 1% of sugarcane expansion in forest land cover (Nassar et al., 2008) (Adami et al., 2012).

The observed dynamics from the direct land use change from sugarcane to other land cover categories (Fig. 4 (B)) follow a similar behavior than the ones from sugarcane expansion. In almost all the harvest years, sugarcane is being transformed to low vegetation and in fewer amounts to annual cropland. A trade-off relationship between sugarcane expansion and sugarcane change to other land cover categories is taking place mostly with the low vegetation land cover category. Randomly pixels were selected and analyzed through the whole time step to identify possible land cover errors (a pixel changing between sugarcane and other land cover categories and vice versa with yearly basis) and such behavior was not present. Additionally, the same analysis (land cover transformation) was performed with the original input data to determine if the data processing methods (projection and re-sample of the input data to 1 km^2) were generating the displayed trade-off trend between land cover categories (especially with low vegetation and the shift of urban and water land cover categories). The same trend was found when processing original land cover input data. Similarities between sugarcane expansion and sugarcane transformed to other land cover categories mainly for the low vegetation land cover can be attributed to the accuracy level from the input data or the advantage from that land cover category to expand in sugarcane abandoned areas.

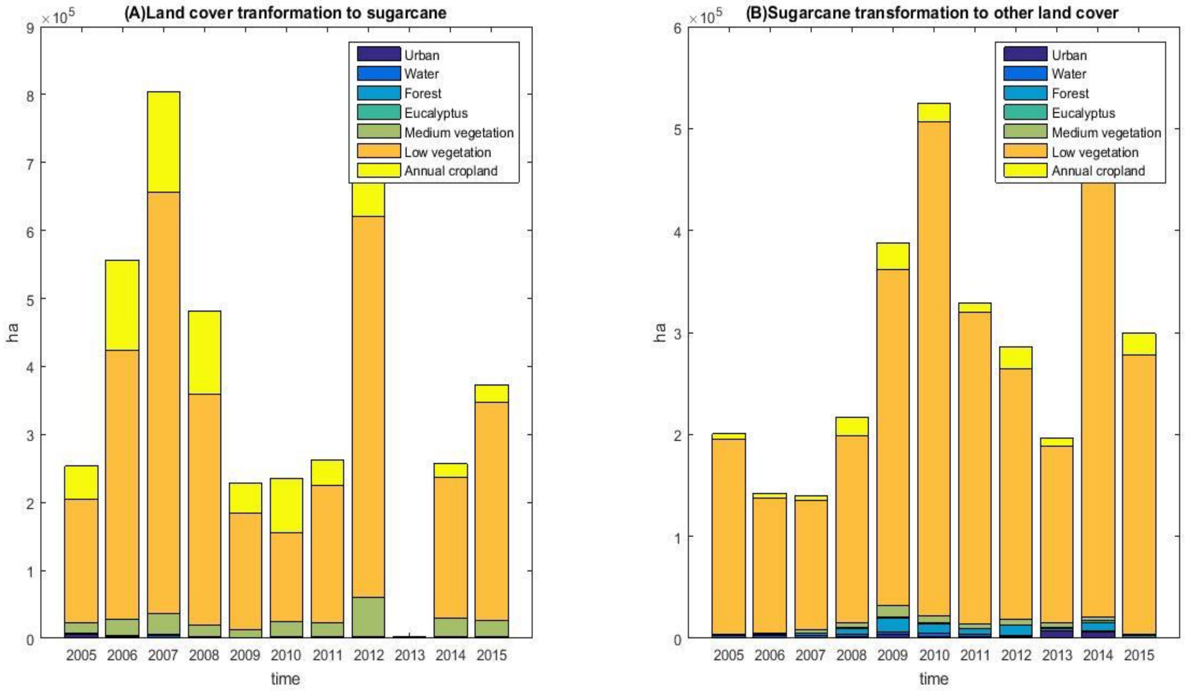

Fig. 4 Land cover transformation from sugarcane land cover category in Sao Paulo state

Fig 5 and Fig 6 sugarcane transformation corroborate spatially with results from Fig 4 and 3. As mentioned before, the land cover transformation to sugarcane for the 2007-2008 harvest year (Fig 5) comes mainly from the low vegetation land cover category and just as in Fig 3, the land use change due to sugarcane expansion is mainly occurring in the North-West part of the state[13]. The spatial dynamics are similar for the entire studied time, displaying large areas of the low vegetation category changing mainly in the North-West part of the state (annexes A). The annual cropland dynamics are also similar for all the harvest years, and similar to

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[13] T+5he land cover transformation maps and sugarcane transformed to other land cover category maps for all harvest years are found in the annexes for each harvest year.

other studies (Aguiar et al., 2011), shifting mainly in the Northeast part of the state (annexes A). As mentioned before, sugarcane expansion is also occurring in the south part of the state, with areas from low vegetation changing into sugarcane (especially for the last years) (annexes A).

The dynamics are more disperse along the state regarding land use change from sugarcane to other land cover categories. There is not a clear concentrated area where sugarcane is being transformed (mainly to low vegetation) to other land cover category. The dynamics are similar for all the harvest years (annexes A). Urban and water land cover categories are rarely transformed into crops (IPCC,2006), but in the Sao Paulo state this category is changing (low quantity) not only to sugarcane but also from sugarcane plantations. These urban areas might only be built in structures that could be easily moved away and used as crops lands. However, low accuracy from the input data may cause these uncommon land use change behaviors (even if they are occurring in low quantity).

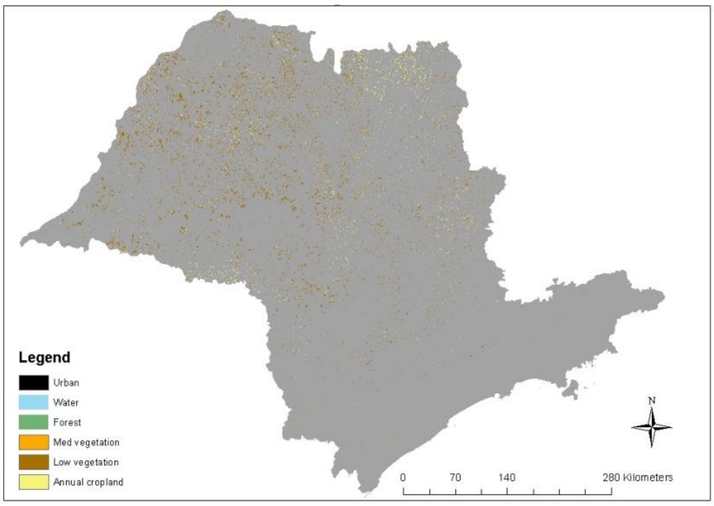

Fig. 5 Land cover transformation to sugarcane in Sao Paulo State from 2007-2008

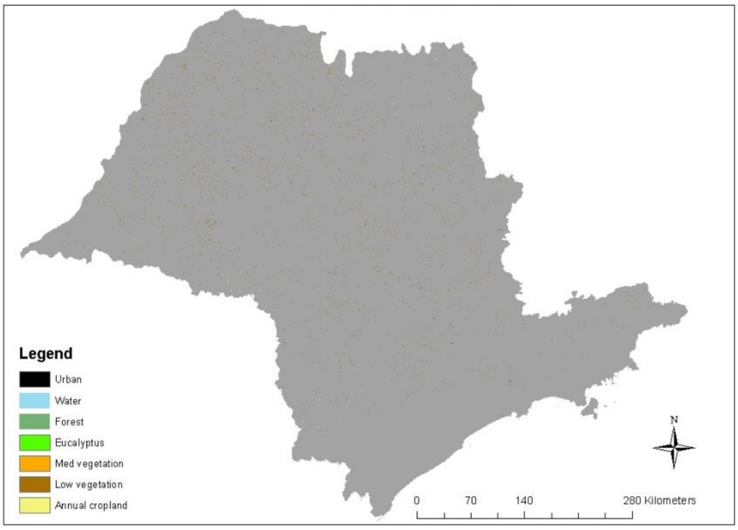

Fig. 6 Sugarcane transformation to other land cover category in Sao Paulo state from 2007-2008.

3.2 CO_2 emissions

CO_2 emissions from land use change were quantified on a yearly basis for two relevant carbon pools, biomass and soil (IPCC, 2006). The CO_2 net fluxes (CO_2 emissions from biomass and SOC from sugarcane production and expansion areas) for each year were taken into account and results are given in Fig 7. Regarding CO_2 emissions from the biomass parameter (Fig 7, A), for almost all the harvest years except 2013-2014, 2011-2012 and 2010-2011, the sugarcane land use and sugarcane expansion is functioning as a carbon sequestration pool (negative values). In 2013-2014, 2011-2012 and 2010-2011 harvest years the net CO_2 flux (total emissions) is positive which indicates that for these years the sugarcane land use and LUC is generating CO_2 emissions. Values vary between -9.47 million t of CO_2 (sequestration) in 2006-2007 (equivalent to sequestrating 1.8 t of CO_2/ha), to 20.5 million t of CO_2 in 2013-2014 (equivalent to emitting 4.22 t of CO_2/ha). On the contrary from the biomass parameter, the SOC (Fig 7, B) is emitting CO_2 for all the harvest years with the exception of 2014-2015 as result from LUC. Nevertheless, it has a similar trend as the one described in the sugarcane expansion (land dynamics). The SOC CO_2 emissions, compared to biomass CO_2 emissions, have low magnitudes. For the total studied time step (2004-2015), the sugarcane land use in Sao Paulo is emitting more CO_2 (16.3 million t) than sequestrating (taking into account carbon net flux in SOC and biomass pools from 2004-2015).

Sugarcane expansion in urban, water and annual cropland land cover categories results in CO_2 sequestration for the biomass pool (0 presence of biomass in those categories). However, the expansion on water and urban land cover categories is unlikely (IPCC 2006). The biggest emissions from the biomass section are produced when forest land cover category is transformed into sugarcane due to the large biomass diiference between categories[14]. Sugarcane maintaining areas can either act as CO_2 sequestration or emission areas (for the biomass section), normally those values are relatively small when compared to the values from LUC. The dynamics between sugarcane expansion with low and medium vegetation are more complex (given that spatial variation in biomass yield) and can result in CO_2 sequestration or emission areas (for the biomass pool). Nevertheless, sugarcane biomass values are generally higher than low vegetation ones (given the yield difference between sugarcane and low vegetation categories in sugarcane areas expansion) and lower than medium vegetation ones. Different from the biomass CO_2 emission dynamics, the SOC is generating CO_2 emissions when sugarcane is expanded into any other land cover category. The expansion in forest category accounts for the highest CO_2 emissions from the SOC pool given the loss of top soil followed by eucalyptus and medium vegetation category. Additionally, sugarcane maintaining areas have no carbon change (IPCC, 2006).

A Spearman’s rho correlation test (given sample size and that variables don’t obey normality) was applied between variables to identify if there was any correlation between parameters (other variables such as sugarcane expansion) and the CO_2 emissions trend. There is a negative correlation of -0.75 (*p*=0.007) between the yield difference from each consecutive harvest year and the CO_2 emissions from biomass. If the yield difference from the last consecutive is positive the sugarcane land use behaves as a carbon sink, if not (negative

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[14] This section would be discussed deeply in the overall discussion

value), the sugarcane land use emits CO_2[15].In regard to CO_2 emissions from SOC, there is a positive correlation of 0.98 (p=0.000) between sugarcane expansion into other land cover categories and the CO_2 emissions from SOC. When the sugarcane expansion tends to increase so does the CO_2 emissions from SOC and when the expansion decreases, the CO_2 emissions from SOC do as well.

CO_2 emission trend from the biomass parameter is explained by the yield difference between consecutive years. The 3 harvest years with CO_2 emission values for the biomass section (positives values), are result of sugarcane productivity drop that can be influenced by several elements such as climatic events. Additionally, almost all the LUC is taking place in low vegetation and annual cropland land cover categories (sugarcane biomass values are a small fraction higher from low vegetation and a big one from annual cropland), which contribute to the carbon sink trend for the other harvest years. The high area magnitude difference between sugarcane current use and expansion is responsible for the negative correlation between yield difference from consecutive years and CO_2 emissions from the biomass parameter (given that yield values affect all the sugarcane maintaining area). Regarding SOC, CO_2 emissions are dependent on sugarcane expansion. This correlation explains the difference between harvest year SOC CO_2 emissions that coincide with the sugarcane expansion dynamics (2012-2013 emission value is drastically low given the low amount of sugarcane expansion). However, the last harvest year from SOC CO_2 emissions follows a different trend (carbon sink behavior). This carbon sink behavior is caused by the change in the input stock change factor for this year. Sugarcane SOC values are lower when sugarcane residues are burnt (compared to green harvest practice), the practice change resulted in carbon storage for all the sugarcane maintaining areas. Other studies performed in Sao Paulo state have reported similar results on how carbon accumulates in soils when the pre-burn practice is shifted to green harvest practice (Cerri et al., 2004) (Czycza, 2009).

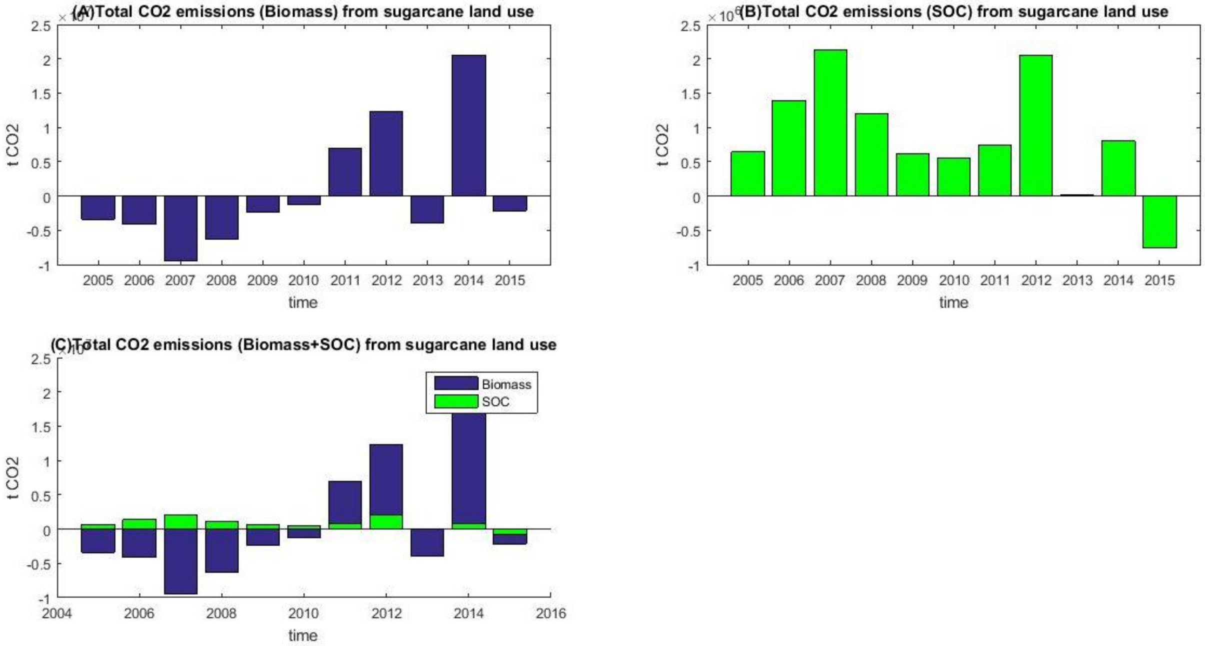

Fig. 7 total CO_2 emissions from sugarcane land use and expansion in Sao Paulo state

Given the spatial distribution and the resolution implemented, it is complicated to determine trends. Fig. 8 displays the spatial distribution for CO_2 emissions or sequestration values for the 2006-2007 harvest year for the biomass section. The trend is similar for all the harvest years with the exception of 2011-2012, 2010-2011 and 2013-2014 (annexes B). The North part of the state is the area that is contributing more to CO_2 sequestration from land use change (Annual cropland shifting to sugarcane). The North-West area is also acting as a sink but with less intensity (low vegetation shifting to sugarcane). Given that the value of sugarcane maintaining area is much greater than expansion (positive yield difference between consecutive years), almost all the state is acting as sink (it must be highlighted that these sequestration values are low compared to the ones in other land cover categories). Some areas in the central and central east section of the state are the ones contributing to CO_2 emissions (mainly from middle vegetation changing). There are some uncommon cases when high emission values are caused by drastically low suitable sugarcane areas expanding on regular or high suitable low vegetation areas. Year 2005-2006 also has a different spatial distribution (see annexes B), even if the whole state for this year is acting as a sink, a large part of the sugarcane maintaining area is releasing CO_2 because of the yield difference between 2006 and 2007 (extremely low quantities).

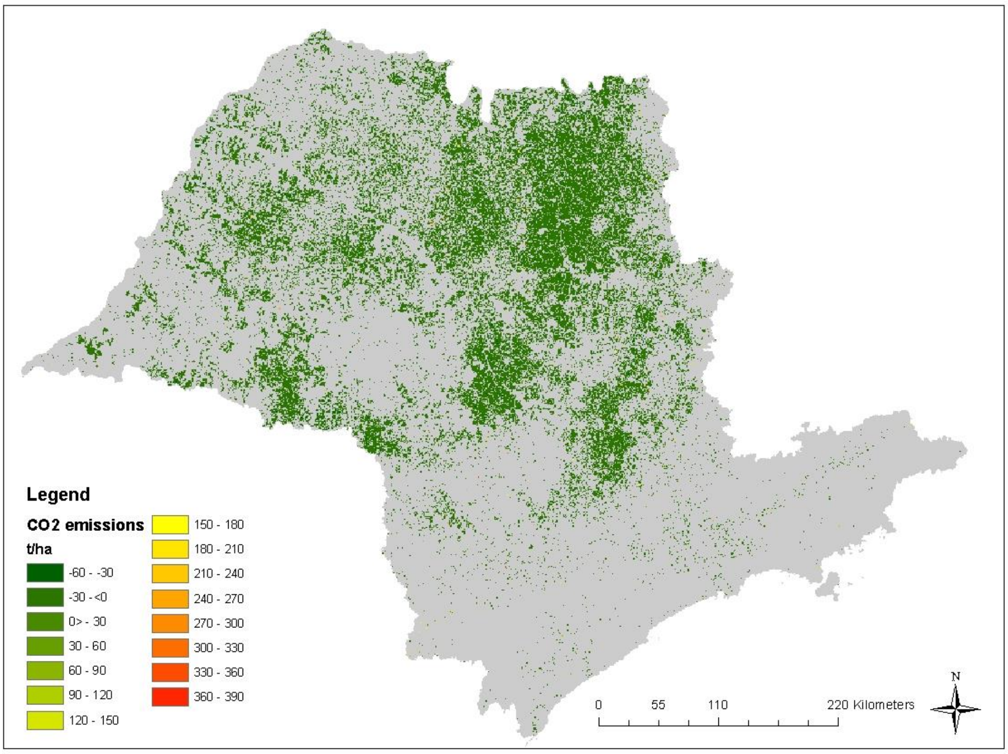

Fig. 8 Spatial distribution of CO_2 emissions or sequestration from biomass 2006-2007

Fig. 9 shows the sensisitity analysys for the CO_2 emissions from the biomass section. For the parameters considered, the maximum variation of CO_2 emissions comes from the yield change. It takes a small % change to shift the emission values in large quantity. Meanwhile, the relevant land cover categories had to increase or decrease in large % to generate a considerable variation in CO_2 emissions or sequestration. Low vegetation had a bigger variation than the medium vegetation category even if the same % change was used for both categories. The results are dependable on yield difference from consecutive years, given the decision to assess current sugarcane land use (as mentioned before the area magnitude from sugarcane maintaining area is considerable larger than the expansion one). The yield gap between consecutive years is the principal driving force behind the increase or decrease in CO_2 emissions for the biomass parameter from sugarcane land use and expansion in Sao Paulo state for the studied time. If the sugarcane yields from consecutive years are highly similar, the CO_2 emissions or sequestration would depend strictly on sugarcane expansion. The second driving force behind the increase or decrease in CO_2 emissions is the LUC in low vegetation areas. On account of the implemented methods, sugarcane biomass values are normally higher than low vegetation ones. The behavior from the 2005-2006 harvest years is an example of how the second driver interacts with the results when the first one is less significant (The toal emissions from this year are ruled by the expansion on low vegetation category).

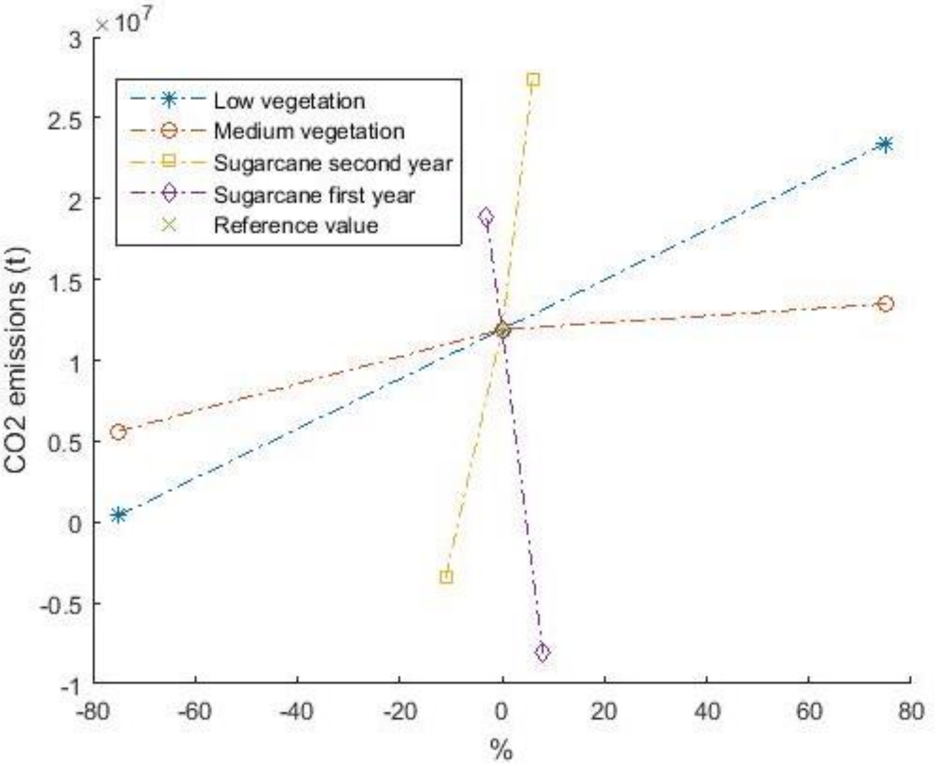

Fig. 9 Sensitivity analysis from Biomass CO2 emissions from Sao Paulo state Brazil, 2011-2012

The SOC CO_2 emission trends (Fig. 10) are spatially more clear than the ones from biomass. Different from biomass, the shift to sugarcane from low vegetation is causing CO_2 emissions by removing soil carbon. Almost all the green area is where sugarcane is not changing in realtionship with the last consecutive year (value of 0). There are several areas in the North and North-West area of the state where the sugar expansion is producing CO_2 emission from the SOC (especially by expanding on low vegetation categories). The trend is similar for all the studied time with an exception from the last harvest year and harvest season 2012-2013 (Extremly low sugarcane expansion). As new plantations of sugarcane can be found in the south part, this expansion is generating emession from the SOC for the last harvest years. Additionally, for the last harvest the pre-burn practice change from the last conecutive year is causing for the whole state to acts as a sink. The different maps can be seen in the annexes C. As mentioned before, the sugarcane expansion in other categories for the SOC parameter (urban and water exception) produces CO_2 emission . The higher values (red in the map) are when forest, eucalyptus or medium vegetation category is transformed.

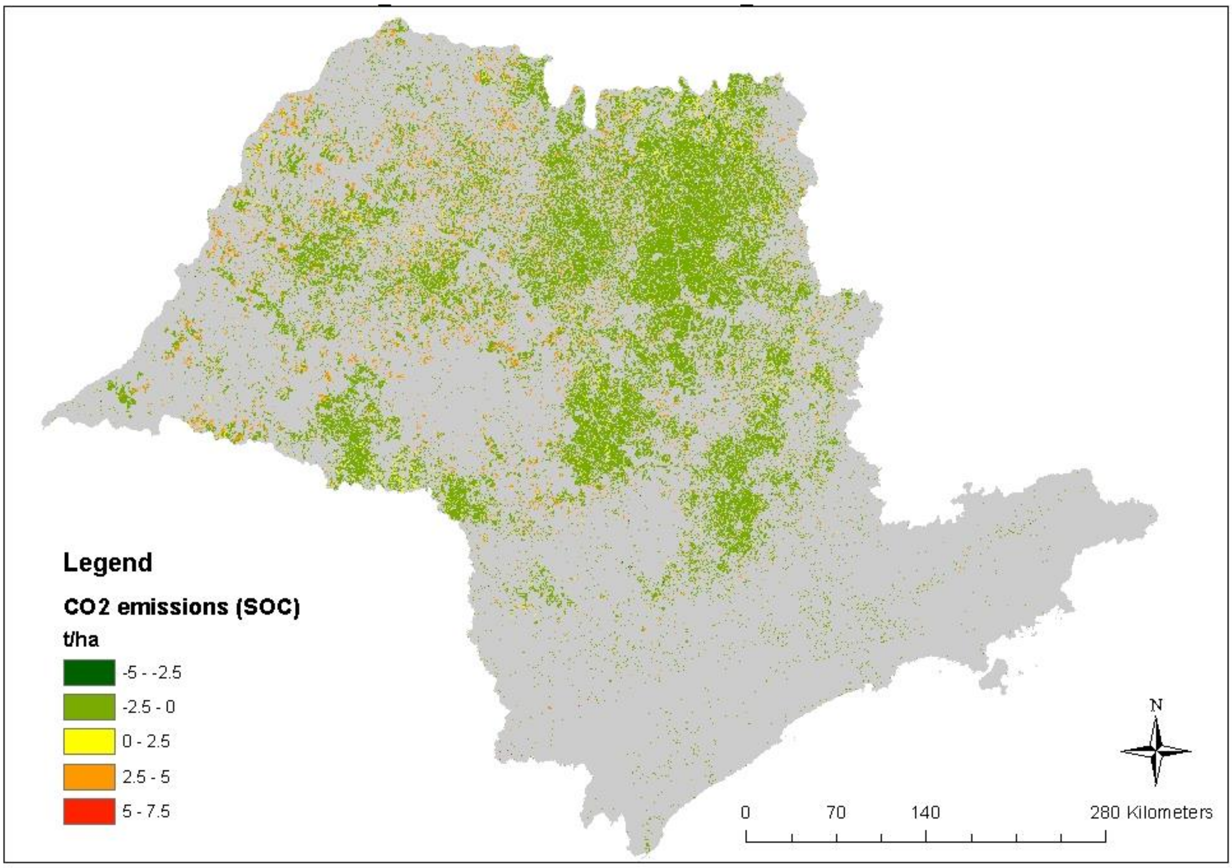

Fig. 10 Spatial CO_2 emissions from SOC 2006-2007

As figure 11 illustrates, the maximum variation for the CO_2 emissions from SOC parameter comes from the change in stock change factors from the sugarcane land cover category. Furthermore, the major change is created when the Flu factor varies. The CO_2 emission value varies dramatically with the % change of this parameter. Different from the other land cover categories, when the stock change factors from the sugarcane land cover category increases the CO_2 emissions tend to reduce and vice versa. Low vegetation stock change factors are also generating a considerable change in the results when the stock change factors are shifted. Medium vegetation and annual cropland category are not disturbing the results in a substantial manner because the biggest interaction comes from sugarcane expanding on low vegetation areas. Even if the analysis suggests the Flu factor is the most important parameter influencing the CO_2 emission from the SOC section, it must be taken into account that this parameter stays constant for the entire studied time step. In reference to that, the results from SOC section would be affected more from the LUC dynamics (especially from the expansion in low vegetation category) from Sao Paulo state as long as the factors remain constant. However, for the studied time step the results suggest that improving sugarcane production (improving score on stock change factors) practices in a future scenario would be more efficient to reduce CO_2 emissions from the SOC than reducing LUC (if the expansion continues on low vegetation category).

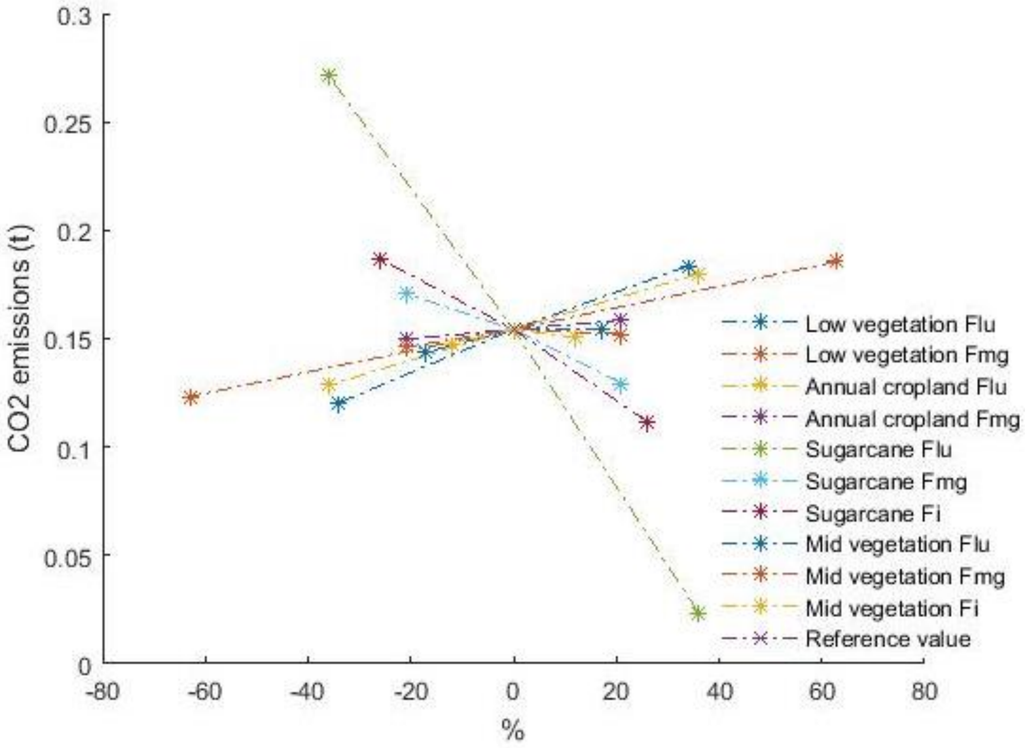

Fig. 11 Sensitivity analysis from SOC CO_2 emissions from Sao Paulo state Brazil, 2004-2005

3.3 Biodiversity

3.3.1 Protected areas[16]

The sugarcane land cover category percentage is less than 1% for all years inside Sao Paulo state protected areas (Fig. 12 (B)). Sugarcane land cover category trend inside the PA's is to increase slightly in area coverage in the first years and then decrease. Some PA's were established within the studied time step. The inclusion of new PA's did not affect the sugarcane land cover trend. In comparison to forest land cover category, the sugarcane coverage in PA's is almost insignificant. The sum of urban, sugarcane and annual cropland land cover categories is close to 1% for the entire time step.

Forest land cover category corresponds to more than 89% of the total PA's area for the entire time step (2004-2015) (Fig. 12). Additionally, it is characterized for increasing the forest area steadily each year with almost 2% difference from the first to the last year (Fig. 12). Ribeiro et al., (2009), reported the effectiveness of PA's in conserving native forest in the Brazilian Atlantic Forest. Nolte et al., (2013), described similar results on how strictly PA's in the Brazilian amazon were limiting deforestation within their limits and enhancing forest conservation. Nevertheless, similar studies performed in other parts of the world (with similar ecosystems and sugarcane culture as Brazil) such as Indonesia, have suggested that PA's have failed in reducing deforestation (Gaveau et al., 2007). As land cover changes have major consequences in biodiversity (Tallmon et al., 2003), protecting and enhancing forest area

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[16] The results were analyzed only for sugarcane and forest land cover category

enlargement will benefit biodiversity. Referring strictly to sugarcane expansion, the results suggest that it is not enhancing direct land use change with in the PA's for the forest category and consequently avoiding impacts on biodiversity from LUC.

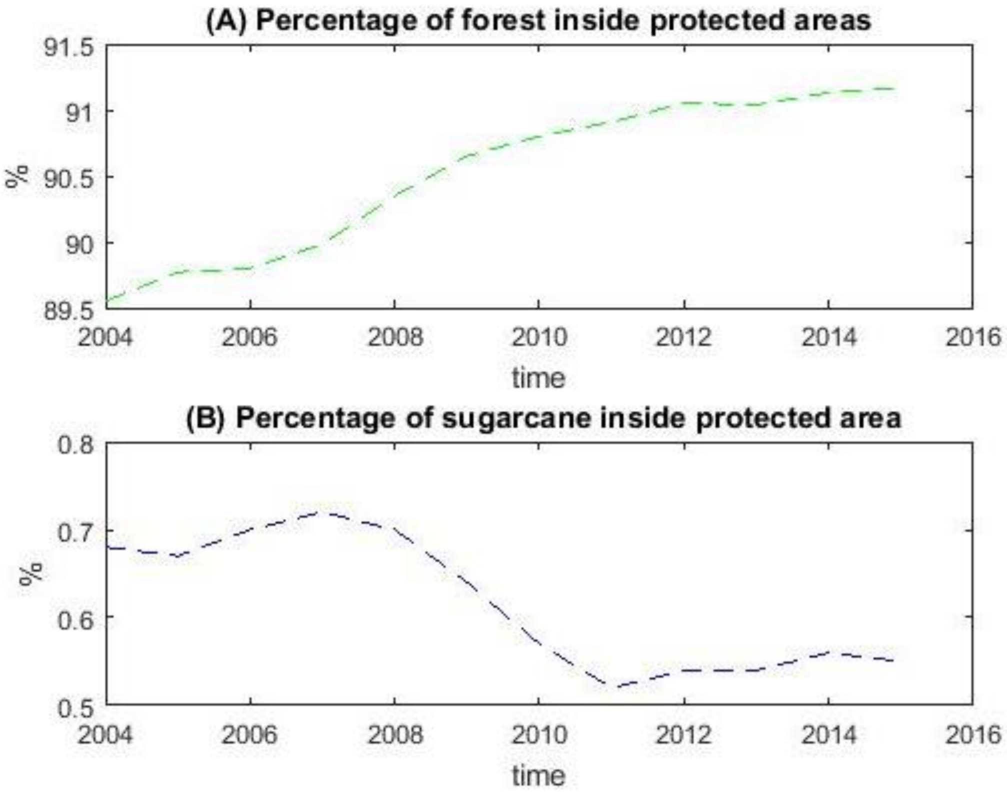

Fig. 12percentage of forest and sugarcane inside PA's[17]

3.3.2 Land cover change dynamics (forest category)

As mentioned before in section 3.1, sugarcane expansion in forest areas is drastically low when compared to other land cover categories. Several studies agree that less than 1% of the expansion is occurring on the forest land cover category (Nassar et al., 2008) (Adami et al., 2012). It can be seen in Fig 13 forest category dynamics that the magnitude of deforestation (Fig. 13 (A)) is considerably low from sugarcane expansion when compared to regeneration values (sugarcane area transformed to forest, Fig. 13(B)). With the exception of the first harvest year, the net balance (Fig. 13 (C) is positive for the rest of the years, showing that more forest is growing from sugarcane plantation than forest cleared due to sugarcane expansion. Land use changes from sugarcane to forest category may suggest low accuracy in this areas given the short time spam that it is taking for forest to grow in sugarcane areas. Nevertheless, sugarcane plantations in the state must guarantee at least 20% of forestry cover in the harvested land (either conserving or reforesting with native species) (Goldember et al., 2008). Reforestation measures might be taking place in those areas but it is less likely taking into account the one year time spam. Net balance (Fig 13, C) and regeneration areas (Fig 13, B) follow the same trend, suggesting that deforestation is not affecting the net balance (giving

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[17] Other land cover percentages are in the annexes.

the low magnitude when compared to regeneration). Additionally, deforestation from sugarcane is low to the point that it is not disturbing the whole state forest area (Fug 13, D tendency to increase in time.

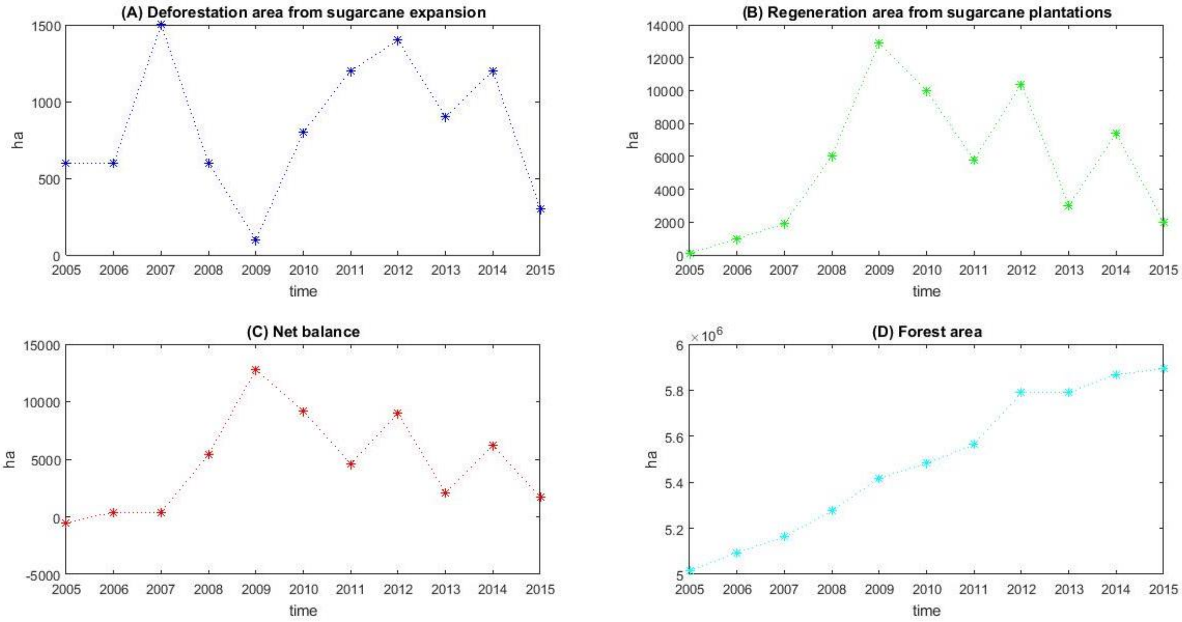

Fig. 13 Forest category dynamics from Sao Paulo state

Sugarcane expansion on forest category was also analysed spatially. Fig 14 is an example of sugarcane expansion causing deforestation for the 2007-2008 harvest season. 2 patches can be seen, one in the upper part already in a mixed area from different categories, and one in the lower area just in the agricultural frontier from a nature area (forest,eucalyptus and medium vegetation). Even if the deforestation magnitude is low, the areas where it is taking place are experiencing habitat fragmentation resulting in habitat loss (Fahrig, 2003). Not only may this fragmentation lead to habitat loss, it could change the properties of the remaining habitat (van den Berg et al., 2001) and consequently have impacts on biodiversity. Additionally, the expansion in specific areas of Sao Paulo state (as the one where patch number two is located) is triggering habitat reduction which could have negative impacts on different biodiversity levels (Jantz et al., 2015). Furthermore, the random process of deforestation and regeneration (e.g. losing forest in a nature area and regenerating it in an area isolated by other land cover categories) could produce specific impacts on biodiversity for those areas.

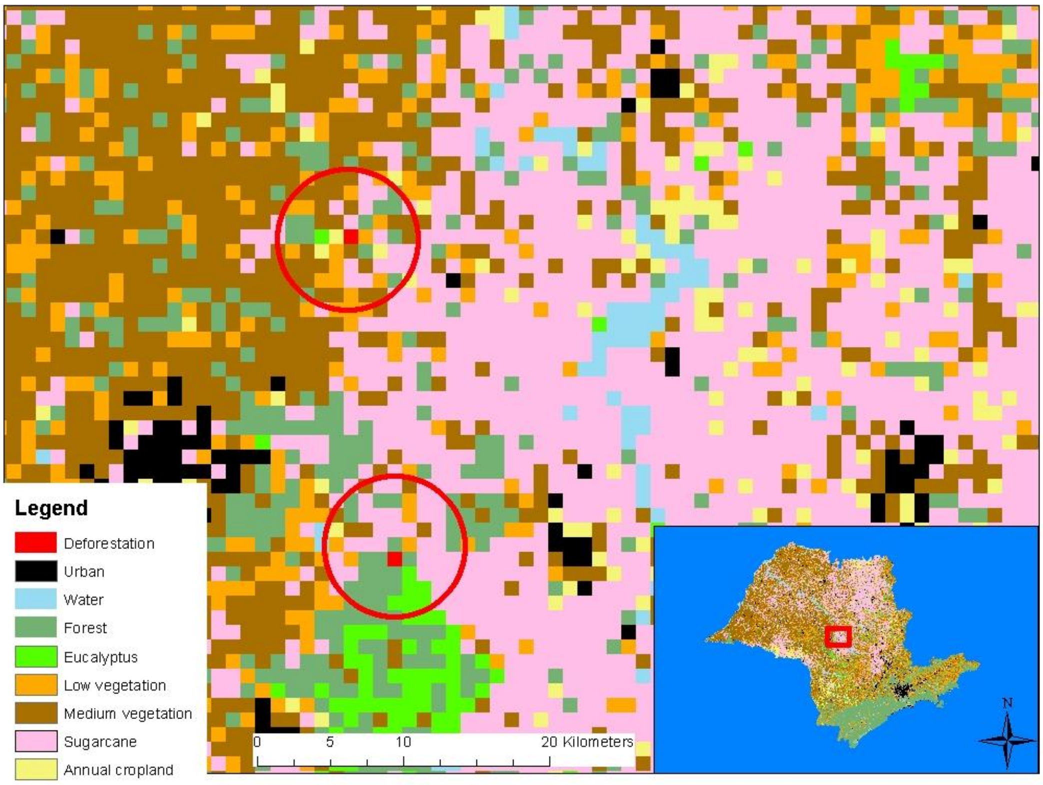

Fig. 14 Deforestation from sugarcane expansion in Sao Paulo state 2007-2008

As mentioned before, the lands scape indicators were measured for the forest land cover category. Fig. 15 displays the same trend for the 3 indicators (since all three indicators depend from the number of patches). It has to be highlighted that consecutive patches (two or more neighboring pixels from forest shifting at the same time) were not found for the whole studied time and for that reason each patch size corresponds to the same pixel size. Additionally, the number of patches evaluated each harvest year corresponds to new areas where sugarcane expanded. The drop in 2009 for the 3 indicators is due to the lack of deforestation (0) from sugarcane expansion. An increase in the trend represents more deforestation from sugarcane and a decrease represents the opposite.

The 2006-2007 harvest season was the one with the highest number of patches (15) generated in the forest land cover category (Fig. 15(A)). 15 patches are equivalent to 0.029% of the entire forest area (Fig. 15 (B)). This means that the sugarcane expansion (for the 2006-2007 season; the one with the largest expansion in forest from sugarcane) is responsible for deforesting 0.029% of the total forest area in the state. In total, sugarcane expansion is responsible for reducing 0.2% (added values form Fig. 15 (B)) of the total forest area in the state for the complete studied time. The landscape indicators are affected by the forest size. As mentioned above, the forest land cover area trend is to increase as time passes. Even if deforestation from sugarcane expansion increases (not the case for the study), the value is lower given that forest land cover category is expanding. In relation with the number of patches generated (Fig. 15 (C)), on average 0.00015[18] patches are generated yearly from sugarcane expansion for each 100 ha of forest. Sugarcane expansion is deforesting on a

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[18] Average from the value in Fig. 13 (C)

yearly basis (average) 0.015ha[19] for every 100 ha of forest. The low deforestation showed by the landscape indicators agrees with other studies (Nassar et al., 2008) (Adami et al., 2012). This suggests that sugarcane expansion is having low impacts on biodiversity in the forest category for the whole state.

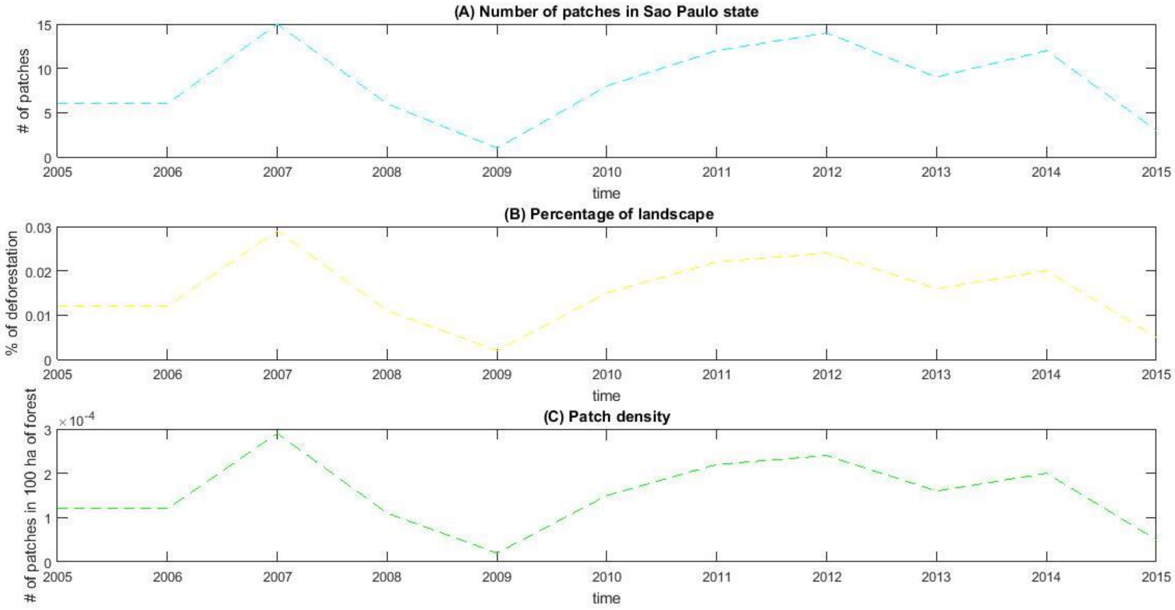

Fig. 15 landscape indicators for Sao Paulo state

3.3.3 Mean species abundance

For the MSA the only driver that was taken into account was LUC (for this reason the MSA is totally dependable LUC dynamics). Fig 16 MSA represents spatially the biodiversity impacts for the 2006-2007 harvest year from sugar expansion (given that when land remains in the current land cover there is no change). Taking into account the MSA classification change (discussed in methods section), the positive impacts in species abundance occur when sugarcane expands on cropland or urban areas. The negative impacts in biodiversity occur when sugarcane expands in low vegetation areas, the negative impact – when sugarcane expands in medium vegetation areas and the negative impact - - when it expands in forest land cover category. However, negative impacts in species abundance may be a consequence of ecosystem disturbance (Alkemade et al., 2009)

The trend is similar for all the harvest years. The largest change is taking place on the North and North-west area of the state with a negative impact in biodiversity. Additionally, in the center part of the state is also a negative impact. The MSA value indicates a decrease in biodiversity in these areas when low vegetation land is transformed into sugarcane. Nevertheless, there are also positive impacts on biodiversity. In the Northern part of the state the MSA value change is showing an increase in biodiversity given the sugarcane expansion into cropland areas. Given that MSA is strictly dependable on LUC dynamics, most of the generated impacts are a decrease in biodiversity given the yearly change from low vegetation

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[19] Patch size 1 km^2 converted to ha

to sugarcane. Negative - - changes are the ones that generate more impact in biodiversity, but for Sao Paulo state it is low (given that sugarcane expands rarely on forest areas). The spatial dynamics are similar for the entire studied time step with the exception from the last years. In these years there is also a decrease in biodiversity in the south part of the state (mainly from the change from low vegetation to sugarcane).

Fig 17 is an example of how the MSA is totally dependable on the LUC dynamics. Harvest year 2012-2013 was the one with the lowest sugarcane expansion (Fig. 2, A). For this reason there is low impact on MSA for this year. It must be taken into account that the no change results is where sugarcane is remaining sugarcane, but this value is already a low MSA value when compared to other land cover categories. Given that the reference year was 2004 the results might be less drastic than they appear. However, the land was transformed before the reference year and areas have been submitted to sugarcane land use change for several decades (Martinelli and Filoso, 2008). The species abundance of these areas might have been affected more drastically in the past than in the studied time step (given the assumption that the land was in equilibrium for 2004). In an overall perspective, the impacts on biodiversity from sugarcane production and expansion are negative but relative low. The PA's are not being affected by the sugarcane industry neither as the forest category in the state (suggesting low biodiversity impacts in these indicators). However, there still is a negative impact from biodiversity from the sugarcane expansion (Northwest section). Nevertheless, the impact on biodiversity could have been worst if sugarcane expanded more in other land cover categories different from low vegetation.

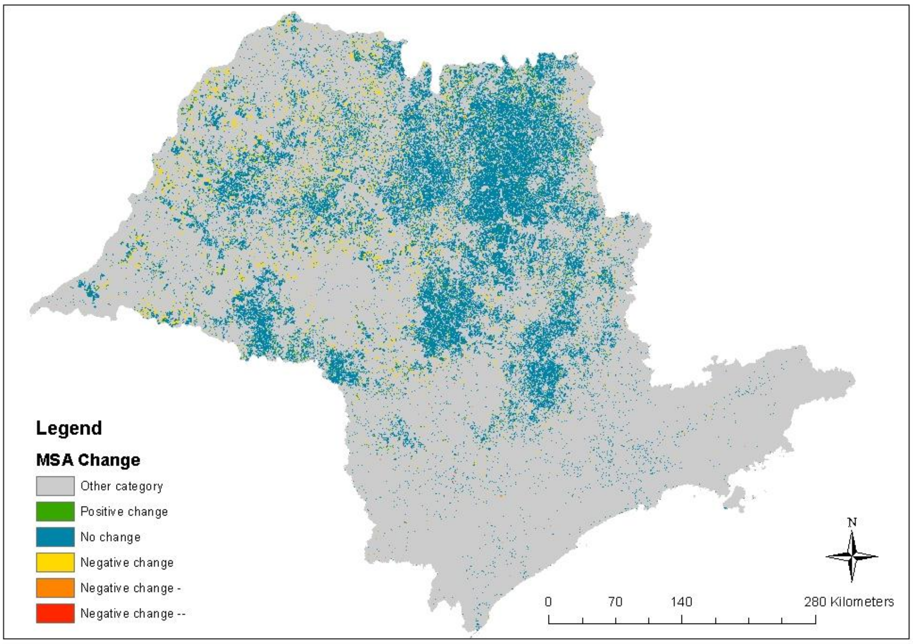

Fig. 16 MSA value change from sugarcane land use for 2006-2007 harvest year

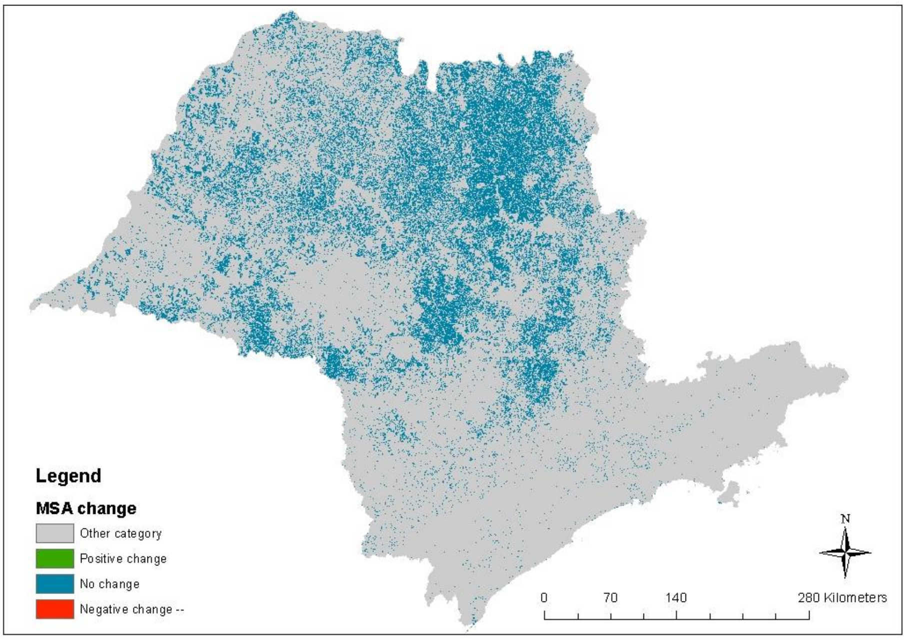

Fig. 17 MSA value change from sugarcane land use for 2012-2013 harvest year

For the MSA indicator, the land cover that is influencing more the results is the sugarcane one (Fig 18.). A small change in the MSA score from the sugarcane category generates a larger shift compared to the other land cover categories. Nevertheless, the magnitude change is low and always with a negative impact on biodiversity. Low vegetation is also important and when the MSA score for low vegetation decreases, the overall MSA score from the sugarcane expansion tends to increase (reduces negative biodiversity impact) and vice versa. The other 2 land cover categories suggest that are not relevant for the results. This is explained because the LUC generates in Sao Paulo state from the studied time step is mainly occurring in the low vegetation category. However, these MSA score for each land cover category are constant for the entire studied time step. Conservancy strategies within the sugarcane land cover category that increase the sugarcane MSA score could reflect higher scores (less negative impacts) when sugarcane induces LUC. The MSA is a good indicator for determining an approximation of the effect from LUC induced from sugarcane expansion. Nevertheless, more empirical methods should be applied in order to have better estimations of the real impacts on biodiversity from the sugarcane expansion in Sao Paulo state.

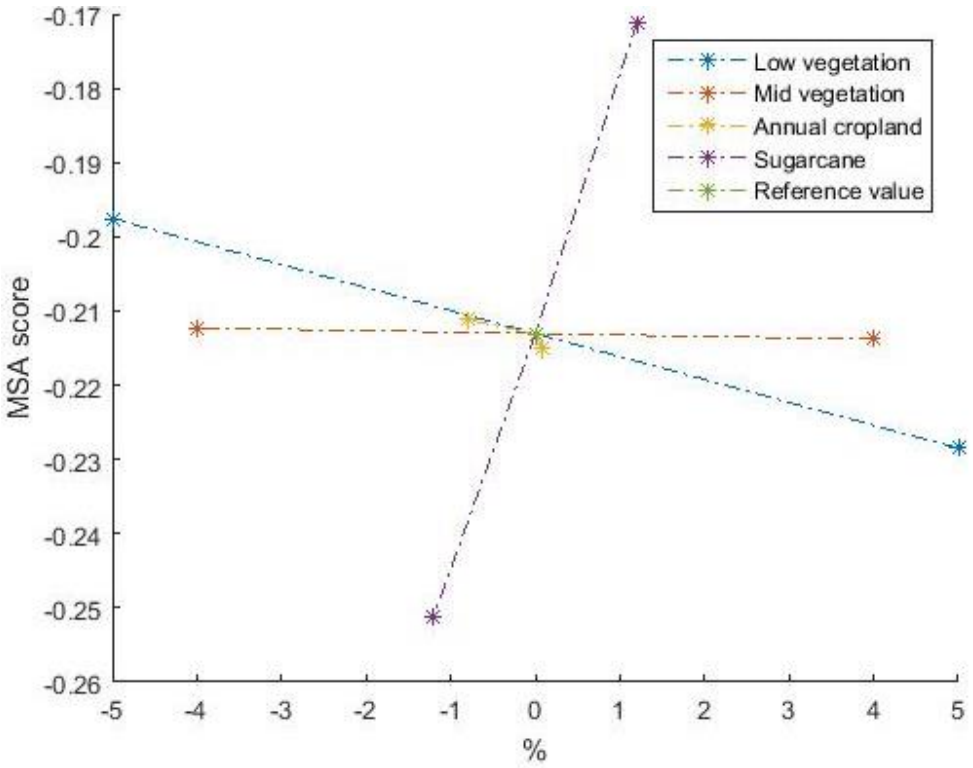

Fig. 18 Sensitivity analysis from the MSA score for Sao Paulo state Brazil, 2007-2006

3.4 Water shortage

The results for water shortage were evaluated in 3 different time steps for each harvest year. It must be highlighted that the spatial distribution of water shortage is the same for all the harvest years (annex E)[20]. When sugarcane is growing (initial step April month, Fig 19) evapotranspiration does not exceed effective precipitation, therefore there is not a water deficiency over this period of time for the whole state. All values are negative; consequently there is a water surplus for the whole state for the initial growing stage of sugarcane. Nevertheless, the areas with the lowest values are located in the Northwest part of the state where the surplus varies from -20 – 0 mm per month. Most of the sugarcane is located in areas where the water surplus exceeds -40 mm per month. It must be highlighted that WS results are not only dependable from sugarcane LUC or sugarcane land use, WS are also dependent on climatic conditions and crop characteristics.

On the contrary, when sugarcane reaches mid stage (months from May to December, Fig 20) the plant demands more water and evapotranspiration is exceeding effective precipitation. This relation results in a water shortage for the whole state especially in the North and Northwest part of the country were the largest deficit values are taking place (80-120 mm per month). The large deficit in the Northwest area is mainly given by the lower precipitation values from this area in comparison to other parts of the state. The mid growing stage coincides with the beginning of the dry season (May to October) where precipitation values

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[20] This procedure would be explained better in the water shortage discussion section

drop drastically when compared to other months. As mentioned before in the LUC section, most of the sugarcane expansion is taking place in the Northwest part of the state where the water deficit is the highest from May to December. Adequate moisture is needed to obtain maximum yield (Allen et al., 1998). The temporary water shortage from the mid growing stage could result in damages to agricultural production and affect considerable the possibilities of obtaining maximum yield. The water shortage for the mid sugarcane growing stage differs from other studies (Cabral et al., 2012; da Silva et al., 2013), underlining that rain water is not enough for sugarcane production in these months. The water absence from these months could affect water availability downstream (from sugarcane production areas) especially in the Northwest section of the state given that the water requirements from sugarcane is not allowing surplus water to reach water bodies.

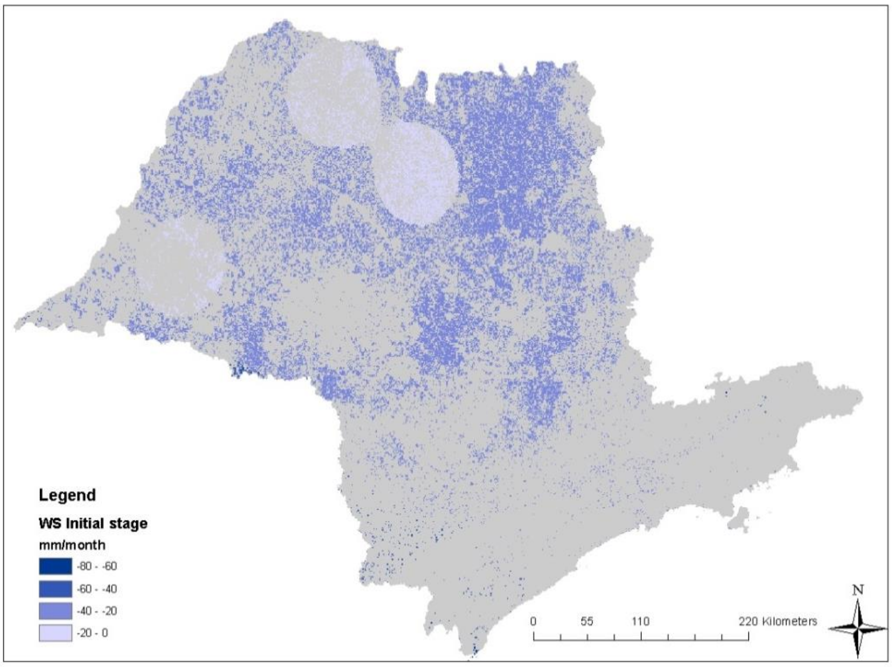

Fig. 19 Water shortage for sugarcane initial growing stage in Sao Paulo state 2012-2013

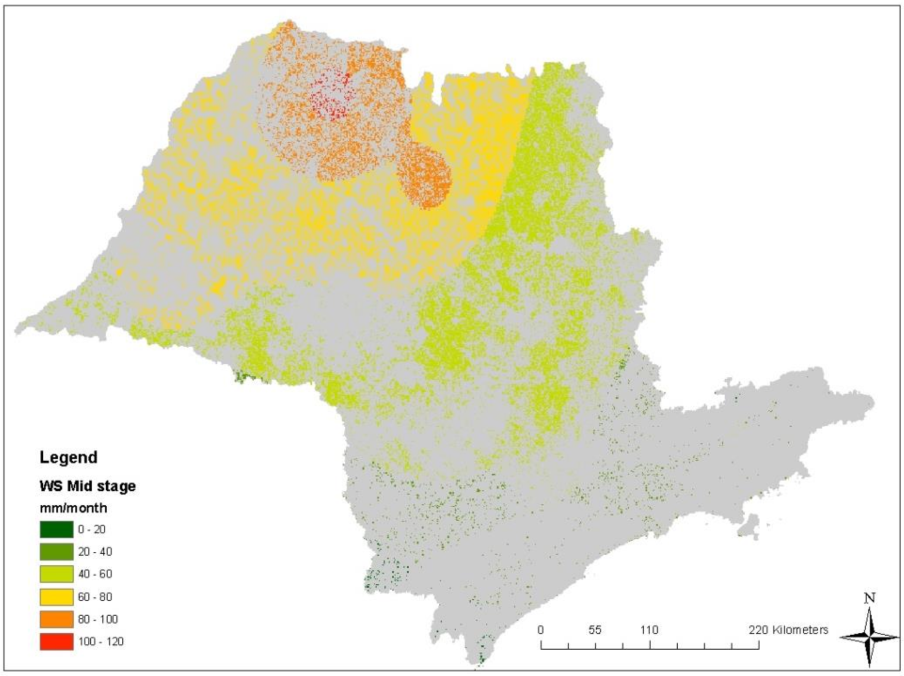

Fig. 20 Water shortage for sugarcane mid growing stage in Sao Paulo state 2012-2013

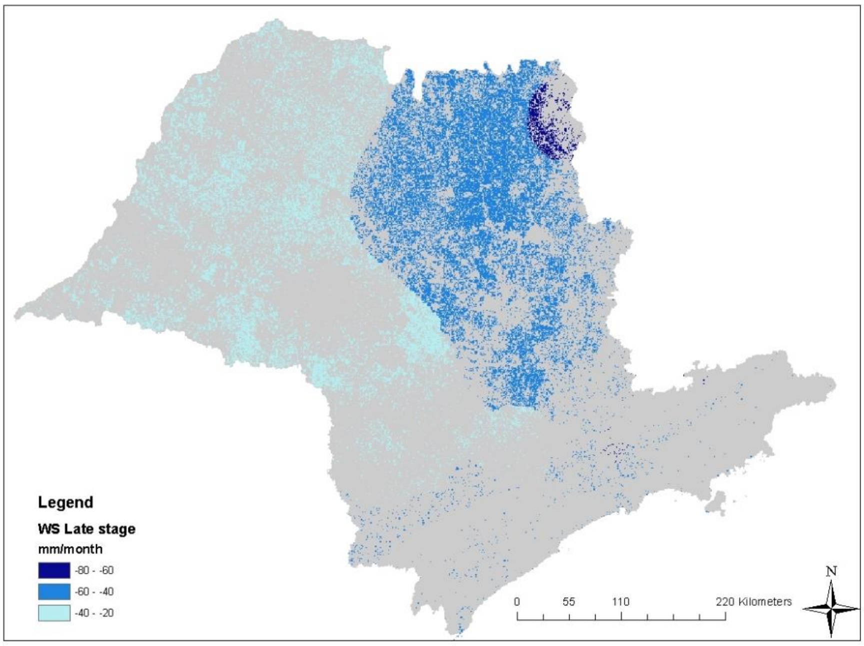

Fig. 21 Water shortage for sugarcane late growing stage in Sao Paulo state 2012

Just as in the initial growing stage, in the late growing stage (January – March) (Fig. 21) evapotranspiration is not exceeding effective precipitation. In consequence, there is not a water deficit for this period of time for the whole state. The largest surplus is occurring on the Northeast area where values go as high as -80 mm per month. The sugarcane expansion that is taking place in the south part of the state in the last harvest years, seems to go more in hand with the water shortage parameter (given that these areas are characterized for more precipitation). If the water shortage is evaluated on a yearly basis, there would be no water shortage because dry months are compensated with wet months and all the water is eventually replenished. The exception would be for just a few areas in the Northwest part of the state.

The sensitivity analysis for the water sections (Fig. 22) shows that the Kc values from all the growing stages are following a linear relationship. However, the most important shift comes from the medium stage (given that is the only generating water shortage). Furthermore, changing the Kc value from the medium stage to lower limit is still generating water shortage. Even low sugarcane yield values from the medium sugarcane growing stage will still generate water shortage. When sugarcane reached the medium growing stage the effective precipitation in the stage is not enough for the adequate development of the crop.

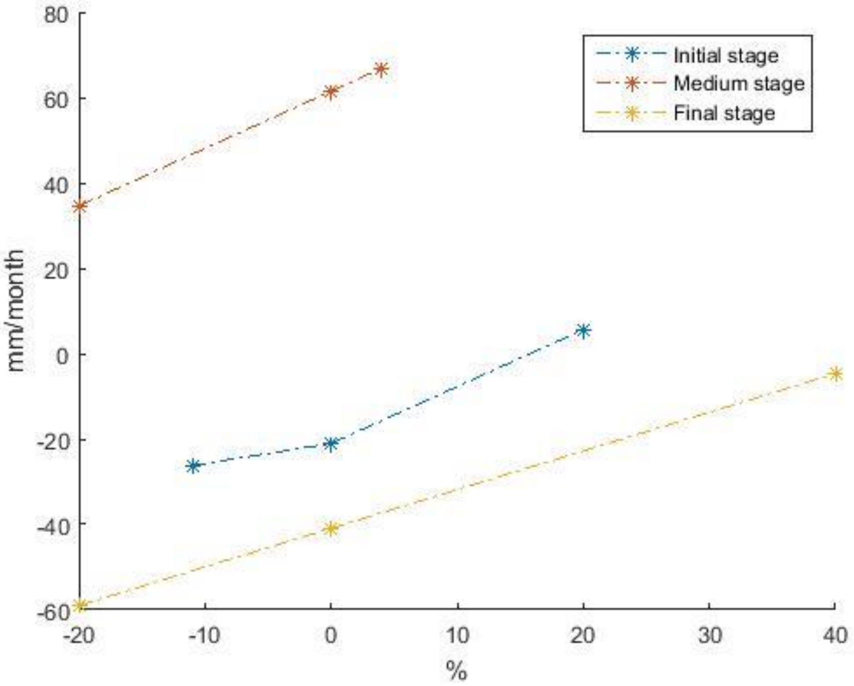

Fig. 22 Sensitivity analysis from the water shortage for Sao Paulo state Brazil, 2014-2015

3.5 Soil erosion

Soil erosion values were quantified for each harvest year and the correspondent maps are present in the annexes F. As show in Fig. 23, Sao Paulo state is losing more than 1 million t of soil in sugarcane plantations areas (taking into account all the land cover under sugarcane use). The soil loss is relatively constant for the whole studied time, with values ranging from 1 million t of soil loss per year to 1.5 million t of soil loss per year. The soil loss dynamics show an increase of soil loss, reaching a peak and then decreasing trend (Fig 23), this trend is repeated two times in the studied time step (2004-2015). 2009 and 2007 correspond to the years with highest soil loss (close to 1.5 million t of soil loss per year); meanwhile 2014 correspond to the one with the lowest soil loss (1 million t of soil loss per year). Nachtergaele et al., (2011) predicted yearly global soil loss values (by the means of RUSLE equation), mean values in Sao Paulo state range approximately from 0 to 5 t of soil loss per hectare per year (regarding land cover). Sugarcane soil loss mean values from the studied time step range from 0.35 to 0.5 t of soil loss per hectare each year. It must be highlighted that the comparison was done visually given the lack of data.

From a spatial perspective (Fig. 24), values vary from 0 t of soil loss per hectare to 130 (this value was the highest one registered and corresponds to the 2006-2005 harvest year). Yearly values above 40 t of soil loss per hectare are rare. Nevertheless, other studies have registered yearly values of 30 t of soil loss per hectare in sugarcane plantations in Sao Paulo state (Sparovek and Schnug, 2001). Furthermore, Bacchi et al., (2000) also registered values of 39 t of yearly soil loss per hectare in sugarcane plantations in Sao Paulo state. However, mean values differ drastically from other studies (but it must be taken into account the size of the study area given that values for other studies are calculated on watershed level and not state level) (Bacchi et al., 2000; Sparovek and Schnug, 2001). For all the harvest years the trend is similar with a big area (in the Northwest) of the sugarcane plantations losing between 0-4.5 t of soil per hectare each year, and a large area (in the central region) losing from 0-1 t of soil per hectare each year. Kertzman et al., (1995) calculated an erosion risk map for Sao Paulo state with the highest erosion risk areas located in the Northwest and some areas in the Middle East section from the state. In the Northwest area where sugarcane is expanding the most, is common to find soil erosion values above 4 or 12.5 t of soil loss per year. Furthermore in Middle East section of the state, several areas present erosion values from 4.5-12.5 t of soil loss per year and also values above 12.5 t of soil loss per year (Less common than in the Northwest section of the state).

There are several sugarcane plantations that are not losing soil in any harvest year. Especially the ones located close to the water bodies. In comparison to other land cover categories, sugarcane is generating more soil loss especially when compared to forest and medium vegetation. Nevertheless, there are Medium vegetation areas with soil loss (in the south section of the state) values up to 16 t of soil loss per hectare per year. However, as mentioned before sugarcane is expanding less in the medium vegetation category and rarely in forest areas. When sugarcane expands in the lower vegetation category the soil loss stays relatively low when compared to soil loss from the sugarcane expansion in other land cover categories other land cover categories.

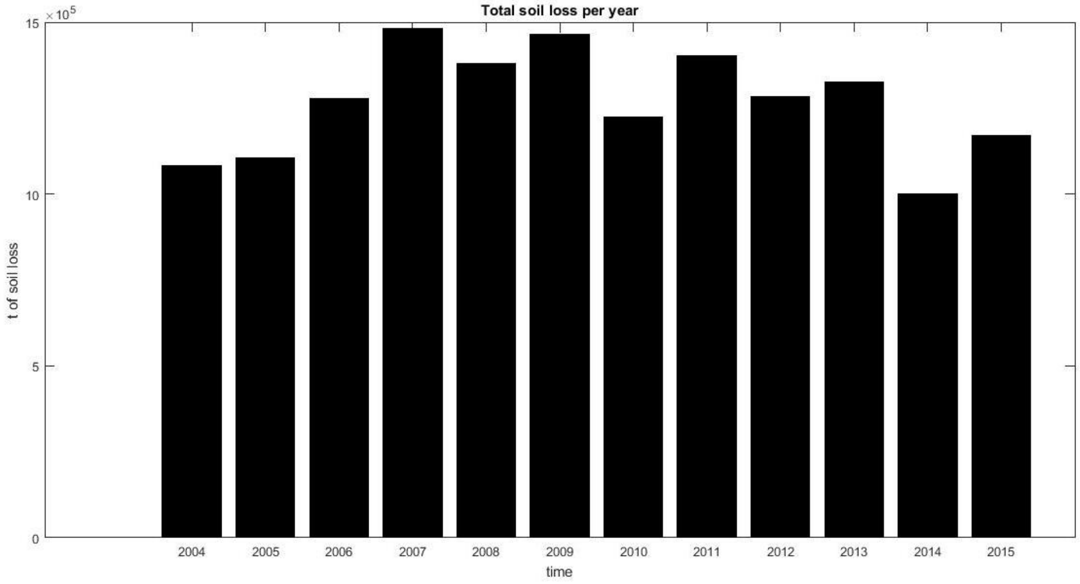

Fig. 23 yearly soil loss from sugarcane plantations in Sao Paulo state

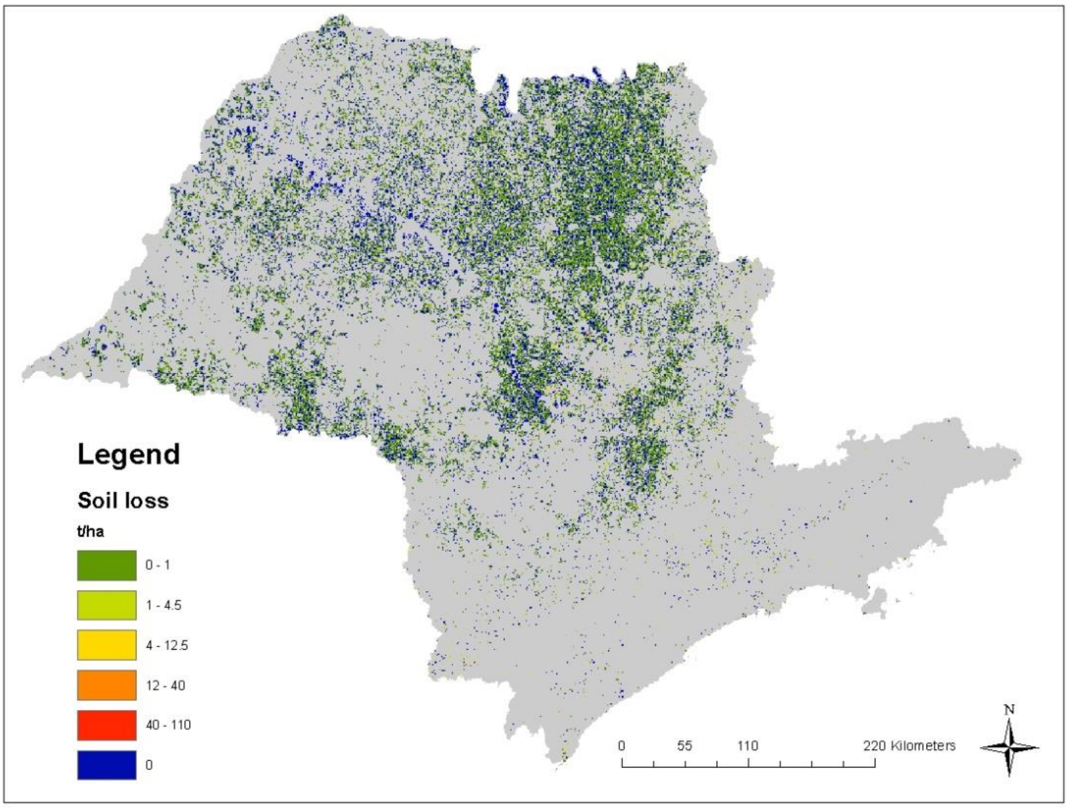

Fig. 24 spatial soil loss from sugarcane plantations in Sao Paulo state in 2012

3.5 Results integration

Fig. 25 represents the integrated results for each harvest year. As mentioned before the scale ranges from -4 to 4. Nevertheless, sugarcane plantations never exceeded a score of 1 (positive EI). Taking into account that sugarcane areas vary between each harvest year, the scores were normalized with their correspondent sugarcane area. As mentioned before in the water section, water shortage is only occurring in the mid stage of the crop (longest stage of the crop). For the results integration, the mid stage results from water shortage were the ones considered.

The scores are similar for all the harvest years (annexes G) with the exception of 2005-2006, 2010-2011, 2011-2012 and 2013-2014. For the rest of the harvest years, the largest % correspond to -1 (more than 55% each year) followed by 0 (approximately 35%). The large % of 0 score illustrates that there are several tradeoffs between positive and negative impacts that tend to balance each other. The % of 1 score never surpasses 1.5% and stays low for all harvest years. Values with a higher negative score than -1, also tend to be low. Scores of -3 and -4 are very rare and never account for more than 1 % of the area (with the exception of 2012, value of 1.2% for -4).

The rest of the years that follow a different trend (2005-2006, 2010-2011, 2011-2012 and 2013-2014) coincide with the harvest years where large areas of sugarcane are releasing CO2 emissions (instead of capturing). These years have dramatically higher % in negative scores than the other ones. Scores of -3 accounts for the largest % (approximately 55%) followed by scores of -2 (approximately 40%). Scores of -1 and 0 are relative rare for these harvest years. The lack of 0 score for these years exemplifies how there are fewer trade of between positive and negative impacts. It must be highlighted the lack of scores above 1 (positive impacts) through all the harvest years, shows how is extremely rare for sugarcane current use or expansion areas to generate more than 1 positive impacts that is not compensated by a negative one.

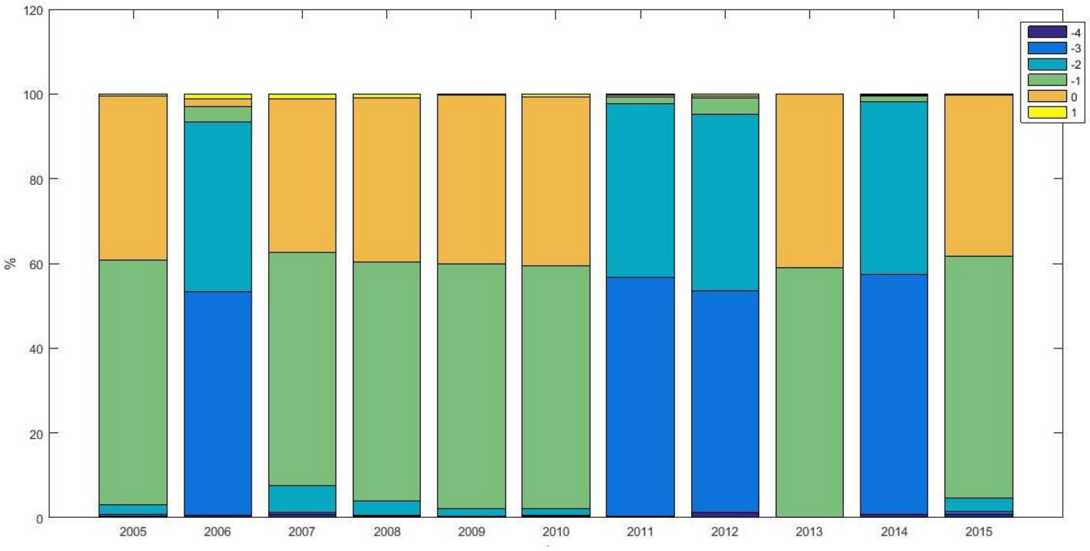

Fig. 25 EI's integration score for each harvest year in %

Even if spatial trends are difficult to assess, the trend is similar for the entire studied time step even with the score distinction between 2005-2006, 2010-2011, 2011-2012, 2013-2014 and the other harvest years. The lowest score areas are registered in the Northwest area of the state when the scores are compared within each harvest year. In the middle section of the state, where sugarcane maintaining areas are large, the results indicate more scores of -1 and 0. However in the years with the different score trend, these areas have values of -2 and -3.

Spatially, there are few areas under sugarcane that have positive impacts. Fig 26 and 27 display the difference in score trend between harvest years. 2011-2012 harvest year is the one with the lowest sugarcane expansion value, however is registering a trend of large areas with -2 and – 3 scores. On the contrary, 2006-2007 harvest year is the one with the highest sugarcane expansion, nevertheless this harvest year is registering large areas with score of 0 and -1.

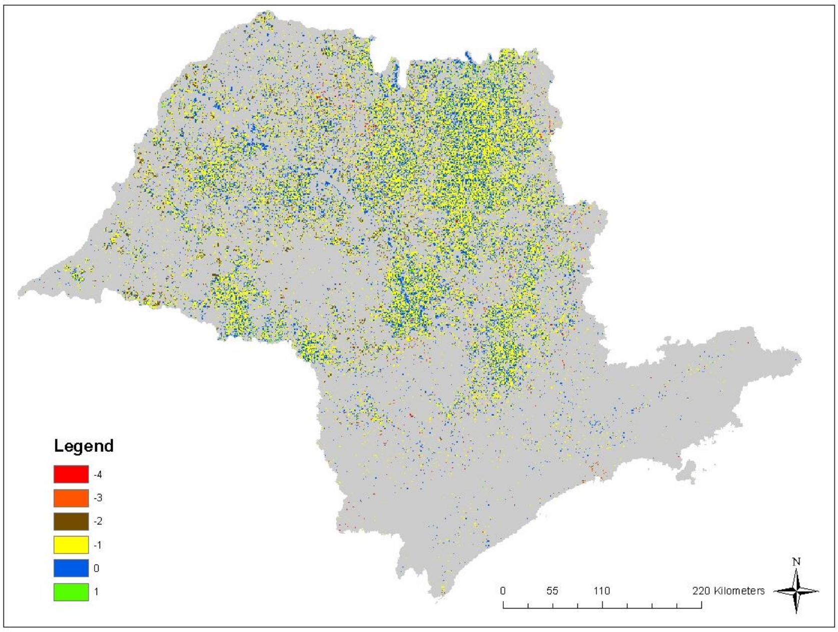

Fig. 26 EI's integration results for 2006-2007 harvest year

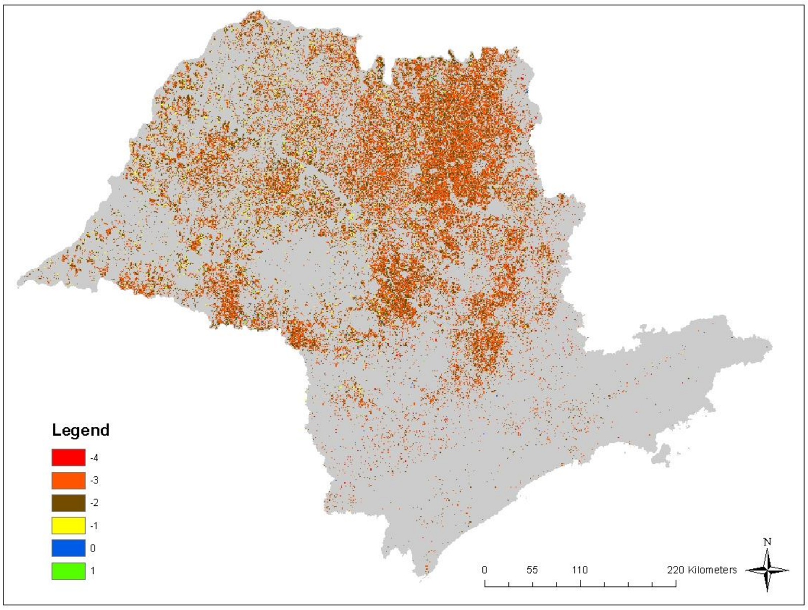

Fig. 27 EI's integration results for 2011-2012 harvest year

4. Discussion

The results should be interpreted with care, especially the ones from the integration section. Even if the results suggest that the Northwest area is the more unsustainable given sugarcane expansion and land use, the integration method assessment did not account for the environmental impact magnitude. A relatively high magnitude positive impact could be compensated by a relatively low magnitude one and vice versa. Soil loss scores are always translated into negative or no change scores, this led to the impossibility of obtaining areas with a perfect score for positive impacts. CO_2 emissions never had a value of no change (given the methodology applied for this section) and the results were always either positive or negative. Meanwhile, water shortage results (given the assumption of using the mid stage results) showed negative impacts the majority of the time, only with a few rare areas with a value of 0. In regards to Biodiversity, the MSA value only changes when sugarcane expands, sugarcane maintaining areas area given a value of 0. Given that sugarcane maintaining areas are drastically larger than expansion areas, vast sugarcane areas had a value of no change in this parameter for the integration part. A higher degree of knowledge is required to understand the relationships between environmental impacts that could be vital for the integration section. Also, more knowledge is needed to translate several indicator scores into real EI's in the best possible manner.

The calculations were based on several input data and as mentioned before, the most important input data for this study was the land cover one. The overall accuracy from the land cover data ranged from 70% to 90% in standard conditions (TUD, 2016). Other studies performed in Brazil with land cover classification have reported accuracies ranging from 63 to 78% (Sano et al., 2010; Beuchle et al., 2015). However, discriminating sugarcane from other crops and grasses was one of the major challenges (TUD, 2016). The discrimination challenges could explain the large tradeoff that is occurring in the whole studied time step (2004-2015) between the low vegetation and sugarcane land cover categories. Even if sugarcane expansion is unlikely to take place in urban and water land cover categories (IPCC, 2006), the data shows that in Sao Paulo state it is occurring (low magnitude). Land cover data from 2013 and 2012 were extrapolated from 2014 and 2011 (lack of satellite coverage) (TUD, 2016). The data extrapolation could be one of the causes for the extremely low sugarcane expansion values for the 2012-2013 harvest year and the disagreement (especially for these years) with other studies. Additionally, the resample from the land cover data (30 m resolution to 1000 m) might have resulted in the loss of land cover classification specificity for some areas.

A wide range of parameters were used to calculate each EI. With regard to CO_2 from the biomass parameter, sugarcane suitability maps were used to establish the spatial difference between sugarcane biomass. For Sao Paulo, suitability values vary approximately from 0.8 to 80%. The approach used for this section resulted in low realistic biomass values for few areas (small amount) as a result of the considerable low suitability values. The same issue was found for the low and medium vegetation categories, given that alfalfa suitability maps were used. Current sugarcane land use was also evaluated and not only expansion, and as mentioned before current land use area is significantly larger than expansion area, the total

CO_2 emissions from biomass in the state are more correlated to the yield change of each consecutive harvest year than to any other variable. Furthermore, the cross multiplication method seemed to be adequate to establish the biomass spatial difference for almost all the harvest years. Nevertheless, the difference between products from the cross multiplication between yield and mean suitability for 2005 and 2006 harvest years (slightly higher result in 2005 than 2006) resulted in large areas of CO2 emission with extremely low values (opposite from what is expected given that 2006 values is slightly larger than 2005).

Regarding the biodiversity section the MSA was the only indicator used for the integration step. Even if the MSA indicator is quantifying the impact on biodiversity from the expansion of sugarcane in Sao Paulo state, the results should be used as a proxy indicator of the possible effect from the sugarcane expansion. The indicator lacks of specific data for the Brazilian scenario. Furthermore, the MSA is not taking into account possible cascade effects (Fragmentation, connectivity loss and possible delays on biodiversity recovery (Lambin et al., 2001)) that can result from LUC. Additionally a negative impact generated from the sugarcane expansion can be compensated by the change of sugarcane to other land cover category leaving aside important and unique local biodiversity characteristics. Furthermore, the MSA assumes the same score for the entire land cover category and this assumption leaves aside the possibility of encountering more biodiverse areas (or higher MSA scores) within the same land cover category. Additionally the score is not changing on time assuming a constant temporal variable. Given the selected method, the LUC is the main driver behind the results from the MSA indicator for the studied time step. Nonetheless, a sensitivity analysis was done in order to establish how each land cover category was affecting the overall score.

The water stress section was evaluated on spatial basis taking into account different climatological parameters such as precipitation, temperature, humidity, evapotranspiration, etc. However the water shortage indicator is not including important relationships between parameters from the hydrological cycle such as ground water. The parameter provides little information to address if the sugarcane production might be generating droughts or water quantity related problems. Nevertheless, the parameter is giving a good approximation of the areas less suitable for sugarcane water requirements in Sao Paulo state (only rain fed). The results suggest that there is a water shortage for the crop when sugarcane reaches the medium growing stage (especially in the Northwest) given that evapotranspiration is higher than the effective precipitation. Nonetheless, the temporal division assumed from this study for the mid growing stage coincides with the dry season. The precipitation monthly average for the mid stage (May to December) is including all the dry months resulting in low effective precipitation average for the medium stage. Additionally, the Kc value has an abrupt shift from the growing stage to medium stage instead of increasing periodically as the crop grows. The Kc value abrupt shift results in suddenly larger values from sugarcane evapotranspiration. The abrupt Kc value change and monthly precipitation average from the mid growing stage could be responsible for the water shortage generated in this period. For further studies the sensitivity analysis should be performed by changing the consecutive months of each growing section.

Given the lack of sugarcane growing stage spatial data, it was assumed the same sugarcane growing process for the whole state. However, in reality there is spatial difference between sugarcane growing stages within the same land cover. Additionally, the implementation of long term monthly averages from climatological parameters resulted in an effective precipitation and reference evapotranspiration base maps (not changing each harvest year). Even if precipitation data was available on monthly basis for the studied time step, the long term averages implementation was done given the lack of data from other climatologic parameters such as humidity and temperature. More powerful hydrological models that include interactions between parameters from the hydrological cycle with specific climatological information for the required time step should be implemented for a better assessment. Furthermore the spatial variation from sugarcane growing stage should be included in order to establish the real effect on the water quantity from the sugarcane land use and expansion.

Regarding soil erosion, the results suggest that sugarcane maintaining areas have low values of soil erosion. However authors have highlighted the soil erosion problems from sugarcane plantations when the sugarcane is under renovation and soils are exposed (Politano and Pissarra, 2005). The sugarcane land cover definition for this study includes areas under renovation and there is not a spatial distinction between them in the sugarcane category. C values differ drastically when a soil is exposed or not (exposed C values result in higher erosion rates) (Biesemans et al. 2000). C values were assigned for sugarcane land cover category with the assumption that all areas are covered with sugarcane (no distinction inside the same category). This assumption might have affected the results and explain the low erosion values from the sugarcane maintaining areas. The results also suggest that when sugarcane expands, the soil erosion increases especially in the Northwest section of the state (even if for this section spatial patterns are difficult to assess). Several sugarcane maintaining areas have a value of 0 for soil erosion, especially the ones close to water bodies. As RUSLE is not intended for water bodies, there might have been overlapping discrepancy between the land cover maps and the K value map (k values map is based on soil type map) explaining the soil erosion values from these areas.

Soil erosion values have to be interpreted with deep care. C and P values are assigned based on literature review and as mentioned before are kept constant for the entire studied time step. Furthermore the values are assumed to be constant within each land cover category. C and P values are time dependable and in order to have a better assessment these values should be calculated for each year with the relevant methodology. With regards to the LS factor, the value was calculated with high resolution (30 m cell size) and then resample to a lower one. The resolution re sample might have resulted in several areas with values of 0 for the LS parameter. If any given driver from the RUSLE equation has a value of 0, the soils erosion immediately becomes 0. Some authors suggest that the R value is the parameter most correlated to soil erosion (Kouli et al., 2009). For this study, the R value is also the one most correlated to the study given that is the only changing on year basis. Furthermore it must be highlighted that the soil parameter only took into account erosion from water. In order to obtain more adequate results, additional empirical measurements should be applied and calculation of wind erosion as well.

The method was adequate to establish a scale of impacts either positive or negative from the sugarcane production and expansion in Sao Paulo state. However, the EI's from other land cover categories in Sao Paulo state were not evaluated. For further studies, the EI from other land cover categories such as expansion of cropland and urban areas should be assessed in order to compare with sugarcane EI's and obtain more arguments to understand better the spatial sustainability of the sugarcane industry. The results were affected also by the decision of assessing not only sugarcane expansion but also sugarcane remaining areas. The sugarcane remaining area evaluation had a direct impact in the results for some indicators such as CO_2 emissions resulting in low spatial difference and difficulty to notice spatial trends between the same land cover category in the state. Furthermore, the sugarcane remaining area assessment is responsible for determining the whole trend from the state in several EI's such as CO_2 emissions were the sink or emission behavior is determined by it. The EI's temporal assessment was done on yearly basis and each impact was quantified in reference to the previous year. However if the quantification had been done with other reference year different from the previous one, the results for some indicators could have been more abrupt (e.g. showing more dramatic land use changes and more CO_2 emissions).

The applied resolution and scale was a limitation for establishing spatial trends for all the EI's in the state. Further studies should be applied on a lower scale (municipality scale) basis to identify possible trend and unsustainable areas that this study might have neglected. However the input data resolution would always be a limitation.

5. Conclusion

Taking into account the limitation of the study approach, applied methods and input data, it can be concluded that there is a constant tradeoff between sugarcane expanding in low vegetation areas and low vegetation areas expanding in sugarcane plantations. Furthermore, the sugarcane expansion is occurring mainly by the displacement of low vegetation areas in the Northwest section of the state for the entire studied time step (2004-2015). Additionally, the Northwest section is the one undergoing the most negative impacts given the magnitude of the sugarcane expansion in this area (especially in biodiversity, soil erosion and water shortage). The study illustrated the high spatial variability of environmental impacts between sugarcane expansion areas and sugarcane maintaining areas; therefore it highlights the importance of assessing spatially the environmental impacts from the sugarcane industry.

Regarding CO_2 emissions from biomass, it was revealed that emissions from the sugarcane maintaining area driven by yield values are more relevant for the whole CO_2 emissions (or sequestration behavior) produced in the state from the sugarcane industry than actual emissions generated from LUC. However, as long as sugarcane keeps expanding on low vegetation areas it will result in a carbon sink behavior for those expansion areas. Enhancements on sugarcane productivity will result in remarkable improvements in CO_2 sequestration from the sugarcane industry. Nevertheless, yield values are also dependable on other variables such climatic factors. Sugarcane LUC is always generating CO_2 emissions in the SOC parameter. However, management improvements will result in substantial carbon accumulation in the soil.

As long as sugarcane keeps expanding, there will be a negative impact on biodiversity. However the approach was not adequate to evaluate the biodiversity impact from the sugarcane maintaining areas. Nevertheless, the real impacts on biodiversity are less than the potential impact given that sugarcane is expanding most of the time in low vegetation areas and is not generating deforestation. The MSA (with only the land use driving force) is a good proxy indicator however is not accounting for relevant interactions from the LUC that would result in more suitable and accurate measurements.

Sugarcane is expanding to the area with less effective precipitation (Northwest), resulting in a possible water shortage for that section. However, important parameters and relationships from the water cycle such as ground water were not taken into account. Regarding soil, sugarcane expansion into other land cover categories is generating more soil loss than sugarcane maintaining areas. However, important variables as sugarcane renovation time were not taken into account. The inclusion of this variable might have resulted in higher values of soil loss for the sugarcane maintaining areas.

On a general conclusion, the Northwest section of the state is the one undergoing the most negative EI’s suggesting that this section is the less suitable for sugarcane production (compared with other sections form the state). Furthermore the sugarcane production (use and expansion) for the entire studied time step (2004-2015) is more inclined to an unsustainable score than to a sustainable one. However, the negative score is low if compared to the maximum potential negative score. The geographical variation between EI’s is mostly determined by previous land use with the exception of the water shortage indicator which is determined more by biophysical characteristics such as precipitation. The internal annual variation between impacts is relative low. However, each indicator inter annual variations are dependable on different factors, CO_2 emissions variations from biomass is more dependable on weather variation that may affect sugarcane yield, but CO_2 emissions variations from SOC are more determined by LUC magnitude. Regarding water shortage inter annual variations; they are determined more by the weather conditions and the location of the sugarcane expansion to the areas with less precipitation (expanding in the Northwest section of the state). Biodiversity inter annual variations are totally dependable on LUC magnitude, while soil erosion inter annual variations are dependable on LUC magnitude and less degree precipitation. However, on general basis the generated impacts from sugarcane are more determined by the previous land use of reference (before sugarcane expansion).

Finally, this study provides a basis to assess spatially the EI generated from the sugarcane production in Brazil and it contributes to identify not only possible areas more suitable for sugarcane expansion, but also key parameters that could be improved to enhance the sustainability of the sector. Furthermore, it offers a chronological picture from the sustainability from the sugarcane industry from 2004-2015 that can result in valuable information for the whole sugarcane industry not only in Sao Paulo state but also in Brazil. However, for further studies more specific and spatial data such as real yield spatial variation or field measurements in soil erosion and biodiversity impacts in Sao Paulo state should be used to obtain more adequate results. Furthermore, future studies should be assessed in a lower resolution (municipality or region) than a state level. The large area is an inconvenient for some EI’s assessment and analysis.

6. References

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