Short title: Sustainability of sugarcane expansion in Brazil

Is the expansion of sugarcane over pasturelands a sustainable strategy for Brazil's bioenergy industry?

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Abstract

Biofuels are fundamental for meeting societal energy needs within the next few decades, but the sustainability of large-scale land use conversions to supply feedstock crops remains unclear. Quantitative data documenting how biofuel crop expansion will affect ecosystem services (ES) is needed to develop sustainable energy policies. Using pairwise comparisons of published and novel environmental, social and economic indicators, we quantitatively assessed the provision of critical ES related to key aspects of the sustainability of pasture-to-sugarcane transitions in Brazil. We found that with the exception of maintaining biodiversity, conversion of pasturelands to sugarcane fields enhanced many ES. Based on the Sustainability index, aimed to capture changes on key sustainability aspects by considering multiple ES and properly integrating them, we concluded that pasture to sugarcane transitions would increase the sustainability by 78% in south-central Brazil. Our results provide science-based empirical evidence that the expansion of sugarcane into degraded pasturelands is a suitable strategy to enhance Brazil’s biomass feedstock supplies for producing bioenergy. Moreover, facing the complex and multidimensional concept of sustainability, our study also illustrates the importance of considering holistically land use change effects rather than individual ESs when establishing sustainable land management practices and bioenergy policies.

Keywords: ecosystem services; land use change; biofuels; sustainability index

Abbreviations:

^{15}N: ^{15}N/^{14}N isotope ratio

ASW: average schooling index

C:N: carbon nitrogen ratio

CCA: canonical correlations analysis

CMI: carbon management index

CR: canonical correlation coefficient

Cseq: carbon sequestration

CYC: carbon cycling index

ELH: employability level per hectare index

ES: ecosystem services

EU-RED: Renewable Energy Directive - European Commission

FRT: Soil fertility index

GBEP: Global Bioenergy Partnership

GEWH: gender equality index

GHG: greenhouse gases

GISQ: General indicator of soil quality

H’: Shannon’s diversity index

HLIF: Humification index

IHa: area devoted to the land use

IRWH: income received per worker index

LUC: land use change

MBC: microbial biomass carbon

NV: native vegetation

PA: pasture

PCA: principal component analysis

PE: people employed in each activity

POC: particulate organic carbon

PWHa: percentage of women in the activity

RSB: Roundtable on Sustainable Biomaterials

SEC: Socioeconomic index

SG: sugarcane

SI: Sustainability index

SOC: soil organic carbon

SOM: soil organic matter

STR: Soil structural quality index

1. Introduction

Crop-based biofuels are often promoted as sustainable energy alternatives for climate change mitigation, but inferences about their sustainability must be supported by holistic assessments of the entire feedstock production system. Land use changes (LUC) for feedstock crops have been reported as the most contentious issue associated with biofuel sustainability [1, 2]. The conundrum is caused by the fact that LUC can greatly alter the provision of many ecosystem services (ES) [3-7]. The basic premise of the ES perspective is that ecosystems provide direct and indirect benefits to humans [3,7]. While it has been acknowledged that sustainability assessments based on ES can provide highly policy-relevant insights [3-7], it remains a relatively unexplored issue in studies regarding the sustainability of biofuels [7]. Besides its relevance, theoretical foundations, versatility and acceptability amongst academics and policy makers [3-7], the ES perspective would also elucidate some environmental and socioeconomic impacts that support LUC decisions related to crop expansion and provide a more systematic view of biofuel sustainability. However, despite the recent efforts to elaborate a unified framework underpinned on ES perspective to evaluate the impacts of biofuel production on different ecosystems [7-10], developing quantitative approaches for ES assessment, even in other research fields, has proven challenging.

Sugarcane (*Saccharum officinarum* L.) is a major biomass source for first generation biofuel, boasting greater carbon savings than corn (*Zea mays* L.), soybean [*Glycine max*. (L.) Merr.] or palm (*Elaeis guineensis*) oil [11]. Based on sugarcane ethanol, Brazil has developed the world’s first biofuel economy and become a world leader for many aspects of the biofuel industry [12]. Currently, Brazil is the world’s largest producer of sugarcane, the second largest producer of bioethanol and has the largest fleet of flex-fuel vehicles (> 20 million). Recently, Jaiswal et al. [13] suggested that expansion of Brazilian sugarcane ethanol provides one near-term and scalable solution to reduce CO_2 emissions from the global transport sector. However, potential negative LUC effects on ES have raised sustainability concerns regarding this industry [1, 2]. Currently, the main scenario for Brazilian sugarcane expansion is the conversion of extensive degraded pastures [13-15].

Previous studies evaluating environmental changes associated with Brazilian sugarcane expansion have provided insightful results regarding soil quality and greenhouse gas (GHG) emissions [16-28]. Soils provide multiple ES, allowing sustained food and fiber production, delivering climate regulation, flood regulation, improved air and water quality and providing a reservoir for biodiversity [4-8, 29]. However, most ES valuation studies either lack or have a poorly defined/generalized soil component [8, 29]. Moreover, the concept of sustainable development embodies interlinkages and balance between economic, social and environmental concerns [30, 31]. It has been recognized that the systematic view of the linkages among ecosystems, human activity and human wellbeing can offer an invaluable lens for studying the sustainability of biofuel systems [3,7], yet social and economic development have not been included in sustainability assessments using an ES approach. Therefore, it is important that quantitative and science-based ES assessment and monitoring strategies be developed, taking into account indicators for all three dimensions, not only to improve land management practices, but also support public policies that promote sustainable biofuel production.

Studies that focus solely on individual ES often fail to unveil synergies and trade-offs that may occur among various services, thus impairing overall conclusions that can be drawn from the investigations. Although previous studies provided guidance for assessing environmental effects associated with pasture-sugarcane conversions in Brazil [16-28], they have not provided an integrated approach that accounts for the social, economic and environmental aspects of sustainability. Currently, most available studies focus on a single indicator or ES, which means that it is neither reasonable nor feasible to determine whether or not the current expansion of sugarcane in Brazil is sustainable. Therefore, acknowledging the complexity and multi dimensionality of sustainability concept [7], our objective was to present a comprehensive ES assessment, based on pairwise comparisons of 62 social, economic and environmental indicators and indexes, and to properly infer about the main sustainability aspects of pasture to sugarcane transitions in Brazil.

2. Material and Methods

We assembled and integrated environmental indicators from 12 previous studies (Table 1) with unpublished social and economic indexes associated with the provision of ES in areas of sugarcane expansion over pastures in Brazil. The environmental assessment used empirical data collected at three field sites, while social and economic indexes were calculated using data made available by the government of surrounding municipalities. Based on conceptual connection of key soil attributes to ES through soil functions [7-8, 29], a set of meaningful soil-related environmental indications was selected to this study. Additionally, we also proposed the inclusion of social and economic indicators for sustainability assessments using an ES perspective. The dataset we assembled, although neither unique nor definitive, provided a comprehensive and relevant set of indicators for studying the direct environmental, social and economic effects of LUC associated with biofuel expansion in Brazil (Table 2). Furthermore, since many of the environmental indicators were associated with individual publications (Table 1), this section focuses on describing the social and economic indicators as well as integrating the entire dataset. Additional methodological information regarding the assessment of soil-related environmental indicators are provided in either Table 1 or the Supplementary Material and Methods.

Table 1. Data source for ecosystem services assessment in pasture-sugarcane transitions in Brazil.

Ecosystem service	**Index**	**Data source**
Soil C sequestration	C sequestration (Cseq)	[16-18]
Maintenance of biodiversity	Shannon's diversity index (H')	[20, 32]
Soil C cycling	C cycling index (CYC)	[21-23]
Soil nutrient provision and acidity buffering	Soil fertility index (FRT)	[24-26]
Soil structuring and water regulation	Soil structural quality index (STR)	[27-28]
Social and economic development	Socioeconomic index (SEC)	This study

2.1. Study sites and sampling procedures for environmental indicators

For indexes regarding the provision of Soil C sequestration, Maintenance of biodiversity, Soil C cycling, Soil nutrient provision and acidity buffering, and Soil structuring and water regulation, information from previous studies (Table 1) was integrated before calculating the ES indexes. Those studies were carried out at the same three study sites (Fig. 2), in areas of native vegetation (NV), pasture (PA) and sugarcane (SG) in south-central Brazil. The pervasive scenario of LUC throughout the region began in the 1980's and involved conversion of native vegetation to extensive pasturelands. Those areas have been cultivated with African grasses [especially *Brachiaria* (syn. *Urochloa*) genera] and characterized by extensive management, continuous grazing, and low grass and beef productivity. The subsequent conversion of pasture to sugarcane required intensive tillage operations and lime application. Sugarcane management also requires annual fertilization as well as pesticide applications to control weeds, pests and diseases. Historically, sugarcane fields were burnt before harvest, but this practice has been gradually banned and is unlikely to happen in new sugarcane areas in south-central Brazil (see Supplementary Table S1).

The climate at all the sites has rainfall concentrated in the spring and summer (October–April), while the dry season is in the autumn and winter (May–September). The mean annual temperature is between 22 and 24 °C. Soils are typical of the Brazilian tropical region, being well-drained and highly weathered, with a predominance of kaolinite, Fe oxides (goethite and hematite), and Al oxide (gibbsite) in the clay-size fraction (see Supplementary Table S1 for further details). For the environmental indicators assessment (Supplementary Tables S2-S7), we sampled LUC chronosequences representing the NV-PA-SG sequence (Supplementary Fig. S1). At each site, a sampling grid with nine points (n=27), spaced 50 m apart (∼1 ha) (Supplementary Fig. S2) was used to identify sampling locations for indicators other than GHG emissions. A chronosequence approach was used because there are no long-term experiments that represent this LUC sequence in Brazil. At each site, the three land uses are located adjacent to each other, minimizing climatic, topographic and soil characteristic differences (Supplementary Fig. S1). For more LUC history and management details within these chronosequences, please see studies from Table 1 and Supplementary Table S1.

Table 2. Ecosystem services, mechanisms and relevance of indicators used to evaluate pasture-sugarcane transitions in Brazil.

Ecosystem service	Mechanisms[1]	Relevance of indicators
Soil C sequestration	Landscape conversion can alter the C balance in agricultural areas.	Besides the knowingly alterations on SOC following LUC [8-9, 16-17], increases on GHG fluxes (e.g. CH_4 emissions from manure and N_2O release from fertilizers) should be take into account for estimations regarding the C balance in agricultural land uses [1-2].
Maintenance of biodiversity	Changes on land use and management practices can lead to the loss or gain of habitats for soil biodiversity.	Shannon's index is widely used in the ecological literature because it accounts for both abundance and evenness of the taxonomic group present [19-20]. It is recognized as the most complete and useful of all diversity indexes [33].
Soil C cycling	Landscape conversion can increase or reduce the quality of soil C and the soil biological activity.	Soil C cycling influences multiple soil functions including provision for soil food web, nutrient recycling and associated ES [4-8]. C lability and composition, and biological activity reflects soil C cycling and are sensitive to LUC [22, 23].
Soil nutrient provision and acidity buffering	Landscape conversion and management practices changes can increase or decrease soil fertility.	The soil fertility index integrates the changes on plant-essential elements and soil acidity attributes, which are key indicators of soil health [34] that supporting many others ES, such as provision of food and biofuel feedstock [8, 26].
Soil structuring and water regulation	Landscape conversion can increase or decrease the soil resistance and resilience to physical degradation.	The soil physical index integrates classic indicators of soil physical quality [34] direct and indirectly related to soil physical functions [27-28] and many provisioning (fresh water retention; food and biofuel provision), regulating (water regulation, gas regulation) and supporting (provision of habitat) ESs [8, 26].
Social and economic development	The wellbeing of individuals straight related to beef and ethanol sectors is influenced by social and economic alterations associated to sugarcane expansion.	Workers' income, employment per hectare, education level and gender equality properly capture the main direct impacts of LUC on the socioeconomic conditions for employees within beef and ethanol sectors [30-31]. Moreover, SEC was computed using procedures adapted from the widely accepted Human Development Index [37].

[1] Adapted from Gasparatos et al. [7], Gissi et al. [8], and Adhikari and Hartemink [29].

2.2. Social and economic development assessment

Social and economic indicators were assessed in 10, 7, and 6 municipalities (n=23) surrounding study sites 1, 2, and 3, respectively (Supplementary Table S7). The number of assessments was variable because a different number of municipalities border each study site.

A Socioeconomic index (SEC) was calculated using four indicators that reflect socioeconomic conditions for employees within beef and ethanol sectors. The amount of available data varied, generally derived from two national socio-economic databases [35, 36]. Based on the available information in these databases, SEC was computed using procedures adapted from the methodology of the Human Development Index [37]. Specifically, SEC consists of four sub-indexes: 1) IRWH, income received per worker index [31]; 2) ELH, employability level per hectare index [38]; 3) GEWH, gender equality index [39]; and 4) ASW, average schooling index. We are unaware of any other municipal-scale approximations of socioeconomic and ES assessments in Brazil.

For the IRWH index, the total income of each activity is obtained by dividing labour income by the number of hectares (IHa) devoted to that sector, thus providing an estimate of income per hectare of each activity (equation 1)1:

$$\mathrm{IRWH} = \frac{\log(\mathrm{IHa}) - \log\big(\mathrm{IHa}(\mathrm{MIN})\big)}{\log\big(\mathrm{IHa}(\mathrm{MAX})\big) - \log\big(\mathrm{IHa}(\mathrm{MIN})\big)} \qquad (1)$$

To obtain the number of people employed per hectare within each sector (PEHa) for subsequent use in calculating EHL, the total number of people employed (PE) within each sector activity was divided by the number of hectares (IHa) devoted to the sector. Similarly, for the IRWH index, we calculated ELH using global minimum and maximum values as shown in equation 2:

$$\mathrm{ELH} = \frac{\mathrm{PEHa} - \mathrm{PEHa(MIN)}}{\mathrm{PEHa(MAX)} - \mathrm{PEHa(MIN)}} \tag{2}$$

GEWH was computed by first dividing the number of women employed by the total number of workers and then multiplying by 100 to express the value as the percentage of women in each activity (PWHa). Then, the value was normalized with an overall goal of achieving a value of 1.0 (the beaconing in 0.5) which would reflect gender equality (equation 3):

$$\mathrm{GEWH} = \frac{\mathrm{PWHa}}{\mathrm{PWHa(0.5)}} \tag{3}$$

Similarly, ASW is a ratio reflecting the average level of schooling per worker per activity (ASWi) in relation to maximum and minimum levels of schooling (equation 4):

$$\mathrm{ASW} = \frac{\mathrm{ASWi} - \mathrm{ASWi(MIN)}}{\mathrm{ASWi(MAX)} - \mathrm{ASWi(MIN)}} \tag{4}$$

Finally, IRWH, ELH, GEWH and ASW sub-indexes were integrated into an overall SEC (equation 5) using an approach developed for computing the Human Development Index, where use of a geometric mean attenuates large variability effects among the indicators [37].

$$\mathrm{SEC} = \sqrt[4]{\mathrm{IRWH} \times \mathrm{ELH} \times \mathrm{GEWH} \times \mathrm{ASW}} \tag{5}$$

Therefore, SEC is an index that measures socioeconomic effects on individuals directly associated with beef and ethanol sectors. Regarding provision of goods (food or biofuel production), although indicator can be expressed in mass or energy per unit area annually [7], we assumed as a metric the financial returns from the farm phase (US\$ ha^{-1} yr^{-1}). Besides allow us fairly comparing this provisioning service of each land use, land profitability is a major aspect taken into account by the farmers, who are the ultimate drivers of LUC to bioenergy expansion in Brazil. Finally, cattle herd and sugarcane production in municipalities surrounding the study sites were obtained from the two main national socio-economic databases [35, 36].

2.3. Environmental ecosystem services assessment

Besides SEC, we computed a composite index for each ES included in this study (Fig.1). Soil C sequestration (Cseq) was calculated by the difference between rates of soil C change and soil GHG emissions [40], while Maintenance of biodiversity was quantified using Shannon’s diversity index (H’) [41]. For Soil structuring and water regulating, Soil C cycling and as well as Soil nutrient provision and acidity buffering, we proposed the Soil structural quality index (STR), the C cycling index (CYC) and the Soil fertility index (FRT), respectively. All three are components of the General Indicator of Soil Quality (GISQ) index [42].

The overall goal was to create a composite index that captures the majority of variance expressed by a set of indicators for each ES (Fig. 1). Therefore, measured values for each indicator were normalized into an ordinal score from 0 to 1. This procedure enables the integration of two or more indicators measured using different units. A linear transformation was used for CYC parameters due to lack of suitable baseline and threshold values in the literature. In this case, parameters were ranked in ascending or descending order depending on whether a higher value was considered “beneficial” or “disadvantageous” in terms of soil function. For “more is better” parameters (e.g. POC, CMI and MBC) each observation was divided by the highest observed value which by definition received a score of 1. For “less is better” parameters (e.g. HLIF, C:N ratio and ^{15}N) the lowest observed value received a score of 1.0. That value was then divided by the other observations to compute their relative scores. For SFT and STR, non-linear transformations were performed using the same approach and values for the baseline and thresholds described by Cherubin et al. [28].

Subsequently, a principal component analysis (PCA) was performed to weight the contribution of each sustainability indicator (Supplementary Figs. S3-S6). The PCA loadings (Supplementary Tables S9-S12) for each indicator were multiplied by corresponding normalized values and summed to generate a raw sub-index for each statistically relevant (*i.e.*, eigenvalue >1 – Kaiser’s criterion) principle component (Supplementary Figs. S7-S10). Each sub-index was then multiplied by the proportion of the total variance explained by the principal component before summing the values into an overall index (Fig. 1).

2.4. Sustainability Index calculation

The main sustainability aspects of the beef and ethanol sectors was assessed by integrating the six ES indexes (*i.e.*, Cseq, H’, STR, CYC, FRT and SEC) into the Sustainability index (SI), also based on the GISQ [42], as further clarified in the Fig. 1. For the SI, ES indexes were normalized as shown for CYC, but considering only a “more is better” relationship for all indexes. Finally, in addition to the SI, a PCA was performed to identify synergies (or co-benefits) and trade-offs among the ES, as described by Le Clec’h et al. [6].

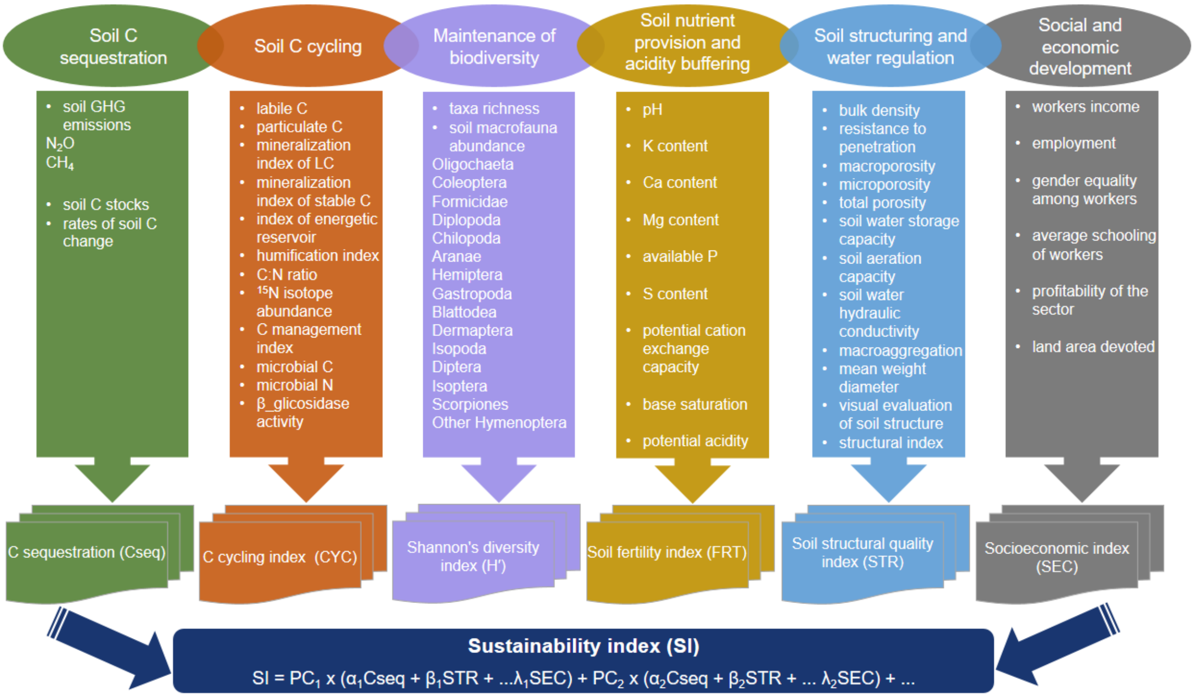

Figure 1. A conceptual overview of the sustainability assessment process used to evaluate pasture-sugarcane transitions in Brazil. STR, CYC, FRT and SI were calculated based on the General Indicator of Soil Quality (GISQ) [42]. Briefly, after conducting a principal component analysis (PCA), values for each indicator are multiplied by their corresponding PCA loading (α, β, λ…) and summed to generate a raw sub-index for each principal component that is statistically relevant (i.e., eigenvalue >1 – Kaiser's criterion). Each sub-index is then multiplied by the overall variability explained by the associated component (i.e., PC_1, PC_2…). The final indexes are obtained by summing the weighted sub-indexes as shown for SI.

2.5. Canonical correlation analysis (CCA) between ecosystem services

The CCA is the logical extension of simple correlation and multiple regression analysis to situations where the objective is to quantify the association between two sets of indicators [43], such as those we used to evaluate the ES (Fig. 1). The CCA focuses on the correlation between a linear combination of one set of indicators (e.g. Soil structuring and water regulating indicators) and a linear combination of another set of indicators (e.g. Soil nutrient provision and acidity buffering indicators). In this method, the variance of the original sets of indicators was redistributed into a pair of canonical variables that are built to maximize the correlation between them [43]. In our study, the standardized canonical correlation coefficient (CR) showed the relative strength of the association between two sets of indicators used to evaluate two ES and its statistical significance was tested by F-test. The canonical scores for each indicator in the linear combinations allow to infer about the main drivers of these correlations, as well as its directions (Supplementary Table S13). The statistical analyses were carried out using the software R, version 3.2.2 [44].

3. Results and Discussion

3.1. Decadal pasture and sugarcane land-use change patterns in Brazil

This discussion is focused on integrated results (indexes) and their implications on the main sustainability aspects of converting extensive degraded pasture (PA) to sugarcane production (SG) in Brazil. Average values for each sustainability indicator may be found in previous studies listed in Table 1 and Supplementary Tables S2-S7. The sites and municipalities evaluated are located along a 1000-km transect within south-central Brazil (Figure 2a-d), the largest sugarcane expansion hotspot in the world, accounting for 93.7% of Brazilian ethanol production [45]. In these locations, most of the recent sugarcane expansion has been placed over extensive pastures (Figure 2a-d) [14]. Over the last years, the number of cattle has generally decreased while sugarcane production, mainly in municipalities surrounding sites 2 (Figure 2f) and 3 (Figure 2g) [36], has increased. Replacement of pasture by sugarcane is likely to continue in Brazil because government policies for sustainable intensification of livestock production [46] can potentially make large amounts of land available for crop establishment. Furthermore, since deforestation is no longer a feasible option (agroecological zoning, law enforcement and market regulation), land spared by livestock intensification is expected to be the primary area for sugarcane expansion for several years.

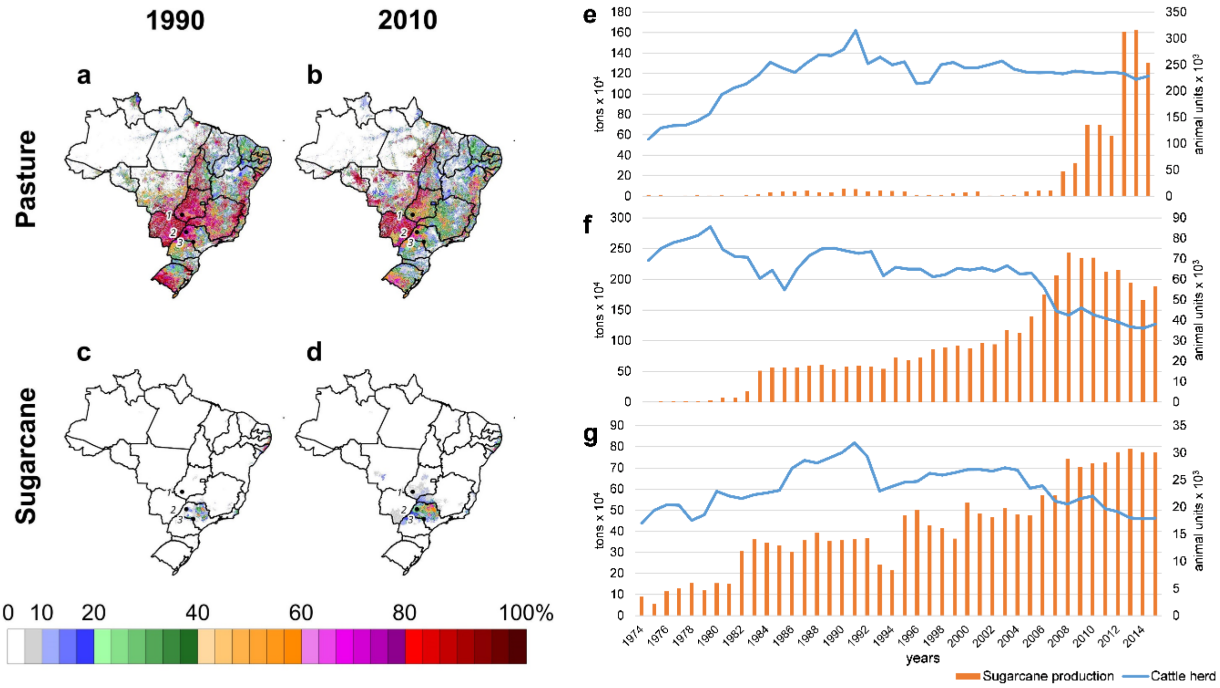

Figure 2. Decadal pasture and sugarcane land-use change patterns in Brazil. 1, 2 and 3: sites evaluated for environmental indicators assessment. a-d: pasture and sugarcane land use change patterns in Brazil according to Dias et al. [14]. e-g: cattle herd and sugarcane production in municipalities surrounding the study sites [35, 36].

3.2. Effects of pasture-sugarcane transitions on the provision of ecosystem services

As discussed in previous studies (e.g., Table 1) and shown here (Fig. 3), areas of native vegetation (NV) have substantial capacity to provide many ES [4-6]. For our assessment, NV was used only as a baseline scenario. We also assumed zero GHG emissions within NV areas. Furthermore, we did not attribute any monetary value to NV areas, because we believe the ES provided by native systems cannot be reliably monetized, and inferences based on standard market prices are not a good option to compare land uses when natural ecosystems are included. Therefore, the following discussion focuses solely on the main sustainability aspects related to PA – SG transitions in Brazil.

3.2.1. Soil C sequestration

Increased attention on soil health has also raised awareness regarding the importance of soil organic C (SOC) storage for both agricultural production and sustainability of soil resources [5, 8-9, 47]. Furthermore, LUC effects on SOC and GHG emissions are a key component associated with assessments of biofuel sustainability [1, 2]. Since biofuels are supposed to be a GHG mitigation option [1, 2], studies indicating that sugarcane expansion may increase emissions are particularly troubling from a climate change perspective. The critical factor is C balance, which greatly depends on the previous land use. Fortunately, replacement of degraded land (which characterizes most Brazilian pastures) with biofuel crops often results in SOC accretion [48].

Based on measurements to a depth of 1m, we observed that prior conversion of NV to PA depleted SOC by 26% (Fig. 3) (~1.0 Mg ha^{-1} yr^{-1}), whereas PA-SG conversion increased SOC by an average of 1.9 Mg ha^{-1} yr^{-1} or 17%. Considering GHG emissions

(Fig. 3), PA areas became a net C source emitting 13.3 Mg CO_2eq. ha^{-1} yr^{-1}. Therefore, the PA – SG conversion may represent a win-win mitigation option, by simultaneously sequestering SOC (5.4 Mg CO_2eq. ha^{-1} yr^{-1}) and providing feedstock to displace gasoline. However, it is important to recognize that: i) SOC is expected to reach a new equilibrium after a few decades, ii) since the largest impact of LUC may occur during the first few years after conversion, recent conversions are likely to show inflated rates of C accumulation that may not be maintained over longer time periods and, (iii) the GHG emission assessment encompass only the farm phase; therefore, emissions associated with other steps of beef or biofuel production life cycle were not included, since it is beyond the scope of this study.

3.2.2. Soil C cycling

In addition to be a major terrestrial C pool, Soil C cycling influences multiple soil functions including provision for soil food web, nutrient recycling and associated ES [8-9]. Here, we assumed some parameters related to C lability, SOC composition and biological activity (Fig. 2) as indicators of changes in Soil C cycling. Following a NV – PA transition, the C cycling index (CYC) decreased by 22% (Fig. 3). Because of incremental changes in labile C within sugarcane areas (Supplementary Table S3) and the link between the quantity of each C fraction and soil C turnover, an enhancement in CYC was expected following PA – SG transition, but only a slight increase (5%) was observed. Perhaps, the negative effects of tillage associated with SG production countered the benefits of higher C inputs on CYC [5].

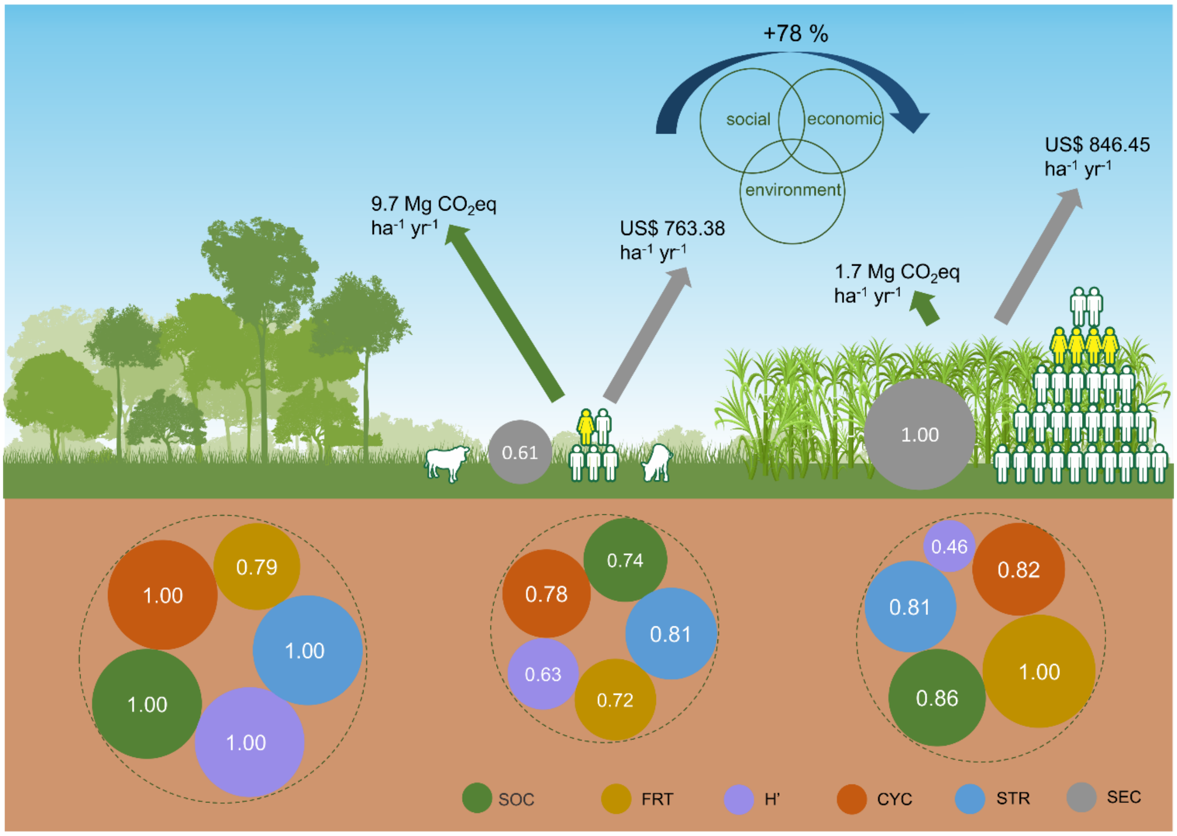

Figure 3. Changes on ecosystem services and sustainability aspects related to pasture-sugarcane land use transitions in Brazil. Green arrows represent greenhouse gases (GHG) emissions (Mg CO_2eq ha^{-1} yr^{-1}), while grey arrows show the average profitability (US\$ ha^{-1} yr^{-1}) for each land use. Human shapes represent the average employability per land use for an area of ~830 ha (smaller area at which it is possible to distinguish workers by gender in each land use), with white representing male workers and yellow female workers. All indexes were linearly normalized assuming the greater value as equal to one (for raw values, see Supplementary Table S8). SOC: soil organic C. FRT: Soil fertility index. H': Shannon's diversity index. CYC: C cycling index. STR: Soil structural quality index. SEC: Socioeconomic index.

3.2.3. Soil biodiversity

In this study, we used litter-dwelling and edaphic macroinvertebrates as a proxy for LUC-induced changes in the Maintenance of soil biodiversity, another important ES [4-8, 49]. This functionally relevant compartment of the soil biodiversity includes ants, termites, coleopterans, earthworms, and other faunal groups that span a variety of trophic positions in the soil food web (see detailed list of macrofaunal groups assessed in the Supplementary Table S4). According to the diversity index (H'), SG areas had the lowest values among the three land uses (Fig. 3). PA – SG transitions decreased soil fauna abundance and taxonomic diversity by 89% and 39%, respectively (Supplementary Table S4). Sugarcane production involves several intensive tillage operations approximately every five years (Supplementary Table S1) that are known to destroy invertebrate habitats. Furthermore, after LUC, sugarcane fields are managed using moderate to high frequency of systematic chemical inputs, such as pesticides and fertilizers (Supplementary Table S1). This also negatively affects the abundance, diversity and equability of belowground communities [50]. Pasture soils harboured the highest abundance of termites and earthworms (Supplementary Table S4), two major ecosystem engineers [51], supported by cattle dung and grass residue inputs [52].

Organisms located at the top of the belowground trophic structure, such as spiders and scorpions which are critical for top-down regulation of soil food webs [53], occurred in lower abundances under SG compared to PA areas. Nevertheless, it should be stressed that total abundance of these predatory groups was extremely low in both land uses compared to the NV reference (*i.e.*, less than 5% of original population, Supplementary Table S4). As expected, NV areas were highly diverse with regard to taxonomic groups, reflecting the multiple ecological functions they provide compared to PA and SG areas. Soil biodiversity as assessed by H' decreased by 27% for PA to SG conversions (Fig. 3).

Maintenance of biodiversity was thus the single ES to suffer depletion following PA – SG transitions. This is important, because soil biodiversity not only contributes to biomass production but is also an important regulator of other soil services including GHG emissions, water purification and nutrient cycling [5]. Accordingly, strategies to decrease biodiversity losses in SG areas must be identified and developed.

3.2.4. Soil nutrient provision and acidity buffering

Despite the biodiversity losses, PA – SG transitions enhanced Soil nutrient provision and acidity buffering by 24% (Fig. 3). In undisturbed or poorly managed ecosystems (*i.e.*, extensive pastureland), most of the nutrient supply results from SOC turnover that is mediated by soil organisms [5, 54]. However, extensive livestock production in Brazil often involves continuous grazing, nutrient removal without replacement by fertilizers, low primary productivity, SOC depletion and soil losses by erosion, frequently leading to long-term land degradation [46]. In contrast, sugarcane cultivation significantly alters soil biogeochemical cycles and plant-available nutrients (Fig. 3; Supplementary Table S5). Soil acidification and higher nutrient removal by cane harvest is replenished by liming and mineral fertilizers and/or organic industry by-products (e.g., vinasse and filtercake) [24]. Collectively, those practices help restore soil fertility to levels even higher than those under undisturbed tropical ecosystems (Fig. 3). Nevertheless, we recognize that fertilizer applications, coupled with biodiversity losses, might impair the soil's capacity to supply nutrients, thus increasing the long-term dependency on external inputs [5, 53].

3.2.5. Soil structuring and water regulation

Soil structuring and water regulation are driven primarily by land cover, C cycling, bioturbation and soil compaction [27, 47, 54]. In poorly managed extensive pastures, continuous cattle trampling coupled with lower C inputs is a primary cause of soil compaction, unbalanced water- to air-filled pore space ratios, and restrictions to both water movement and root growth (Supplementary Table S6). Overall, NV – PA transitions resulted in reduced provision of Soil structuring and water regulation services as noted in the literature [4, 6] and observed in this study (-19%, Fig. 3). In our assessment, PA – SG transitions did not significantly alter the soil structural quality (STR) index (Fig. 3). Sugarcane cultivation requires intensive mechanization (Supplementary Table S1), which is the main driver of soil compaction [47]. However, deep tillage performed for sugarcane planting alleviates soil compaction in the short-term [27], maintaining soil structure and water regulation similar to the conditions found in pasture areas. Currently, identifying ways to reduce soil compaction in sugarcane fields is one the major challenges required to increase the sustainability of Brazilian sugarcane production.

3.2.6. Social and economic development

LUC effects go beyond the environmental dimension of sustainability as they also influence economic and social aspects, and consequently the human wellbeing within the impacted areas [3, 7, 55]. Socioeconomic indexes have been widely used to evaluate the performance of human activities and the welfare of society [37], thus also providing valuable information on ES provision [31]. However, LUC associated to biofuels production can influence human wellbeing in multiple ways. Most commonly, this happens through rural development and the generation of income and employment for those involved into feedstock production [3, 7]. Moreover, those influences imposed by the ecosystem changes on human wellbeing tend to be highly context specific. Finally, the ES perspective has conceptual limitations in capturing properly impacts of later stages that are not directly linked to LUC [7]. Accordingly, while recognizing that the social groups impacted by LUC go beyond the industry's workers and farmers, we restricted this assessment of the social and economic impacts of LUC associated to biofuel production to individuals directly related with the livestock and sugarcane industry.

Our assessment showed that PA – SG transitions increased the social and economic development for workers by 64% within 23 municipalities across south-central Brazil. Specifically, conversion to SG production increased the employment per hectare, as well as workers' income (Supplementary Table S7). These results are associated with the expansion of ethanol production through a very organized chain of stakeholders (*i.e.*, producers, farm workers, truckers, mills, input suppliers, etc.) compared to the livestock sector, which is still associated with labour exploitation and illegal slaughterhouses in some municipalities.

Workers within the sugarcane industry generally had a higher level of education compared to livestock employees in Brazil (Supplementary Table S7). Conversely, the livestock industry attracts more female workers, probably because in Brazil it still consists of some family-owned-and-operated cattle ranches that include more women in the workforce. Additionally, farmer profit per hectare was also higher for sugarcane than livestock production (Figure 3). On average, we verified that sugarcane production was more profitable by US$ 83.07 ha^{-1} yr^{-1}compared to extensive livestock farming in Brazil. In this sense, PA – SG transitions enhanced social and economic development for workers, and increased ES-related to provisioning of goods.

3.3. Overall sustainability of PA-SG conversions in Brazil

Based on the Sustainability index, aimed to capture changes on key sustainability aspects by considering multiple ES and properly integrating them (Fig. 1), our results suggested that PA – SG transitions would increase the sustainability by 78% in south-central Brazil (Fig. 3). Except for Maintenance of biodiversity, this index reflected an overall improvement of the ES evaluated in areas undergoing LUC. However, biodiversity conservation is highly relevant to fulfilling environmental goals and this undesirable outcome could eventually impair other ES [5, 49]. Therefore, the sugarcane sector should continue to strive for management strategies that create synergies and reduce trade-offs among ES in sugarcane fields. Adoption of reduced tillage is one practice that could at least partially alleviate the negative effects of sugarcane crop on biodiversity. Despite the dissonant result for H’, values of the Sustainability index provide strong evidence that PA – SG conversions are not only feasible, but also provide a sustainable approach for increasing bioenergy production in Brazil.

In the last United Nations Framework Convention on Climate Change (UNFCCC), the Brazilian government announced an ambitious goal, stating that by 2030 they would reduce GHG emissions by 43% compared to 2005 levels [56]. To do so, several strategies were established, including that sugarcane should account for 16% of Brazil’s energy supply by 2030. Meeting this mandate will likely require a substantial increase in sugarcane production area and therefore, the impacts of sugarcane expansion cannot be overlooked. The development of integrated approaches is a complex task and time-consuming process, but we believe this unprecedented effort will be one of the main drivers for bioenergy policies and land management in Brazil for the next years. Only a multidisciplinary view, supported by science, can promote an informed, orderly, predictable, and responsible transition toward the increased use of biofuels, without impairing the provision of ES.

3.4. Interactions among ecosystem services

A substantial effort has been made in recent years to better understand relationships between ES and the environmental factors that influence them [4, 6, 8, 55]. In our study, canonical correlation analysis (CCA) was a useful tool to explore these connections and drivers. Most ES included in this assessment are significantly correlated (Fig. 4). Although those correlations are well known, CCA enables to describe and quantitatively express the complex interrelationships among large groups of indicators. It also provides a method for calculating which indicators are more relevant for these relationships. However, CCA is not an indicator of causality. Some contentious relations were revealed here and need to be studied more purposefully by other means. To mention but a few, the correlation between Soil nutrient provision and acidity buffering and Soil C sequestration is mainly explained by the positive effect of cation exchange capacity and sulphur contents on SOC; while particulate soil C has a large influence on the correlation between Soil C cycling and Soil structuring and water retention (Supplementary Table S7). Other correlations, despite their statistical significance, are undeniably complex and remain elusive (*i.e.*, Social and economic development and Maintenance of biodiversity).

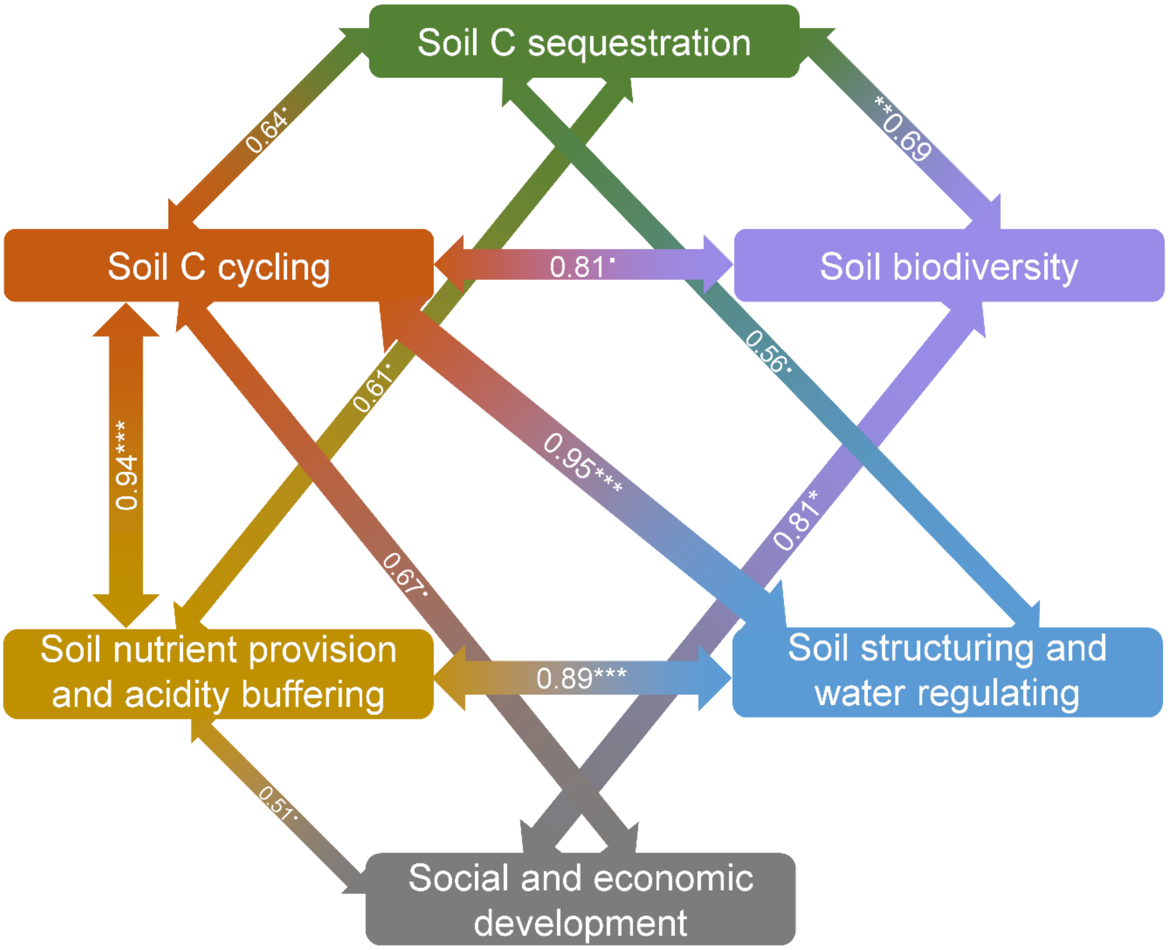

Figure 4. Schematic representation of canonical correlations among ecosystem services in areas of pasture-sugarcane transitions in Brazil. Arrow thickness is scaled to illustrate the relative strength of the correlation, also represented by the canonical correlation coefficients. Significance codes for the canonical correlation coefficients (test F): ·p<0.1; *p < 0.05; **p < 0.01; ***p < 0.001.

We applied principal component analysis to calculate the scores of each ES in the Sustainability index, and also to identify possible conflicting objectives and trade-offs, as well as synergies and co-benefits among ES [6] in pasture and sugarcane areas in Brazil. In both land uses, a tendency for synergy was observed among most of ES evaluated, except for Soil C cycling and Soil structuring and water retention in pasture areas, Soil nutrient provision and acidity buffering, and Soil C cycling and Soil C sequestration in sugarcane fields (Fig. 5). In general, best management practices applied to improve one ES also tended to support others. The inverse was true, as unsustainable management practices tend to degrade multiple ES. Building soil organic matter (SOM), for example, enhances soil C, soil nutrient status, improves water holding capacity, and supports soil biota [5, 8, 57], whereas, soil compaction by excessive and non-controlled machine traffic degrades soil structural quality, increasing soil mechanical resistance to root growth and impairing soil biota [19, 28].

In pasture areas, the first PCA axis, which accounted for 54% of the variance, was positively correlated with Soil structuring and water regulating and Soil C sequestration (synergies). The same axis was negatively correlated with Soil nutrient provision and acidity buffering, and Soil C cycling (Fig. 5a), reiterating the role of SOM turnover on soil fertility. In sugarcane areas, improvements on C stocks and SOM quality has potential to partially alleviate the effects of intensive mechanization on soil compaction, since Soil C sequestration, Soil C cycling and Soil structuring and water regulating were synergetic ES (Fig .5b). The trade-offs among Soil C sequestration, Soil C cycling, and Soil nutrient provision and acidity buffering (Fig. 5b) allow us to infer that the improvements on soil fertility in sugarcane areas are associated to supply of liming and mineral fertilizers, not being related to SOM turnover. Accordingly, further assessments should evaluate the capacity of these soils to self-sustaining sugarcane cropping, since long-term dependency on external nutrient inputs might negatively affect the C footprint of Brazilian ethanol.

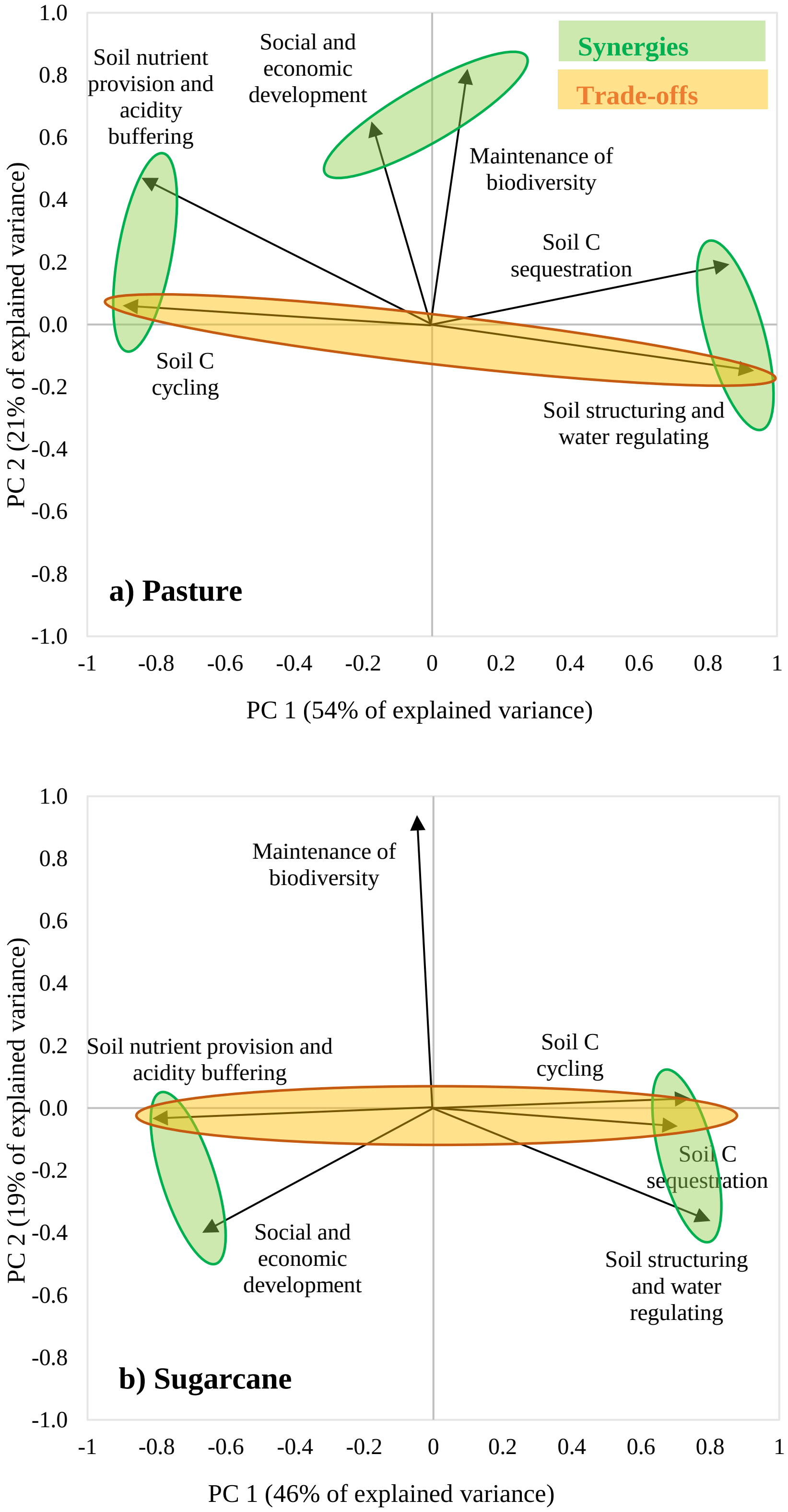

Figure 5. Synergies (or co-benefits) and trade-offs among ecosystem services in areas of pasture (a) and sugarcane (b) under land use transitions in Brazil.

3.5. Research gaps and challenges

Despite our unprecedented effort to gather and properly integrate 62 social, economic and environmental sustainability indicators, some research gaps remain that undermine our ability to derive conclusions regarding the overall sustainability of sugarcane expansion in Brazil. By considering strict conceptualizations about the ES and its applicability in sustainability assessments, one may neglect important processes knowingly affected by LUC. In this sense, there is no consensus about dealing with the socioeconomic development as an ES [3, 7]. However, we adopted and emphasized the relevance of including this socio-economic dimension into sustainability assessments of biofuel production. Since the basic premise of the ES is that ecosystems provide direct and indirect benefits to humans [3, 7], we believe that changes in the socioeconomic development ought to be approached as an ES.

Even though addressing most of ES admittedly affected by the LUC, our study did not include some important ES such as water-related and cultural services [3, 7, 10]. Although not quantified here, it is expected that both land uses will differ in their effects on water quality. Despite pasture and sugarcane areas being predominantly under rainfed conditions, both can impair the water quality, mainly groundwater [58]. In this sense, we encourage further studies evaluating the effects of sugarcane expansion on water pollution and including water-related services into a sustainability assessment perspective. It is worth mentioning that some studies have used indicators related to soil buffer capacity to reflect groundwater quality protection from nutrient leaching [8]. In our study, soil buffer capacity increased after the conversion to sugarcane (Supplementary Table S5). Moreover, cultural services are mainly provided and linked to natural landscapes [8, 59]. Accordingly, since our study focuses solely on the sustainability of pasture to sugarcane conversions, cultural ES were not considered. Finally, as stressed by

Gasparatos et al. [7], there is no single methodology that can capture and meaningfully integrate the multiple biofuel sustainability impacts.

The proposed effort, though complex and challenging, is not the only needed activity, as many other indicators may be required to provide an even more complete accounting of ES. Our study should be viewed as a starting point for those more comprehensive analyses using quantitative approaches to integrate wide datasets under an ES perspective for properly evaluating the outcomes of sugarcane expansion in Brazil. Furthermore, although it is difficult to develop a universally applicable sustainability assessment method, a framework that can synthesize the existing evidence on bioenergy's environmental and socioeconomic impacts is needed [7, 60]. The limitations of such approach are recognized, but the need for a pragmatic and operational methodology has been justified. In this sense, we encourage the application and further development of our approach to assess and monitor the sustainability in other areas of biofuel expansion across the world.

4. Conclusions and suggestions for policy makers

- Our study illustrates the importance of considering holistically the effects of LUC by researchers and policy makers who often deliberate on ES individually. Ecosystem services are interrelated and any sustainability assessment must treat them as such.
- Based on the Sustainability index, aimed to capture changes on key sustainability aspects by considering multiple ES and properly integrating them, we concluded that pasture to sugarcane transitions would increase the sustainability by 78% in south-central Brazil.

- The Sustainability index provide sound empirical evidence that expansion of sugarcane over pasturelands enhances environmental, economic, and social components of sustainability at the regional scale in Brazil.
- Regarding indirect LUC effects and food security issues, pasture – sugarcane transitions seems to have far less impact than previously thought in Brazil [13, 15]. In this sense, besides providing feedstock to displace gasoline and mitigating climate change, the expansion of sugarcane cropland could also contribute to a broader sustainability agenda in Brazil.
- Many methods for biofuel certification and verification exist (e.g. EU-RED, GBEP, Bonsucro, RSBS) [61]. However, they are general schemes and essentially qualitative, and do not provide an integrated means to assess quantitatively the effects of crop-based biofuels expansion.
- Decision-making toward a clean-energy based economy would be facilitated by the development of a sustainability index incorporating measures of environmental, social, and economic indicators.
- In the light of the findings summarized here, we conclude that the Sustainability index provides a sensitive and science-based approach for quantifying changes on main sustainability aspects in areas under LUC for biofuel production using an ES perspective. This metric can be very useful helping decision makers to understand the magnitude of LUC impacts and support improvements or even new public policies for land conservation.
- However, there is no single methodology that can capture and meaningfully integrate the multiple outcomes of biofuels expansion. In this sense, though complex and challenging, the proposed effort presents recognized limitations, as

many other indicators may be required to provide an even more complete accounting of ES.

- Our study should be view as a starting point for those more comprehensive analyses using quantitative approaches to integrate wide data sets under an ES perspective for properly evaluate the outcomes of sugarcane expansion in Brazil.
- Finally, we encourage the application and further development of our approach for assessing and monitoring the sustainability in other areas of biofuel crops expansion across the world.

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Author contributions

C.C.C., C.E.P.C., B.J.F. and C.A.D conceived and designed the project. D.M.S.O., M.R.C., A.L.C.F., A.S.S., J.G.G., N.M.S.D., T.R.D. and A.N.A. conducted the experiments and provided data. D.M.S.O., M.R.C., A.L.C.F. and A.S.S. analyzed data and calculated the indexes. D.M.S.O., M.R.C., A.L.C.F., A.S.S., N.M.S.D., A.N.A., K.P., D.L.K., P.S. and C.E.P.C. wrote the paper. All authors approved this manuscript.

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