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

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Supplementary Material and Methods

S1. Soil C sequestration assessment

For soil fertility and soil organic matter (SOM) analysis, samples were firstly air dried, mixed and passed through a 2 mm sieve. Soil subsamples were ground and sieved through a 100 mesh (0.149 mm) sieve and soil organic carbon (SOC) was determined by the dry combustion method. The equivalent soil mass technique [1], which adjusts for different soil mass differences between land uses, was applied to calculate the SOC stocks down to 1.0 m. The rates of SOC stock change associated with both LUC phases (NV-PA and PA-SG) was calculated considering the difference in SOC stocks between the current and the previous land use, and the time since LUC (Mg C ha^{-1} yr^{-1}). Soil GHG emissions (CO_2, CH_4 and N_2O) were measured in a field-scale experiment in the Region 2, encompassing a plenty of events assumed to influence the GHG dynamics (e.g. feces and urine deposition in pasture areas, and organic amendments and fertilizers application in sugarcane fields) in dry and rainy seasons. Despite the local effects on GHG dynamics, we assumed this assessment as representative of the emissions in pasture and sugarcane areas in the three regions, owing to the fact that the GHG emissions sampling and quantification are quite expensive and laborious processes.

GHG fluxes were calculated by the linear shifts in the gases concentration along the incubation time inside static chambers. Gas samples were collected using 20-ml nylon syringes at the beginning of the incubation and at 10, 20 and 30 min thereafter. The total number of gas samples was 9800. The concentrations of the CO_2 and N_2O were determined using gas chromatography with a ^{63}Ni electron capture detector operated at 81 °C, while CH_4 used a flame ionization detector. GHG were converted into carbon dioxide equivalent (CO_2eq.), according to its global warming potential [2]. The *Soil C sequestration* was determined by subtracting the GHG fluxes (Mg CO_2eq. ha^{-1} yr^{-1}) from

the rates of SOC stock change in CO_2eq. (Mg CO_2eq. ha^{-1} yr^{-1}) [3]. The CO_2 fluxes were not taken into account, since it is already included in the global balance of C by the rates of SOC stock change.

S2. Soil C cycling indicators measurements

Twelve indicators were assessed in order to quantify changes in the *Soil C cycling* by the soil C cycling index (CYC) in soil samples from 0-0.3 m layer. The labile C (LC), the particulate organic C (POC) and the C management index (CMI) were determined as described in Oliveira et al. [4]. SOM molecular characterization for estimations of mineralization index of LC (furfural content/pyrrole content), mineralization index of stable C (pyrrole content/phenol content) and the index of energetic reservoir (sum of aliphatic compounds/sum of aromatic compounds) [5] was performed by pyrolysis–gas chromatograph/ mass spectrometry, as detailed described in Oliveira et al. [6]. The humification index (HLIF) of SOM was obtained by laser-induced fluorescence spectroscopy [7]. Microbial soil C (MBC) and N (MBN) were measured by fumigation/extraction method [8]. Enzymatic activity of β-glucosidase was measured as described by Tabatabai [9]. The isotope composition of N were determined using a mass spectrometer and the results were expressed as $\delta^{15}N$ (‰) using air composition as reference.

S3. Soil biodiversity evaluation

Soil blocks of 0.25 x 0.25 x 0.1 m were collected from 0-0.1, 0.1-0.2, and 0.2-0.3 m soil layers for macrofauna extraction, and invertebrates were hand-sorted according to the standard Tropical Soil Biology and Fertility Institute soil monolith method [10]. Organisms from the litter were added with the 0-0.1 m soil macrofauna. Earthworms were

preserved in 92.8% ethanol and all the others individuals in 70% ethanol for subsequent laboratory identification and counting. The invertebrates were sorted into the taxonomic groups: Aranae, Blattodea, Chilopoda, Coleoptera, Dermaptera, Diplopoda, Diptera, Formicidae, others Hymenoptera, Gastropoda, Hemiptera, Isopoda, Isoptera, Oligochaeta, and Scorpiones. Total abundance of organisms (individuals m^{-2}) and taxonomic richness (number of macrofauna groups) were used to calculate Shannon's diversity index (*H'*) for each sample using the formula:

$$H' = -\sum_{i=1}^{s} p_i \log_2(p_i)$$

where:

p_i = probability of meeting a taxon I on a plot, and s = total number of taxa encountered on the plot. *H'* is at a maximum when all taxa are of equal abundance and is 0 when there is only one taxon. For further details regarding macrofauna sampling and counting, see Franco et al. [11].

S4. Soil nutrient provision and acidity buffering

Nine indicators of soil fertility were determined in soil samples from the 0-0.3 m layer. Soil available phosphorus, exchangeable potassium, calcium and magnesium were measured by ion-exchange resin method, and sulphur-sulphate was determined by turbidimetric method. Active acidity (pH $CaCl_2$) was measured by potentiometric method using a digital pH meter, whereas the potential acidity was quantified by SMP buffer solution method. Both base saturation and potential cation exchange capacity were calculated based on the results of parameters listed above. Methods and analytical procedures used in this study were described by Raij et al. [12].

S5. Soil structuring and water regulating indicators

Undisturbed soil samples (100 cm^{-3}) collected from the 0-0.30 m layer were used to quantify or calculate soil physical-hydraulic indicators, that included: soil texture, bulk density, total porosity, macro- and micro-porosity, water-filled pore space, soil water storage capacity, soil aeration capacity and structural stability index. For a detailed description of the method used for each parameter, see Cherubin et al. [13]. Soil monoliths (0.1 x 0.1 x 0.1 m) were sampled down to 0.3 m to determine soil aggregate stability by wet sieving (30 cycles per minute for 10 min). The percentage of soil aggregates with diameter ≥250 μm (macroaggregates) and the mean weight diameter of aggregates were used for STR index calculation. In addition, in-field measurements were taken to assess soil resistance to penetration, using a digital penetrometer (0.01 in 0.01 m down to 0.3 m), field-saturated hydraulic conductivity using a simplified falling-head technique [14], and the visual evaluation of soil structure, which consists of extraction a soil slice (0.2 x 0.1 x 0.25 m) and evaluate it using a key chart described by Guimarães et al. [15]. A total of 12 soil parameters were included to represent *Soil structuring and water regulating indicators* ES and calculate the STR index.

Supplementary Figures

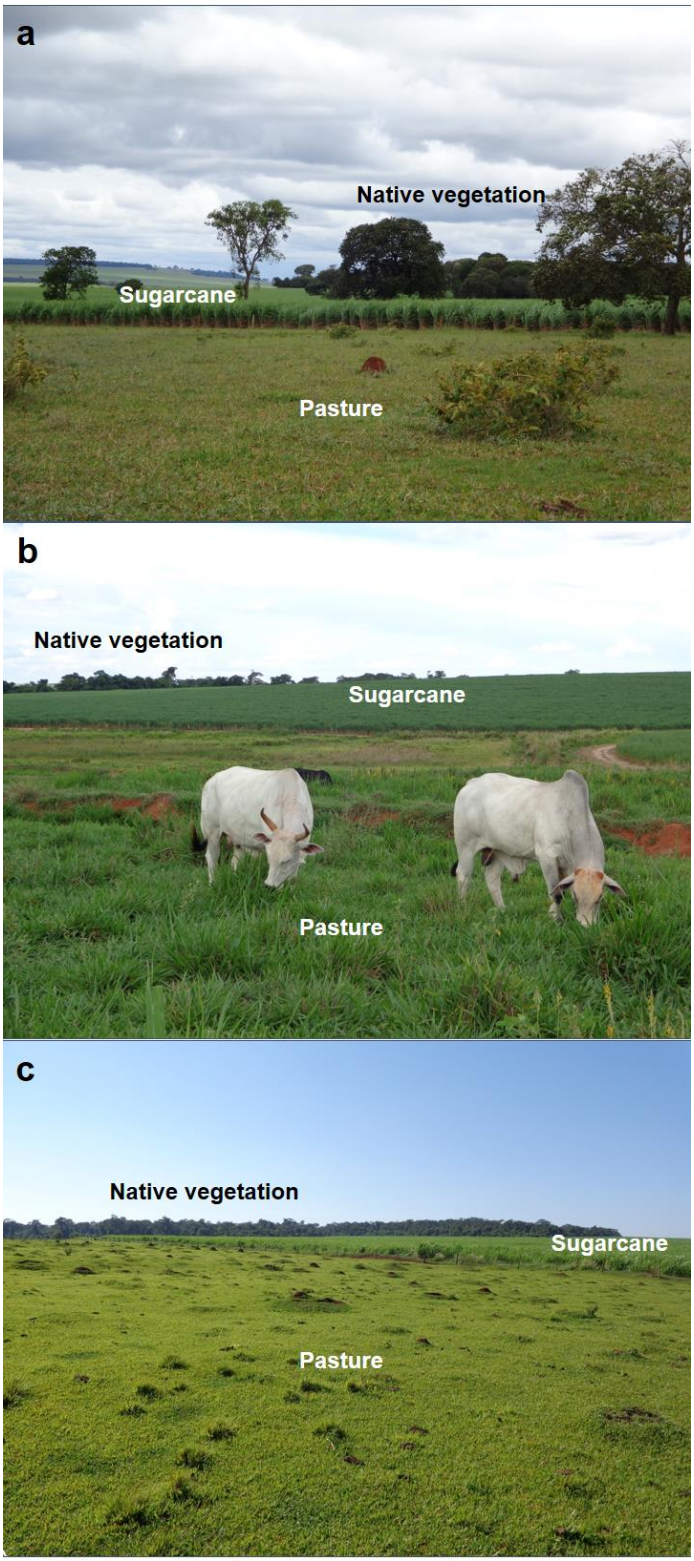

Figure S1. Chronosequences sampled for environmental indicators assessment at sites 1 (**a**), 2 (**b**) and 3 (**c**).

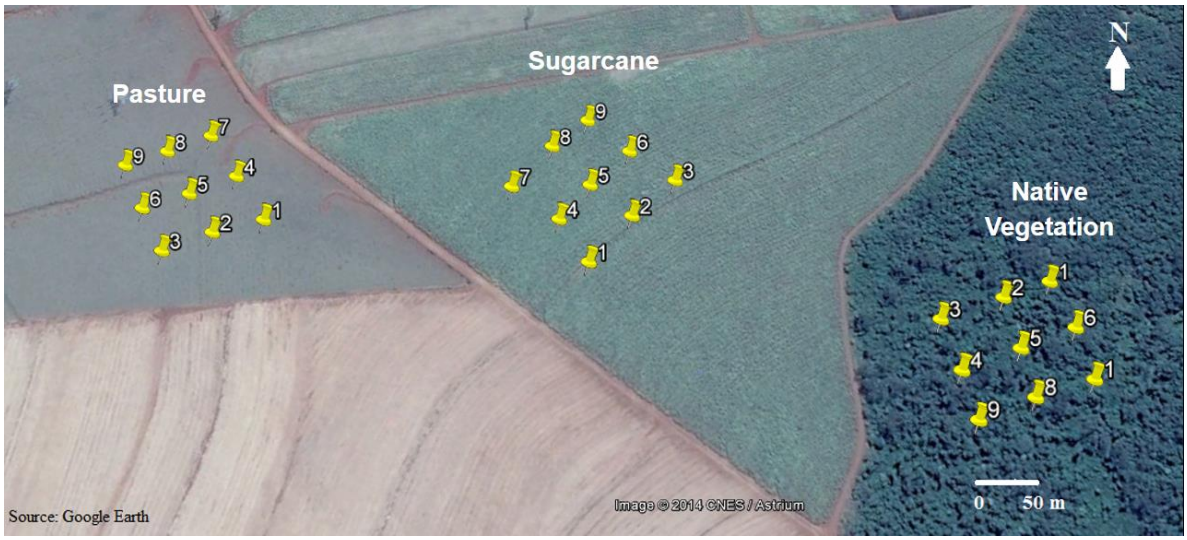

Figure S2. Example of sampling design for environmental indicators assessment (study site from Region 3).

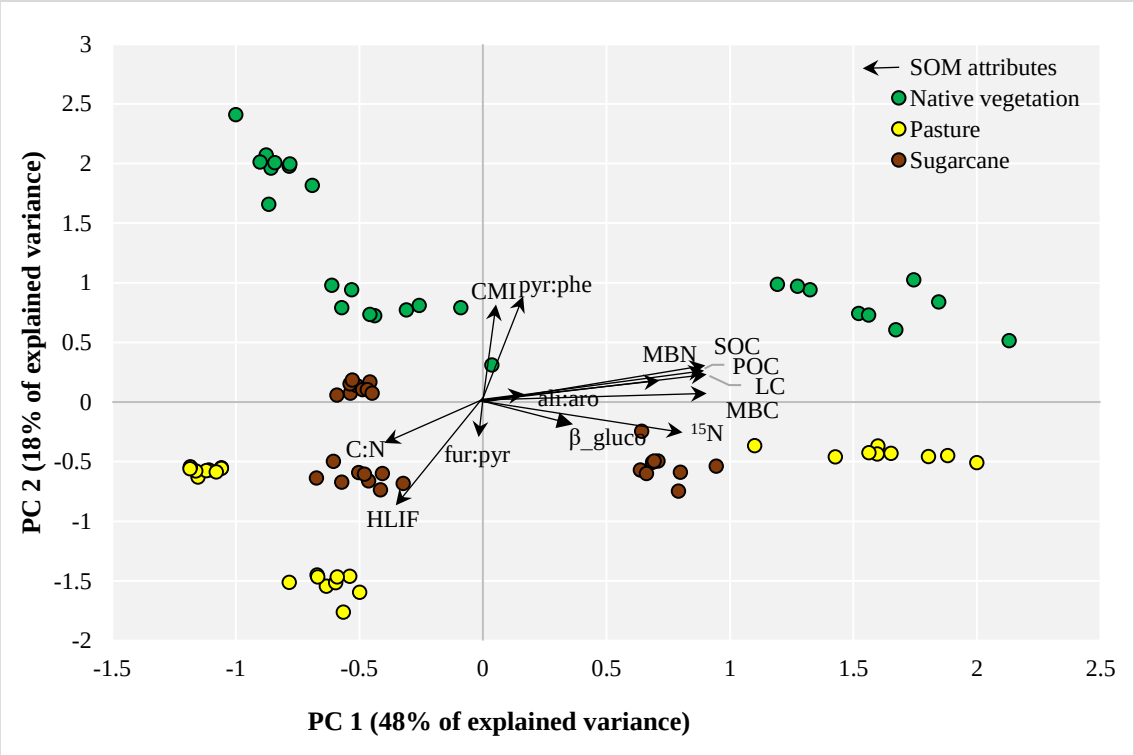

Figure S3. Principal component analysis of soil C cycling indicators in native vegetation, pasture and sugarcane areas in Brazil. For the calculation of the C cycling index, two more principal components (PC3 and PC4) were taken into account (Fig. S7). SOC: soil C content. POC: particulate soil C. LC: labile soil C. MBC: soil microbial biomass C. MBN: soil microbial biomass C. β_Gluco: β_Glucosidade activity. ^{15}N: ^{15}N isotope abundance. fur:pyr: mineralization index of LC. pyr:phe: mineralization index of stable C. ali:aro: index of energetic reservoir. HFIL: Humidification index. C:N: soil C:N ratio. CMI: C management index.

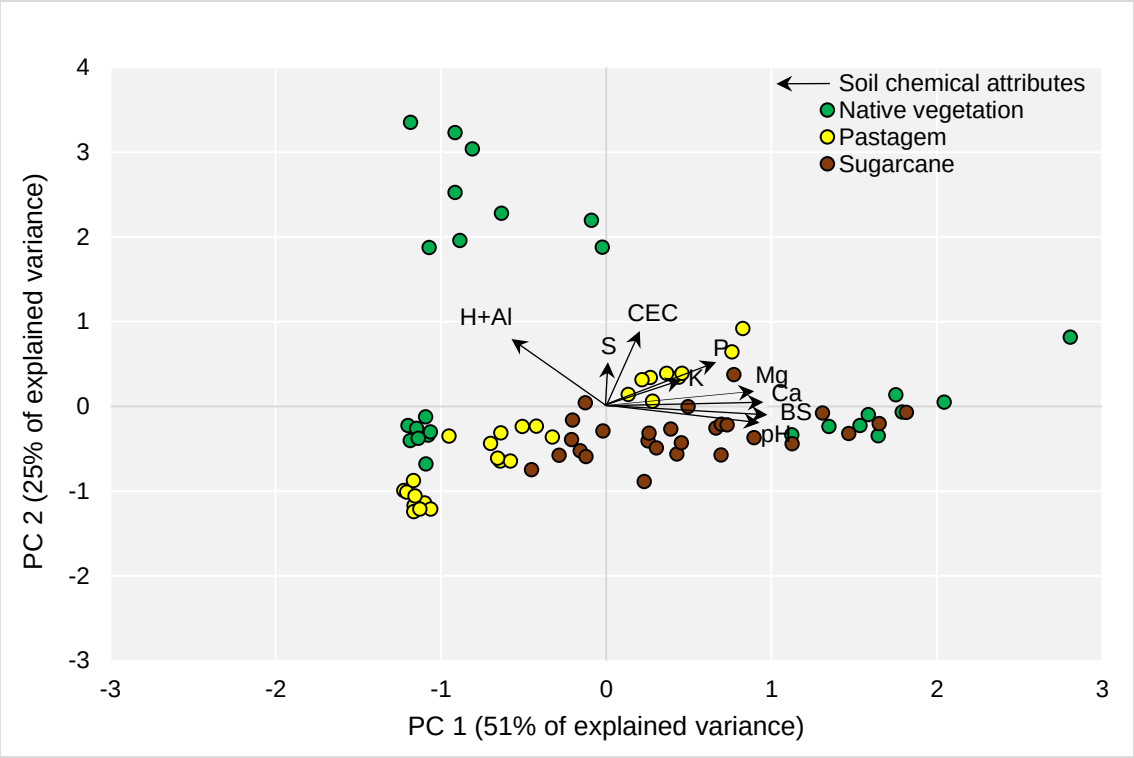

Figure S4. Principal component analysis of soil nutrient provision and acidity buffering indicators in native vegetation, pasture and sugarcane areas in Brazil. P: available phosphorus. S: sulfur. K: potassium. Ca: calcium. Mg: magnesium. CEC_{pH7}: potential cation exchange capacity. pH: potential of hydrogen. BS: base saturation of CEC. H+Al: potential acidity.

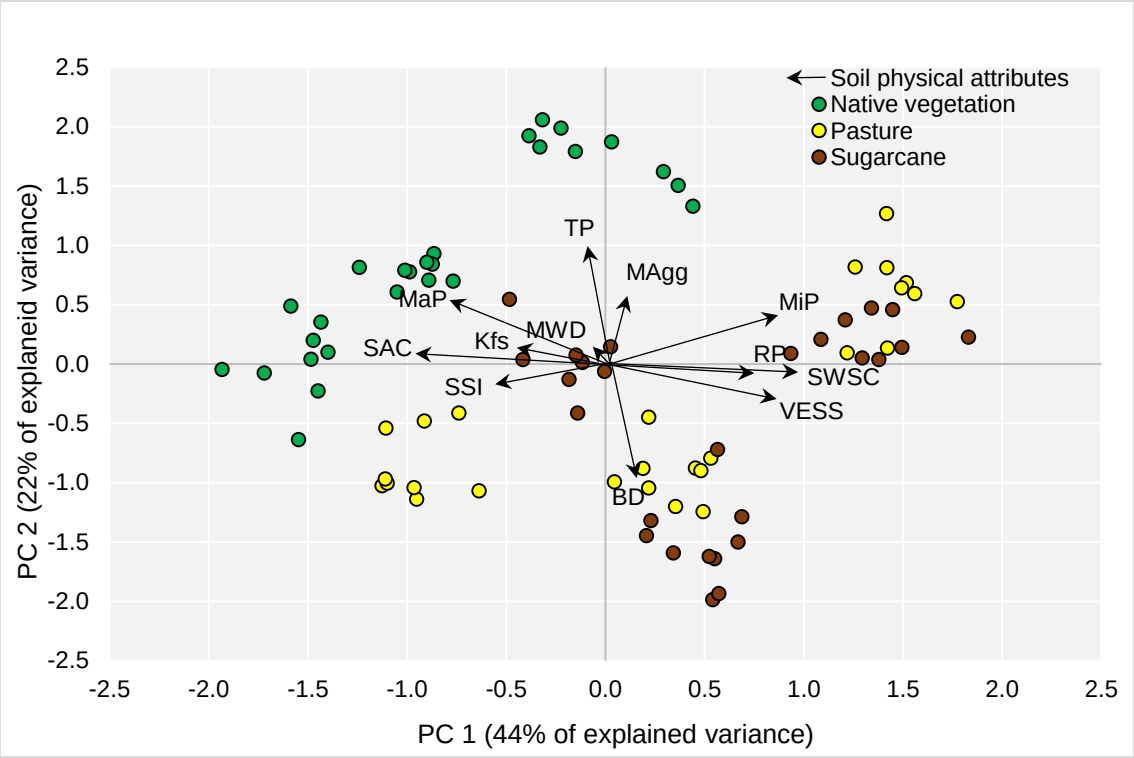

Figure S5. Principal component analysis of soil structuring and water regulating indicators in native vegetation, pasture and sugarcane areas in Brazil. For the calculation of the soil structural quality index, one more principal component (PC3) were taken into account (Fig. S9). BD: bulk density. RP: soil resistance to penetration. MaP: macroporosity. MiP: microporosity. TP: total porosity. SWSC: soil water storage capacity. SAC: Soil aeration capacity. Kfs: Soil water hydraulic conductivity. MAgg: macroaggregation. MWD: Mean weight diameter of soil aggregates. VESS: visual evaluation of soil structure. SSI: soil structure stability index.

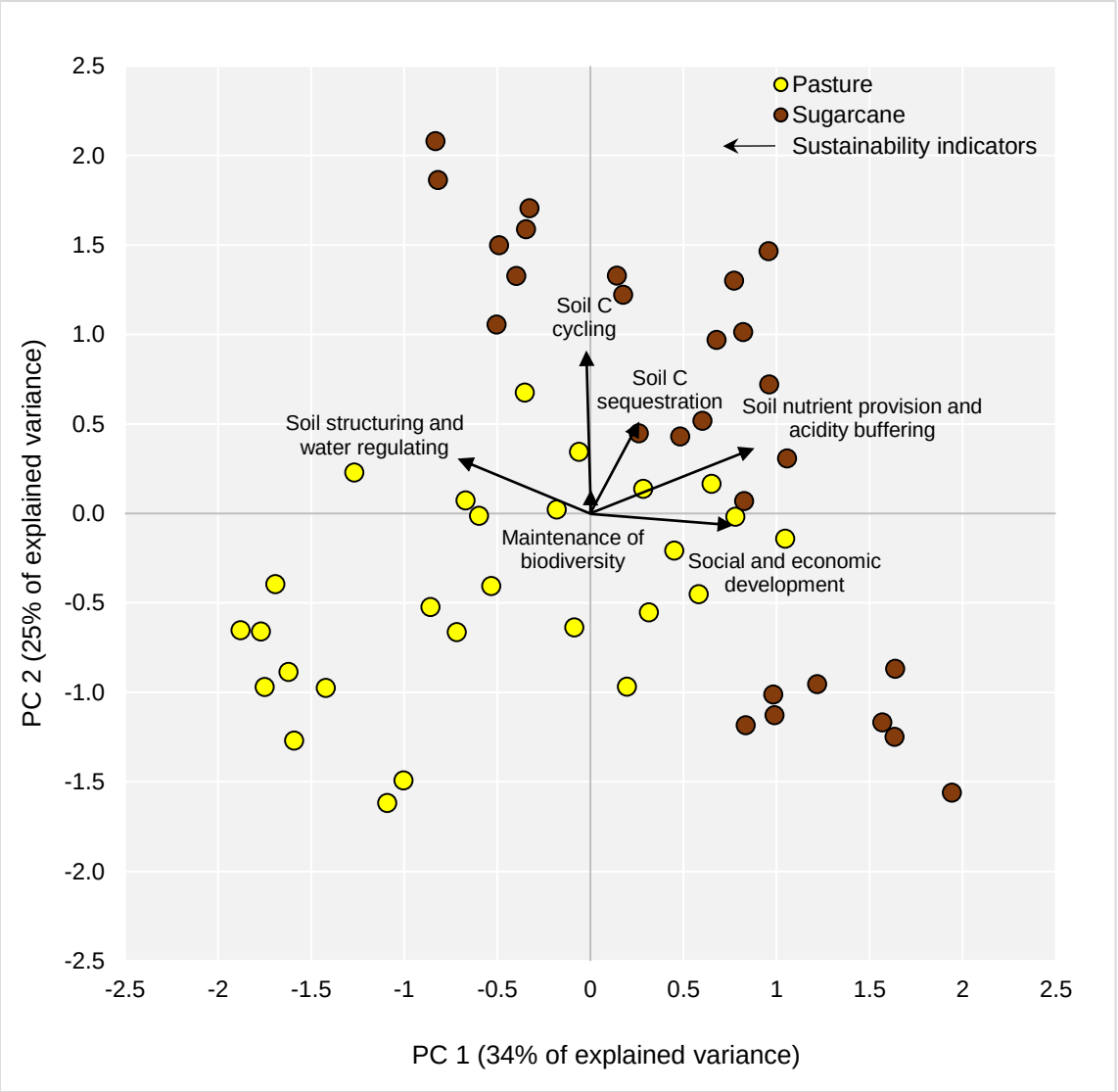

Figure S6. Principal component analysis of ecosystem services quantified by integration of sustainability indicators in pasture and sugarcane areas in Brazil. For the calculation of the sustainability index, one more principal component (PC3) were taken into account (Fig. S10).

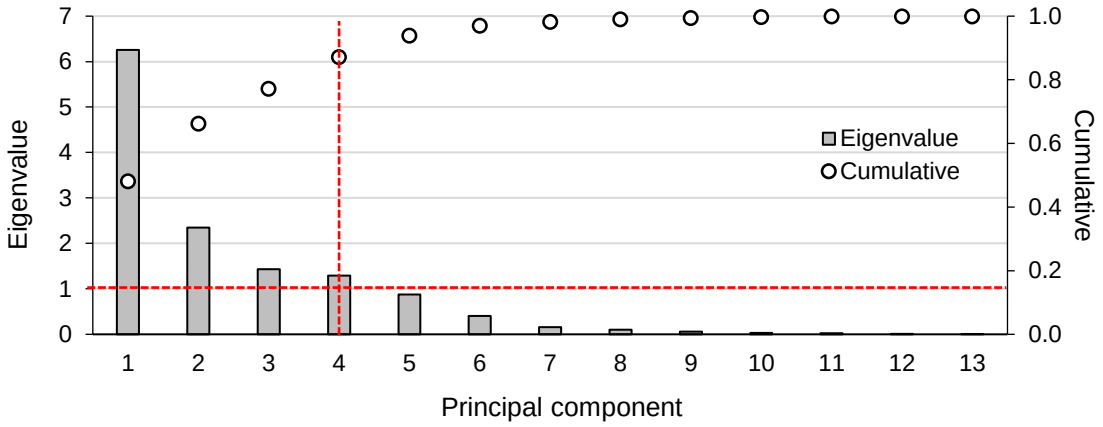

Figure S7. Scree plot of eigenvalues and explained cumulative variance by each principal component of soil C cycling indicators in native vegetation, pasture and sugarcane areas in Brazil. *dashed red lines indicate that four factors were retained by the Kaiser's criterion (eigenvalue ≥ 1).

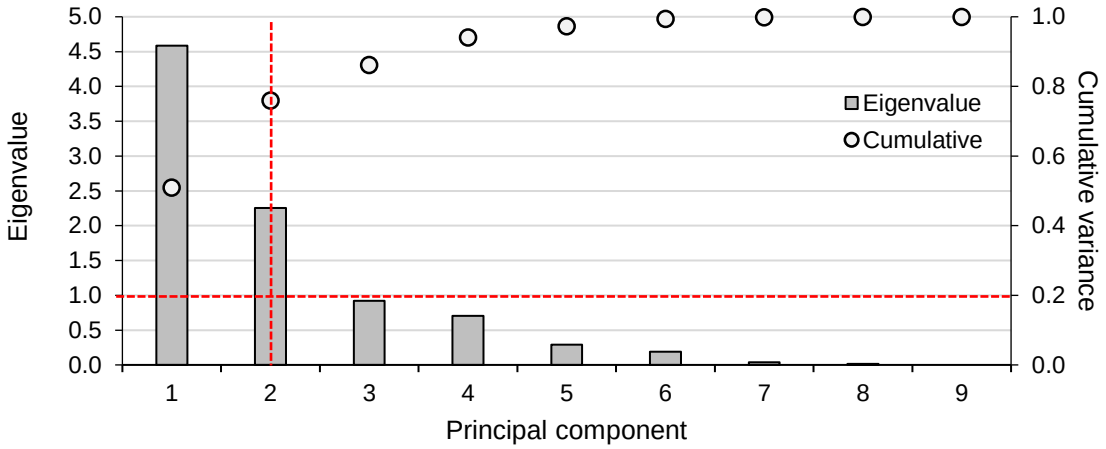

Figure S8. Scree plot of eigenvalues and explained cumulative variance by each principal component of soil nutrient provision and acidity buffering indicators in native vegetation, pasture and sugarcane areas in Brazil. *dashed red lines indicate that four factors were retained by the Kaiser's criterion (eigenvalue ≥ 1).

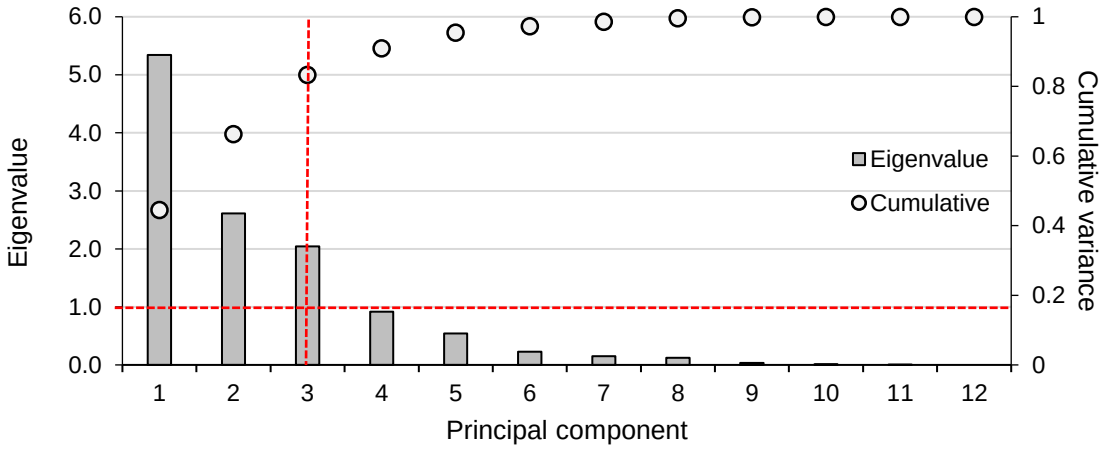

Figure S9. Scree plot of eigenvalues and explained cumulative variance by each principal component of soil structuring and water regulating indicators in native vegetation, pasture and sugarcane areas in Brazil. *dashed red lines indicate that four factors were retained by the Kaiser's criterion (eigenvalue ≥ 1).

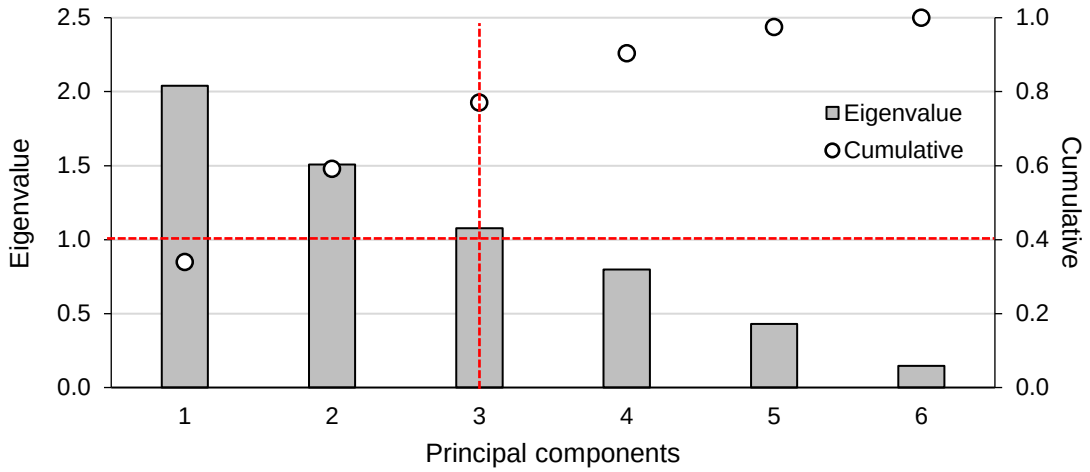

Figure S10. Scree plot of eigenvalues and explained cumulative variance by each principal component of ecosystem services quantified by integration of sustainability indicators in pasture and sugarcane areas in Brazil. *dashed red lines indicate that four factors were retained by the Kaiser's criterion (eigenvalue ≥ 1).

Supplementary Tables

Table S1. Land use history and brief description of study sites sampled for environmental indicators assessment.

Site	Land use	Description
Region 1 17º56′16″S; 51º38′31″W clayey Acrudox soils[16] Awa (Köppen)	**Native vegetation**	Cerradão forest formation, Cerrado biome, characterized by sclerophyllous and xeromorphic species. The vegetation is dense compared to the Cerrado *stricto sensu* (savanna).
	Pasture	Conversion from native vegetation at 1980. Composed by tropical grasses of the genus *Brachiaria* and supports 1.5 AU ha^{-1} full year.
	Sugarcane	Conversion from pasture at 2009. Cultivar RB855453 with mean yield of 81.5 Mg ha^{-1}. Conventional tillage procedures and chemical fertilization. At the sampling time, sugarcane was in the third ratoon cropping of its cycle. Sugarcane is mechanically harvested without burning since its implantation.
Region 2 21º14′48″S; 50º47′04″W loamy Hapludalf soils Aw (Köppen)	**Native vegetation**	The local vegetation is seasonal semi-deciduous forest, Atlantic forest biome, in which a portion of the trees defoliates during the dry season.
	Pasture	Conversion from native vegetation at 1980. Composed by tropical grasses of the genus *Brachiaria* and supports 2 AU ha^{-1} full year. Annually 120 kg ha^{-1} of the fertilizer formulation 20:5:19 are applied.
	Sugarcane	Conversion from pasture at 2010. Cultivar SP791011 with a mean yield of 80 Mg ha^{-1}. Conventional tillage procedures and chemical fertilization + vinasse application. At the sampling time sugarcane was in the fourth ratoon cropping of its cycle. Mechanically harvested without burning since its implantation.
Region 3 23º05′08″ S; 49º37′52″ W clayey Hapludox soils Cwa (Köppen)	**Native vegetation**	The local vegetation is seasonal semi-deciduous forest, Atlantic forest biome, in which a portion of the trees defoliates during the dry season.
	Pasture	Conversion from native vegetation at 1980. Composed by tropical grasses of the genus *Cynodon spp*. and supports 1 AU ha^{-1} full year.
	Sugarcane	Conversion from pasture at 1990. Cultivar CTC6 with a mean yield of 85 Mg ha^{-1}. Conventional tillage procedures and chemical fertilization + vinasse and filtercake application. At the sampling time sugarcane was in the fifth ratoon of its cycle. Pre-harvest burning between 1990 and 2002. Since 2013, 50% of straw has been removed for energy production.

AU: animal units.

Table S2. Soil C sequestration indicators (mean ± standard deviation) in native vegetation, pasture and sugarcane areas in Brazil.

Region	Land use	Soil C stocks	Rates of soil C stock change	N_2O emissions	CH_4 emissions	Total emissions	Soil C sequestration
		Mg C ha^{-1}	Mg C ha^{-1} yr^{-1}	---------- Mg CO_2eq ha^{-1} yr^{-1} ----------			
1	**NV**	94.28 (±8.30)					
	PA	72.25 (±7.10)	-0.64 (±0.36)				-11.9 (±2.21)
	SG	91.02 (±5.41)	3.75 (±1.22)				12.03(±4.19)
2	**NV**	82.73 (±8.72)					
	PA	72.35 (±4.08)	-0.30 (±0.33)	7.89 (±1.92)	1.83 (±0.12)	9.73(±2.03)	-10.70 (±2.31)
	SG	76.54 (±7.70)	1.04 (±2.24)	1.79 (±0.29)	-0.08 (±0.06)	1.71(±0.29)	21.13 (±7.79)
3	**NV**	212.02 (±16.21)					
	PA	141.87 (±18.37)	-2.06 (±0.77)				-17.14 (±2.62)
	SG	167.17 (±12.25)	1.05 (±1.01)				2.13(±3.45)

NV: native vegetation. PA: pasture. SG: sugarcane.

Table S3. Soil C cycling indicators (mean ± standard deviation) in native vegetation, pasture and sugarcane areas in Brazil.

Region	Land use	SOC	POC	LC	MBC	MBN	β_Gluco	^{15}N	fur:pyr	pyr:phe	ali:aro	HFIL	C:N	CMI
		---------- g kg^{-1} ----------			------ mg kg^{-1} -----		mg kg^{-1} h^{-1}	δ ‰	---------- unitless ----------					
1	NV	15.28 (±0.11)	1.83 (±0.31)	2.58 (±0.23)	446.32 (±106.74)	51.45 (±6.10)	55.68 (±6.07)	6.71 (±0.60)	2.99 (±0.44)	0.55 (±0.07)	0.99 (±0.11)	59.59 (±6.58)	13.74 (±1.63)	100.00
	PA	9.26 (±0.38)	1.01 (±0.11)	1.72 (±0.31)	308.54 (±192.03)	21.83 (±1.21)	39.29 (±3.41)	6.64 (±0.32)	3.11 (±0.56)	0.36 (±0.05)	1.30 (±0.22)	100.14 (±16.52)	14.77 (±1.56)	59.63 (±7.85)
	SG	9.70 (±0.87)	1.66 (±0.12)	2.16 (±0.21)	453.21 (±105.93)	19.95 (±2.45)	58.88 (±6.62)	7.66 (±0.87)	4.03 (±0.65)	0.29 (±0.04)	0.84 (±0.13)	76.89 (±9.85)	13.96 (±2.11)	78.73 (±4.56)
2	NV	13.99 (±1.1)	2.14 (±0.17)	2.96 (±0.32)	770.77 (±156.22)	68.46 (±34.18)	123.87 (±19.27)	8.55 (±1.01)	1.38 (±0.23)	0.50 (±0.07)	0.71 (±0.09)	78.67 (±8.21)	11.47 (±1.57)	100.00
	PA	9.44 (±0.79)	1.27 (±0.16)	2.01 (±0.19)	400.93 (±91.73)	27.08 (±2.74)	266.57 (±16.32)	8.11 (±0.56)	3.06 (±0.41)	0.28 (±0.03)	1.19 (±0.16)	99.44 (±14.78)	13.76 (±1.85)	60.14 (±7.85)
	SG	9.67 (±0.1)	1.77 (±0.09)	2.41 (±0.29)	607.37 (±84.34)	17.72 (±3.29)	207.16 (±27.12)	8.33 (±0.89)	2.69 (±0.52)	0.30 (±0.04)	0.62 (±0.08)	87.03 (±5.52)	13.65 (±0.95)	79.55 (±10.52)
3	NV	32.68 (±1.45)	5.44 (±0.63)	7.87 (±0.88)	1901.47 (±681.00)	76.98 (±19.80)	286.93 (±56.64)	9.26 (±1.63)	2.31 (±0.23)	0.52 (±0.07)	1.52 (±0.22)	63.59 (±7.85)	12.07 (±1.14)	100.00
	PA	22.19 (±0.51)	3.50 (±0.29)	5.19 (±0.63)	1691.35 (±563.98)	113.25 (±23.80)	104.89 (±16.78)	9.58 (±1.37)	3.52 (±0.42)	0.39 (±0.04)	0.98 (±0.13)	79.67 (±3.56)	13.07 (±0.78)	60.32 (±5.78)
	SG	19.55 (±0.26)	2.97 (±0.19)	4.66 (±0.35)	828.73 (±29.86)	25.57 (±4.72)	42.71 (±6.01)	9.90 (±0.95)	3.15 (±0.38)	0.29 (±0.04)	0.68 (±0.07)	86.34 (±8.12)	14.22 (±0.98)	78.96 (±6.19)

NV: native vegetation. PA: pasture. SG: sugarcane. SOC: soil C content. POC: particulate soil C. LC: labile soil C. MBC: soil microbial biomass C. MBN: soil microbial biomass C. β_Gluco: β_Glucosidade activity. ^{15}N: ^{15}N isotope abundance. fur:pyr: mineralization index of LC. pyr:phe: mineralization index of stable C. ali:aro: index of energetic reservoir. HFIL: Humidification index. C:N: soil C:N ratio. CMI: C management index.

Table S4. Maintenance of biodiversity indicators (mean ± standard deviation) in native vegetation, pasture and sugarcane areas in Brazil (continued).

Region	Land use	Olig	Cole	Form	Dipl	Chil	Aran	Hemi	Gast	Blat	Derm	Isopo	Dipt	Isopt	Scor	Hyme
		----------Individuals m^{-2} ----------														
1	NV	3.56 (±7.06)	24.89 (±32.11)	3.56 (±7.06)	3.56 (±7.06)	1.78 (±5.33)	0.00	0.00	1.78 (±5.33)	0.00	0.00	37.33 (±112)	0.00	65.78 (±80.18)	0.00	8.89 (±11.62)
	PA	8.89 (±16.22)	307.56 (833.14)	55.11 (±64.55)	0.00	7.11 (±8.43)	1.78 (±5.33)	0.00	0.00	0.00	0.00	0.00	0.00	1093.33 (±927.55)	1.78 (±5.33)	0.00
	SG	3.56 (±7.06)	10.67 (±13.86)	0.00	14.22 (±12.51)	0.00	0.00	0.00	0.00	0.00	1.78 (±5.33)	0.00	0.00	0.00	0.00	3.56 (±7.06)
2	NV	21.33 (±27.71)	81.78 (±91.37)	144 (±209.99)	44.44 (±77.47)	16 (±25.3)	24.89 (±22.78)	1.78 (±5.33)	3.56 (±7.06)	0.00	10.67 (±17.89)	83.56 (±193.13)	12.44 (±22.31)	10.67 (±21.17)	0.00	7.11 (±11.62)
	PA	373.33 (±308.7)	247.11 (±192.52)	78.22 (±112.13)	0.00	8.89 (±18.09)	1.78 (±5.33)	0.00	0.00	0.00	16 (±21.17)	8.89 (±21.33)	0.00	78.22 (±199.27)	0.00	1.78 (±5.33)
	SG	24.89 (±21.33)	21.33 (40.79)	1.78 (±5.33)	92.44 (±113.92)	35.56 (±106.67)	0.00	0.00	0.00	0.00	1.78 (±5.33)	0.00	0.00	0.00	0.00	1.78 (±5.33)
3	NV	8.89 (±11.62)	24.89 (±31.1)	272 (±308.6)	32 (±17.89)	81.78 (±72.64)	30.22 (±35.28)	0.00	5.33 (±11.31)	1.78 (±5.33)	0.00	0.00	5.33 (±16)	151.11 (±217.35)	5.33 (±16)	0.00
	PA	60.44 (±46.49)	5.33 (±8)	14.22 (±16.87)	30.22 (±38.74)	5.33 (±8)	1.78 (±5.33)	0.00	0.00	0.00	0.00	0.00	0.00	924.44 (±1465.39)	0.00	0.00
	SG	10.67 (±21.17)	19.56 (±31.78)	55.11 (±91.25)	7.11 (±14.11)	8.89 (±14.11)	1.78 (±5.33)	0.00	0.00	0.00	0.00	0.00	0.00	1.78 (±5.33)	0.00	0.00

NV: native vegetation. PA: pasture. SG: sugarcane. Olig: Oligochaeta. Cole: Coleoptera. Form: Formicidae. Dipl: Diplopoda. Chil: Chilopoda. Aran: Araneae. Hemi: Hemiptera. Gast: Gastropoda. Blat: Blattodea. Derm: Dermaptera. Isopo: Isopoda. Dipt: Diptera. Isopt: Isoptera. Scor: Scorpione. Hyme : other Hymenoptera.

Table S4. Maintenance of biodiversity indicators (mean ± standard deviation) in native vegetation, pasture and sugarcane areas in Brazil (end).

Region	Land use	Total abundance	Taxonomic richness
		Individuals m^{-2}	Number of groups
1	**NV**	151.11 (±123.19)	2.56 (±1.24)
	PA	1475.56 (±949.23)	3.44 (±1.13)
	SG	33.78 (±16.87)	1.67 (±0.71)
2	**NV**	462.22 (±244.55)	6.44 (±2.07)
	PA	814.22 (±568.98)	4.22 (±1.64)
	SG	179.56 (±154.46)	2.33 (±1)
3	**NV**	618.67 (±472.54)	5.44 (±1.24)
	PA	1041.78 (±1455.77)	3.33 (±1.12)
	SG	104.89 (±123.71)	2.22 (±1.64)

NV: native vegetation. PA: pasture. SG: sugarcane.

Table S5. Soil nutrient provision and acidity buffering indicators (mean ± standard deviation) in native vegetation, pasture and sugarcane areas in Brazil.

Region	Land use	P	S	K	Ca	Mg	CEC_{pH7}	pH	BS	H+Al
		-------- mg kg^{-1} --------		---------- $cmol_c$ dm^{-3} ----------				unitless	%	$cmol_c$ dm^{-3}
1	**NV**	4.53 (±0.39)	2.99 (±1.36)	0.83 (±0.09)	3.01 (±0.73)	2.51 (±0.61)	84.89 (±8.90)	3.81 (±0.09)	7.42 (±1.42)	78.55 (±8.51)
	PA	2.69 (±0.25)	2.68 (±0.95)	0.53 (±0.09)	2.50 (±0.63)	1.29 (±0.32)	51.28 (±4.34)	3.76 (±0.06)	8.45 (±2.14)	47.00 (±4.48)
	SG	6.33 (±1.78)	16.58 (±5.38)	0.55 (±0.15)	19.20 (±5.35)	8.32 (±1.29)	59.12 (±4.55)	4.99 (±0.23)	46.94 (±8.59)	31.05 (±4.76)
2	**NV**	13.24 (±2.80)	7.96 (±1.24)	2.68 (±0.41)	84.43 (±24.48)	16.50 (±3.09)	117.75 (±23.63)	6.35 (±0.52)	87.15 (±4.09)	14.14 (±2.63)
	PA	4.59 (±1.01)	8.68 (±1.55)	3.53 (±1.08)	7.49 (±1.50)	4.02 (±0.74)	58.60 (±3.15)	3.95 (±0.12)	25.85 (±5.43)	43.56 (±4.80)
	SG	13.53 (±3.86)	6.36 (±1.82)	2.88 (±0.95)	31.02 (±6.35)	12.50 (±2.40)	74.26 (±6.36)	5.03 (±0.32)	61.75 (±8.06)	27.87 (±6.14)
3	**NV**	12.55 (±2.85)	15.89 (±3.30)	2.51 (±0.83)	15.09 (±6.63)	8.19 (±2.94)	179.84 (±26.52)	3.71 (±0.17)	15.10 (±7.44)	154.03 (±32.96)
	PA	9.61 (±2.54)	7.70 (±2.77)	4.29 (±0.40)	28.92 (±4.32)	16.10 (±2.60)	103.30 (±4.97)	4.57 (±0.07)	47.53 (±5.19)	53.99 (±5.36)
	SG	8.11 (±2.47)	5.44 (±1.92)	2.41 (±0.83)	47.43 (±17.06)	18.99 (±6.51)	102.28 (±12.57)	5.39 (±0.57)	65.86 (±15.84)	33.46 (±11.99)

NV: native vegetation. PA: pasture. SG: sugarcane. P: available phosphorus. S: sulfur. K: potassium. Ca: calcium. Mg: magnesium. CEC_{pH7}: potential cation exchange capacity. pH: potential of hydrogen. BS: base saturation of CEC. H+Al: potential acidity.

Table S6. Soil structuring and water regulating indicators (mean ± standard deviation) in native vegetation, pasture and sugarcane areas in Brazil.

Region	Land use	BD	RP	MaP	MiP	TP	SWSC	SAC	K_{fs}	MAgg	MWD	VESS	SSI
		Mg m^{-3}	MPa	---------- m^3 m^{-3} ----------			-----unitless -----		cm h^{-1}	%	mm	score	%
1	**NV**	1.26 (±0.03)	1.09 (±0.07)	0.25 (±0.02)	0.29 (±0.01)	0.54 (±0.01)	0.48 (±0.03)	0.52 (±0.03)	171.35 (±61.66)	0.89 (±0.01)	3.32 (±0.29)	1.81 (±0.26)	5.90 (±0.49)
	PA	1.62 (±0.05)	1.99 (±0.16)	0.17 (±0.02)	0.23 (±0.01)	0.40 (±0.02)	0.48 (±0.03)	0.52 (±0.03)	48.21 (±17.61)	0.93 (±0.02)	4.08 (±0.22)	2.00 (±0.19)	7.94 (±1.14)
	SG	1.44 (±0.10)	1.52 (±0.29)	0.16 (±0.05)	0.33 (±0.01)	0.49 (±0.04)	0.64 (±0.09)	0.36 (±0.09)	311.45 (±74.24)	0.79 (±0.04)	1.37 (±0.29)	2.48 (±0.29)	4.29 (±0.42)
2	**NV**	1.30 (±0.05)	0.51 (±0.16)	0.22 (±0.02)	0.29 (±0.01)	0.51 (±0.02)	0.44 (±0.06)	0.56 (±0.06)	141.09 (±42.02)	0.79 (±0.09)	4.15 (±0.14)	1.80 (±0.14)	11.43 (±1.06)
	PA	1.61 (±0.06)	2.69 (±0.22)	0.07 (±0.02)	0.33 (±0.01)	0.40 (±0.02)	0.69 (±0.03)	0.31 (±0.03)	3.15 (±0.77)	0.85 (±0.02)	4.29 (±0.20)	2.91 (±0.20)	7.12 (±0.77)
	SG	1.66 (±0.04)	1.86 (±0.20)	0.05 (±0.02)	0.33 (±0.01)	0.38 (±0.02)	0.74 (±0.05)	0.26 (±0.05)	5.14 (±2.08)	0.68 (±0.08)	3.11 (±0.16)	3.66 (±0.16)	7.10 (±0.37)
3	**NV**	1.00 (±0.07)	2.22 (±0.65)	0.24 (±0.04)	0.39 (±0.01)	0.63 (±0.03)	0.58 (±0.05)	0.42 (±0.05)	39.77 (±10.78)	0.92 (±0.04)	3.84 (±0.34)	2.52 (±0.34)	7.16 (±0.83)
	PA	1.35 (±0.09)	2.53 (±0.43)	0.05 (±0.04)	0.46 (±0.03)	0.50 (±0.03)	0.93 (±0.03)	0.07 (±0.03)	1.75 (±0.81)	0.97 (±0.01)	4.72 (±0.14)	3.16 (±0.14)	6.27 (±0.56)
	SG	1.40 (±0.07)	2.33 (±0.31)	0.07 (±0.03)	0.43 (±0.02)	0.50 (±0.02)	0.86 (±0.06)	0.14 (±0.06)	0.81 (±0.28)	0.85 (±0.05)	2.59 (±0.31)	3.25 (±0.31)	4.11 (±0.68)

NV: native vegetation. PA: pasture. SG: sugarcane. BD: bulk density. RP: soil resistance to penetration. MaP: macroporosity. MiP: microporosity. TP: total porosity. SWSC: soil water storage capacity. SAC: Soil aeration capacity. Kfs: Soil water hydraulic conductivity. MAgg: macroaggregation. MWD: Mean weight diameter of soil aggregates. VESS: visual evaluation of soil structure. SSI: soil structure stability index.

Table S7. Social and economic development indicators in pasture and sugarcane areas in Brazil.

Region	Municipality	Land Use	Iha	Eha	F/M workers	Schooling	IRWH	ELH	GEWH	ASW
			US$ ha^{-1}	jobs ha^{-1}	%	years	---------- unitless ----------			
1	**Aparecida do Rio Doce**	Pasture	0.625	0.001	0.161	4.548	0.248	0.000	0.237	0.011
		Sugarcane	24.974	0.029	0.087	5.333	1.007	0.242	0.092	0.137
	Cachoeira Alta	Pasture	2.831	0.003	0.106	5.132	0.559	0.020	0.130	0.105
		Sugarcane	128.957	0.124	0.158	6.254	1.345	1.037	0.230	0.285
	Caçu	Pasture	3.172	0.003	0.142	5.289	0.582	0.019	0.200	0.130
		Sugarcane	19.195	0.015	0.175	8.167	0.953	0.118	0.264	0.592
	Caiapônia	Pasture	5.476	0.003	0.122	5.359	0.695	0.020	0.160	0.141
		Sugarcane	61.503	0.060	0.043	6.620	1.193	0.495	0.006	0.343
	Itarumã	Pasture	1.847	0.002	0.126	4.893	0.471	0.008	0.168	0.066
		Sugarcane	12.685	0.011	0.083	6.444	0.868	0.086	0.085	0.315
	Jataí	Pasture	5.220	0.003	0.107	5.009	0.685	0.022	0.130	0.085
		Sugarcane	56.967	0.034	0.041	7.750	1.177	0.280	0.002	0.525
	Mineiros	Pasture	7.898	0.007	0.289	6.449	0.770	0.053	0.487	0.316
		Sugarcane	24.732	0.018	0.160	7.584	1.005	0.145	0.236	0.498
	Perolândia	Pasture	3.453	0.004	0.263	4.979	0.600	0.032	0.437	0.080
		Sugarcane	32.165	0.026	0.100	6.177	1.059	0.210	0.118	0.272
	Rio Verde	Pasture	15.470	0.011	0.252	6.201	0.909	0.085	0.415	0.276
		Sugarcane	28.138	0.026	0.087	6.105	1.032	0.216	0.091	0.261
	Serranópolis	Pasture	1.445	0.001	0.187	5.248	0.421	0.007	0.287	0.123
		Sugarcane	11.441	0.008	0.090	7.112	0.846	0.065	0.098	0.423
2	**Adamantina**	Pasture	9.623	0.003	0.184	10.714	0.811	0.017	0.281	1.001
		Sugarcane	57.069	0.049	0.063	7.359	1.177	0.402	0.046	0.462
	Araçatuba	Pasture	50.475	0.014	0.250	8.499	1.152	0.112	0.410	0.645
		Sugarcane	79.923	0.030	0.133	7.695	1.246	0.249	0.183	0.516
	Bento de Abreu	Pasture	2.157	0.001	0.130	4.500	0.503	0.005	0.177	0.003
		Sugarcane	22.563	0.017	0.119	8.296	0.986	0.137	0.154	0.613
	Flórida Paulista	Pasture	3.521	0.005	0.357	6.736	0.604	0.036	0.620	0.362
		Sugarcane	42.736	0.041	0.205	6.432	1.118	0.335	0.322	0.313
	Guararapes	Pasture	18.627	0.014	0.260	6.514	0.947	0.114	0.430	0.327
		Sugarcane	25.700	0.021	0.188	7.578	1.013	0.170	0.291	0.497
	Lavínia	Pasture	1.206	0.002	0.089	6.268	0.383	0.011	0.096	0.287
		Sugarcane	10.319	0.012	0.098	7.196	0.825	0.096	0.113	0.436
	Valparaíso	Pasture	9.531	0.005	0.345	8.673	0.809	0.041	0.598	0.673
		Sugarcane	56.036	0.047	0.171	7.708	1.173	0.390	0.257	0.518
3	**Bernardino de Campos**	Pasture	10.539	0.015	0.180	7.148	0.830	0.120	0.275	0.428
		Sugarcane	11.945	0.016	0.165	5.777	0.855	0.128	0.245	0.208
	Chavantes	Pasture	8.668	0.009	0.254	6.600	0.789	0.069	0.420	0.340
		Sugarcane	90.273	0.101	0.202	7.085	1.272	0.840	0.316	0.418
	Ipaussu	Pasture	15.689	0.016	0.254	6.618	0.911	0.129	0.420	0.343
		Sugarcane	70.457	0.069	0.176	7.519	1.221	0.569	0.267	0.488
	Piraju	Pasture	3.370	0.002	0.551	4.490	0.595	0.015	0.118	0.002
		Sugarcane	8.310	0.015	0.448	6.500	0.781	0.117	1.000	0.324
	Santa Cruz do Rio Pardo	Pasture	12.819	0.011	0.215	7.836	0.870	0.091	0.343	0.539
		Sugarcane	24.664	0.019	0.127	5.768	1.005	0.155	0.171	0.207
	Timburi	Pasture	0.583	0.001	0.159	7.000	0.234	0.002	0.233	0.404
		Sugarcane	39.670	0.044	0.179	6.537	1.102	0.361	0.273	0.330

IHa: average income for workers per hectare. EHa: average employment per hectare. F/M workers: ratio between female and male workers. IRWH: income received per worker index. ELH: employability level per hectare index. GEWH: gender equality index. ASW: average schooling index. Data source: IBGE[17] and Ipeadata[18].

Table S8. Ecosystem services indexes and sustainability index (SI) (mean ± standard deviation) in pasture and sugarcane areas in Brazil.

Region	Land use	CYC	H'	FRT	STR	SEC	SI
	NV	4.73 (±0.10)	0.59 (±0.38)	3.26 (±0.19)	8.81 (±0.30)		
1	**PA**	3.50 (±0.15)	0.39 (±0.26)	3.17 (±0.13)	8.31 (±0.33)	0.15 (±0.08)	1.85 (±0.36)
	SG	4.17 (±0.10)	0.40 (±0.38)	6.52 (±0.31)	8.95 (±0.84)	0.28 (±0.12)	4.54 (±0.51)
	NV	4.77 (±0.12)	1.41 (±0.51)	8.24 (±0.1)	9.13 (±0.23)		
2	**PA**	3.61 (±0.13)	0.98 (±0.39)	5.36 (±0.33)	7.93 (±0.60)	0.25 (±0.12)	2.23 (±0.32)
	SG	4.15 (±0.11)	0.55 (±0.40)	7.47 (±0.31)	6.98 (±0.67)	0.37 (±0.07)	3.46 (±0.82)
	NV	4.69 (±012)	1.24 (±0.24)	5.52 (±0.29)	9.50 (±0.37)		
3	**PA**	3.97 (±0.18)	0.67 (±0.39)	6.98 (±0.49)	5.98 (±0.38)	0.24 (±0.10)	2.33 (±0.20)
	SG	3.28 (±0.16)	0.54 (±0.53)	7.61 (±0.51)	6.22 (±0.64)	0.42 (±0.10)	3.41 (±0.43)

NV: native vegetation. PA: pasture. SG: sugarcane. CYC: C cycling index. H': Shannon's diversity index. FRT: Soil fertility index. STR: Soil structural quality index. SEC: Socioeconomic index.

Table S9. Loadings of soil C cycling indicators with each retained principal component (PC) and their communalities.

Soil C cycling indicators	PC1	PC2	PC3	PC4	Communality
	Loadings				
Soil organic carbon	0.8736	0.3464	-0.0869	0.2411	0.9488
Labile carbon (LC)	0.9171	0.2193	-0.1209	0.1865	0.9386
Particulate organic carbon	0.8973	0.2803	-0.1517	0.1803	0.9392
Mineralization index of LC	-0.0141	-0.2938	0.8991	0.0368	0.8962
Mineralization index of stable C	0.1645	0.8560	-0.2893	0.2233	0.8934
Index of energetic reservoir	0.1513	0.0410	0.0323	0.9629	0.9529
Humification index	-0.3372	-0.8796	-0.0507	0.0122	0.8901
Soil C:N ratio	-0.4007	-0.3814	0.7496	0.0949	0.8769
Soil ^{15}N isotope	0.8121	-0.2675	-0.2124	-0.3793	0.9200
Carbon management index	0.0655	0.8307	-0.3940	-0.1480	0.8716
Microbial biomass C	0.9219	0.0708	-0.0873	0.1105	0.8747
Microbial biomass N	0.7179	0.1801	-0.1235	0.0246	0.5636
β_Glucosidase activity	0.3687	-0.1974	-0.6012	0.4759	0.7627

Table S10. Loadings of soil nutrient provision and acidity buffering indicators with each retained principal component (PC) and their communalities.

Soil nutrient provision and acidity buffering indicators	PC1	PC2	Communality
	Loadings		
Available phosphorus	0.67613	0.56293	0.774
Sulfur content	0.00455	0.55219	0.305
Potassium content	0.44704	0.34312	0.318
Calcium content	0.93744	0.07069	0.884
Magnesium content	0.89683	0.18363	0.838
Potential cation exchange capacity	0.20752	0.9142	0.879
pH $CaCl_2$	0.94711	-0.15638	0.921
Base saturation	0.97746	-0.10119	0.966
Potential acidity	-0.56827	0.79599	0.957

Table S11. Loadings of soil structuring and water regulating indicators with each retained principal component (PC) and their communalities.

Soil structuring and water regulating indicators	PC1	PC2	PC3	Communality
	Loadings			
Bulk density	0.138	-0.956	0.011	0.933
Soil resistance to penetration	0.747	-0.074	0.308	0.659
Macroporosity	-0.797	0.552	-0.098	0.950
Microporosity	0.850	0.424	-0.001	0.902
Total porosity	-0.100	0.968	-0.105	0.959
Soil water storage capacity	0.970	-0.080	0.002	0.947
Soil aeration capacity	-0.970	0.080	-0.002	0.947
Soil water hydraulic conductivity	-0.466	0.138	-0.707	0.736
Macroaggregation	0.090	0.557	0.495	0.563
Mean weight diameter	-0.057	0.066	0.944	0.898
Visual evaluation of soil structure	0.849	-0.297	-0.027	0.809
Soil structural index	-0.591	-0.157	0.565	0.693

Table S12. Loadings of ecosystem service indexes with each retained principal component (PC) and their communalities.

Ecosystem service index	PC1	PC2	PC3	Communality
	Loadings			
Soil C sequestration	0.266	0.527	-0.599	0.708
C cycling index	-0.017	0.910	0.083	0.835
Shannon's diversity index	0.004	0.124	0.766	0.603
Soil fertility index	0.880	0.371	0.011	0.913
Soil structural quality index	-0.702	0.303	-0.483	0.818
Socioeconomic index	0.777	-0.071	-0.375	0.750

Table S13. First pair of canonical variables between ecosystem services (continued). See Tables S3-S8 for acronyms.

CANONICAL VARIABLES	VARIANCE EXPLAINED (%)	P-VALUE
SOIL C SEQUESTRATION AND SOIL C CYCLING		
$U1 = 0.96Cstock - 0.25GHG$ $V1 = -0.79POC - 0.09MBC - 0.02$β_Gluco $- 0{,}37\delta^{15}N + 0.32fur{:}pyr - 0.68$pyr: phe $- 0.17$ali: aro $- 0.55$HFIL $- 0.68$C: N $- 0.08CMI$	88.19	0.058
SOIL C SEQUESTRATION AND MAINTENANCE OF BIODIVERSITY		
$U1 = -0.74Cstock + 0.66GHG$ $V1 = -0.09Olig + 0.07Cole + 0.60Form + 0.71Dipl + 0.55Chil - 0.54Aran + 0.01Derm + 0.03Isop - 0.01Scor - 0.19Hyme - 0.42Tax$	60.42	0.001
SOIL C SEQUESTRATION AND SOIL NUTRIENT PROVISION AND ACIDITY BUFFERING		
$U1 = 0.98Cstock + 0.22GHG$ $V1 = -0.44P + 1.01S - 0.08K + 0.88CEC - 0.98BS - 0.63HAl$	86.49	0.082
SOIL C SEQUESTRATION AND SOIL STRUCTURING AND WATER REGULATING		
$U1 = 0.92Cstock - 0.38GHG$ $V1 = -0.08BD - 0.04RP + 0.36MaP + 0.20MiP + 0.36Kfs + 0.44Magg + 0.33MWD + 0.39VESS - 0.51SSI$	72.52	0.074
SOIL C CYCLING AND MAINTENANCE OF BIODIVERSITY		
$U1 = -0.53POC + 0.04MBC - 0.31$β_Gluco $- 0.41\delta^{15}N - 0.21fur{:}pyr + 0.78$pyr: phe $+ 0.13$ali: aro $- 0.32$HFIL $- 0.62$C: N $+ 0.40CMI$ $V1 = -0.62Olig + 0.05Cole - 0.45Form + 0.31Dipl - 0.05Chil + 0.31Aran - 0.32Derm - 0.08Isop + 0.01Scor - 0.22Hyme + 0.22Ind + 0.03Tax$	51.96	0.062
SOIL C CYCLING AND SOIL NUTRIENT PROVISION AND ACIDITY BUFFERING		
$U1 = -0.34POC - 0.18MBC - 0.29fur{:}pyr + 0.02$pyr: phe $+ 0.10$ali: aro $+ 0.07$HFIL $+ 0.26$C: N $- 0.10CMI$ $V1 = -0.22P - 0.34S - 0.08K + 0.36CEC - 1.17BS - 0.89Al$	78.16	$2.32e^{-11}$
SOIL C CYCLING AND SOIL STRUCTURING AND WATER REGULATING		
$U1 = -0.65POC - 0.25MBC - 0.03$β_Gluco $- 0{,}39\delta^{15}N - 0.24fur{:}pyr + 0.54$pyr: phe $- 0.11$ali: aro $- 0.07$HFIL $+ 0.11$C: N $+ 0.07CMI$ $V1 = 0.07BD - 0.05MaP - 0.56MiP - 0.33Kfs + 0.09Magg + 0.14MWD - 0.08VESS + 0.09SSI$	71.72	$1.02e^{-08}$
SOIL C CYCLING AND SOCIAL AND ECONOMIC DEVELOPMENT		
$U1 = -0.99POC + 0.14MBC + 0.12$β_Gluco $- 0.33\delta^{15}N + 0.42fur{:}pyr + 0.59$pyr: phe $- 0.02$HFIL $+ 0.10$C: N $- 0.79CMI$ $V1 = -0.44IRW - 0.15ELH + 0.50GEWH - 0.53ASW$	58.82	0.086

Table S13. First pair of canonical variables between ecosystem services (end). See Tables S3-S8 for acronyms.

CANONICAL VARIABLES	VARIANCE EXPLAINED (%)	P-VALUE
SOIL NUTRIENT PROVISION AND ACIDITY BUFFERING AND SOIL STRUCTURING AND WATER REGULATING		
$U1 = -0.24P - 0.61S + 0.04K + 0.18CEC - 0.82BS - 0.60HAl$ $V1 = -0.21BD + 0.18RP - 0.14MaP - 0.76MiP - 0.40Kfs + 0.10Magg + 0.04MWD - 0.18VESS - 0.18SSI$	64.78	$1.35e^{-09}$
SOIL NUTRIENT PROVISION AND ACIDITY BUFFERING AND SOCIAL AND ECONOMIC DEVELOPMENT		
$U1 = -0.82IRW + 0.80ELH + 0.74GEWH + 0.67ASW$ $V1 = -0.05P + 0.02S + 0.46K - 1.15CEC + 0.49BS + 0.03HAl$	66.42	0.096
MAINTENANCE OF BIODIVERSITY AND SOCIAL AND ECONOMIC DEVELOPMENT		
$U1 = -0.38Olig + 0.02Cole + 0.62Form + 0.22Dipl + 0.07Chil - 0.88Aran - 0.11Derm + 1.08Isop + 0.33Scor - 0.08Hyme + 0.01Ind - 0.11Tax$ $V1 = 1.32IRW - 0.65ELH + 0.19GEWH - 0.33ASW$	78.36	0.021

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