

Condition of the soil resource and provision of ecosystem services from a Brazilian Oxidic soil under conventional and integrated livestock-based systems

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Abstract

Integrated crop-livestock-forest systems promote soil health and deliver more ecosystem services (ES) compared to conventional livestock systems, although most studies on the subject poorly describe the soil component of these systems. This preliminary study assessed the condition of the soil resource and its role in the provision of ecosystem services from a Brazilian Oxidic soil under conventional and integrated livestock-based systems. Five systems were studied from pasture only to partial and fully integrated crop-livestock-forest systems. All are located on one of the Brazilian Agricultural Research Corporation (Embrapa) Research Farms. Data for the quantification of the soil resource and ES for each of these livestock-based systems were retrieved from previous studies and used to quantify soil health, the provision of food and fibre and climate regulation, as well as report their impacts on receiving environment. Soil organic carbon content, a key component of soil health, was higher in the most integrated system. Soil-based grass yields were lower in integrated systems due to competition for resources from the trees or space taken by crops but had the highest overall provision of food and fibre. Carbon sequestration by trees in the integrated systems offsets enteric methane emissions from beef production, and this ES contributes to mitigating climate change. Future studies should include analysis of all the natural resources and a wider range of soil-based ecosystem services, along with impacts on receiving environments to provide a more complete picture of the performance of integrated livestock-based systems.

Keywords: crop-livestock-forest system, tropical grasslands, sustainability, Ferralsols.

Introduction

Grasslands cover about 40% of the world's land area (Sun et al. 2022) and half of them have been degraded to some extent (Bardgett et al. 2021). In Brazil, the

world's second-largest beef producer and leading beef exporter, grasslands cover 159 million ha and are primarily used for extensive beef production (Brazilian Institute of Geography and Statistics 2019). As more than 60% of Brazilian grasslands are degraded (Souza et al. 2020), grassland recovery and restoration are needed to increase grass yield and improve animal husbandry, while arresting deforestation and environmental impacts (Feltran-Barbieri and Féres 2021). Expanding the adoption of integrated crop-livestock-forest systems is seen as an option for addressing this issue (Salton et al. 2014, Alves et al. 2017b).

Integrating livestock, crop and forestry, either in time or space, aims to benefit the agroecosystem from synergistic effects among its components (Balbino et al. 2011). These integrated systems are known to be more productive and profitable than monocultures (Kichel et al. 2014), as well as have better environmental, economic and social outcomes (Costa et al. 2018). They have also gained attention worldwide as a possible way to better sustain soil as a natural resource, also known as natural capital - the stock of natural resources (Costanza and Daly 1992), as well as strengthen and expand the provision of ecosystem services, the beneficial flows (amounts per unit of time) yielded from stocks (amounts) to fulfil human needs (Costanza et al. 1997).

In tropical regions, studies describing and quantifying the role of soils in the provision of ecosystem services from agricultural and forestry systems are limited (Rodrigues et al. 2021) and only date back to the early 2000s (Portela and Rademacher 2001). In Brazil, the leading country in studying integrated crop-livestock-forest systems (Valani et al. 2020), studies of the influence that livestock-based systems have on the provision of ecosystem services have increased in recent years (Prado et al. 2016), but analysis is still limited to livestock and pasture measures and not the underlying soil and its health, as it influences the provision of ecosystem services.

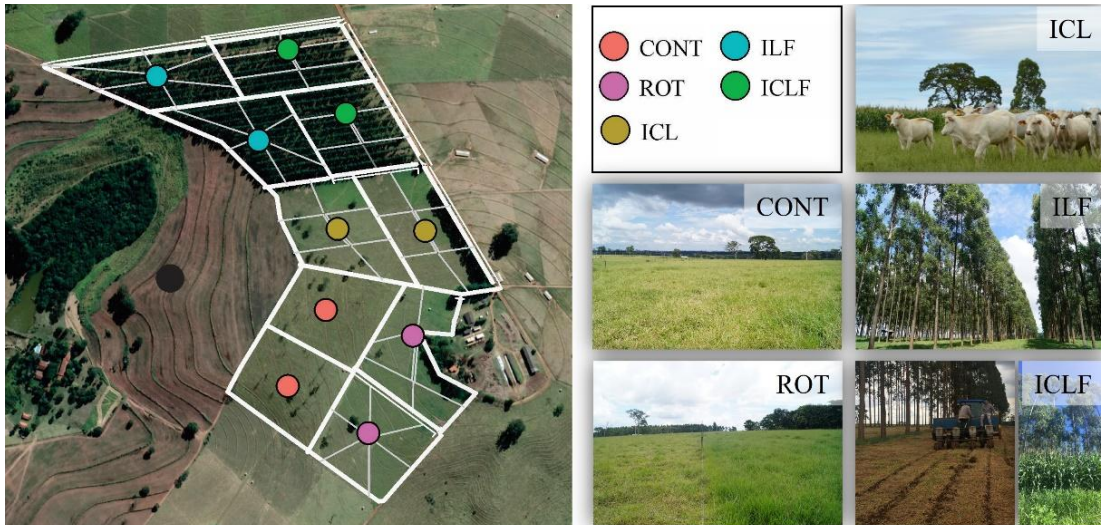


Figure 1 Location of the five livestock-based systems (21°58'23" S 47°51'05" W). CONT: continuous grazing, ROT: rotational grazing, ICL: integrated crop-livestock system, ILF: integrated livestock-forest system, ICLF: integrated crop-livestock-forest system. Adapted from Valani et al. (2022).

A recent comprehensive review of soil ecosystem services in tropical regions (Rodrigues et al. 2021) urged scientists, farmers and governments to acknowledge soils as a finite resource and to make greater use of an ecosystem services assessment approach to monitor and report on the condition of the soil resource. The natural capital-ecosystem services framework of Dominati et al. (2010), which Dominati et al. (2014a) used to quantify and value the ecosystem services from agro-ecosystems, can be used to ensure the contribution that soils make to the provision of services is captured in future analysis of integrated crop-livestock-forest systems in Brazil.

This paper aims to describe and quantify the differences in the condition of the soil as a natural resource from a Brazilian Oxidic soil and impacts of this on the provision of three ecosystem services (provision of food, provision of fibre and climate regulation) and emissions to receiving environments under five livestock-based systems, ranging from non-integrated through to partial and fully integrated crop-livestock-forest system.

Materials and Methods

Study site and livestock-based systems

The five livestock-based systems studied, which varied from pasture only to partial and fully integrated crop-livestock-forest systems are part of a research unit at the Brazilian Agricultural Research Corporation (Embrapa) in São Carlos, São Paulo State, Brazil. The area was part of a coffee farm that went out of business during the Great Depression of 1929 and was bought

by the Brazilian government in 1935. The climate is humid subtropical with dry winter and hot summer (Alvares et al. 2013), with annual rainfall of 1,420 mm and average mean temperature of 21°C. The soil is classified as a sandy clay loam “*Latossolo Vermelho-Amarelo Distrófico*” (Santos et al. 2018), corresponding to an Oxidic soil in the New Zealand Soil classification system (Hewitt 2010) and a Ferralsol in the World Reference Base for Soil Resources – WRB/FAO (IUSS Working Group WRB 2015). The soil’s parent materials are derived from diabase and sandstone (Calderano Filho et al. 1998). The soil is in an advanced weathering stage, with an overall good natural draining capacity, but poor natural fertility.

Five livestock-based systems were studied: continuous grazing (CONT), rotational grazing (ROT), integrated crop-livestock (ICL), integrated livestock-forest system (ILF) and integrated crop-livestock-forest (ICLF). The systems cover a total area of 30ha on a flat topography, entirely managed by rainfed agriculture (Figure 1). The systems are used for growing Canchim (5/8 Charolais and 3/8 Nelore) and Nelore steers from weaning (240 kg live weight) to finishing at 442 kg of live weight (Meo-Filho et al. 2022).

The continuous grazing system (CONT) was established in 1998, based on a monoculture of signal grass (*Urochloa decumbens* ‘Basilisk’). This system receives no inputs but is not degrading due to its controlled low cattle stocking rate, which ranges from 2.8 revised stock units (RSU) per hectare in the dry season to 8.3 RSU ha⁻¹ in the rainy season, or 0.5 to 1.5 animal units (UA, 1,000 lb of live weight) per



Figure 2 Integrated livestock-forest system in March 2019, with trees' spacing of 15 m x 4 m (167 stems ha⁻¹).

hectare. One RSU is defined as an animal with an intake of 6000 MJ ME year⁻¹ or 550 kg DM year⁻¹. As an example, ewes are roughly 1 RSU each, while steers 5.5 RSU each. The stocking rate in CONT represents a typical condition for Brazilian grasslands, as the national average rate is 5.06 RSU ha⁻¹ (Brazilian Institute of Geography and Statistics 2019). The rotational grazing system (ROT) was established in 2007, based on a monoculture of palisade grass (*Urochloa brizantha* 'Piatã'). The system is divided into six paddocks, and the grazing management was kept as six days of grazing and 30 days of rest throughout the year. The stocking rate ranged from 8.3 to 16.5 RSU ha⁻¹, or 1.5 to 3.0 AU ha⁻¹, depending on forage availability in each season.

The integrated crop-livestock system (ICL) was also established in 2007. The grass and stocking rates are managed as ROT. Additionally, maize (*Zea mays* 'DKR390PRO2') was sown using no-tillage and cut for silage production in two of the six paddocks every year. The silage produced went to dairy cows or beef feedlots in the same research farm, but not part of the systems studied in this work. The integrated livestock-forest system (ILF) was established in 2011, with grass and stocking rates also managed as in the ROT system. Eucalyptus (*Eucalyptus urograndis* cl. GG100) was planted with spacing of 15 m x 2 m (333 stems ha⁻¹)

throughout the system. Grazing started 13 months after eucalyptus was planted, when the trees were about 5 m tall and had 6 cm of diameter at breast height. The trees were thinned in 2016 due to overshadowing, resulting in a spacing of 15 m x 4 m (167 stems ha⁻¹), as shown in Figure 2. The trees were thinned again later in 2019, leading to a tree spacing of 30 m x 4 m (83 stems ha⁻¹). Timber was sold in reverse auctions, making its destination unknown. However, considering timber diameters from these two thinning periods, the trees harvested in 2016 may have been used for firewood in local pottery industries and the trees harvested in 2019 may have been used for energy, fencing or wood products, such as furniture. The integrated crop-livestock-forest system (ICLF) was also established in 2011 with grass and stocking rates managements as ROT, maize managed as ICL and trees as ILF.

Lime and fertilisers were regularly applied in ROT, ICL, ILF and ICLF according to regional recommendations (Cantarella et al. 2022). Lime was applied to achieve 60% of base saturation on grasslands and 70% on maize. Superphosphate was applied on grasslands to increase available phosphorus to 12 mg dm⁻³ and potassium chloride to increase exchangeable potassium to 3% of the cation exchange capacity. Nitrogen was applied to the grasslands at rates of 157

kg N ha⁻¹ during 2013/14 and 202 kg N ha⁻¹ in 2014/15 using urea and ammonium sulphate. Maize fertilisations included 500 kg ha⁻¹ of a 08–28–16 formulation (N–P₂O₅–K₂O) during sowing and 500 kg ha⁻¹ of a 20–05–20 formulation via top-dressing 30 days after germination. Trees were not fertilised.

Mineral supplements were offered *ad libitum* to all animals in all systems throughout the year, and proteinaceous supplement during autumn and winter, as described by Meo-Filho et al. (2022). A single feeding trough was shared between all paddocks in ROT, ICL, ILF and ICLF. A more detailed description of these livestock-based systems and management can be found in the work of Valani et al. (2022).

Condition of soil natural resource and soil-based ecosystem services

The condition of soil resource was described in terms of soil physical and chemical properties, as well as soil organic carbon content. The data was retrieved from the work of Valani et al. (2022) for the topsoil of the five livestock-based systems and includes properties commonly used in soil health assessments.

The ecosystem services assessed included the provision of food and fibre, as well as climate regulation (the proxy used was the degree to which enteric methane from the livestock could be offset by carbon sequestered by trees). Data for calculating the provision of food and fibre in these systems was retrieved from several studies, including grass yields (Pezzopane et al. 2020b), maize yields (Pezzopane et al. 2020a) and fibre production from trees harvested in 2016 and 2019 (Pezzopane et al. 2021). In order to quantify the contribution from soil natural capital stocks, the impact of added capital (nutrient inputs) was subtracted from the total yield. It was assumed that one kg of added N ha⁻¹ produced an extra 24.5 kg of grass yield (Bernardi et al. 2011) and extra 15.30 kg of maize yield (Primavesi et al. 2003, 2008). It is important to mention that the livestock-based systems are rainfed, so there is no added built capital in terms of irrigation.

The proxy for the climate regulation service for each of the five systems was the degree to which enteric methane emissions from the livestock could be offset by carbon sequestered by trees. Data for enteric methane emissions was retrieved from the work of Meo-Filho et al. (2022), who assessed emissions periodically over two years. Data on carbon sequestration by trees was retrieved from Pezzopane et al. (2021) and assumed linear increments of carbon capture through time (from 2011 to 2019, the studied timeframe) and comprises carbon from the whole plant, including roots, stem, branches, leaves and inflorescences. Additionally, soil organic carbon (SOC) stocks down to 100 cm was retrieved from Bernardi et al. (2018). The SOC stocks

also provide an insight into the condition of the soil resource, as organic matter is a key measure of soil health (Bongiorno et al. 2019).

Results

Condition of the soil resource

All soils had the same soil textural class, sandy clay loam, with an average clay content of 28% (Table 1). ROT was the livestock-based system with lowest soil pH, P and K contents, while the systems with trees (ILF and ICLF) accounted for the highest soil pH, as well as P, K, Ca and Mg contents (Table 1). Total organic carbon (TOC) contents range from 1.95 to 2.38% with the highest content in the ICLF, the most-integrated system (Table 1). This was also the system with the highest bulk density and resistance to penetration. The lowest stocking rate in CONT led to the lowest resistance to penetration and highest macroporosity (Table 1).

Provision of food and fibre

Soil-based grass yield ranged from 5.3 to 11.5 tonnes DM ha⁻¹ year⁻¹ in the following order: ROT > ICL > ICLF > CONT > ILF (Table 2). Changes in grassland management from continuous to rotational grazing doubled the soil-based grass yield in the grazing-only systems, reflecting differences in nutrient inputs and system's management. Soil-based silage production in ICLF was 7% higher than ICL, while soil-based fibre production in ICLF was 6% higher than ILF (Table 2).

Climate regulation

A proxy for exploring climate regulation across the five livestock-based systems was to sum up the quantities of soil organic carbon stocks to 100 cm with the amount of carbon being sequestered by trees growing on the two integrated systems with forestry as a measure of the total organic stocks in the five livestock-based systems, but also compare the annual carbon sequestration rate of the trees with annual emissions from the livestock from each system. In this analysis enteric methane was used as the proxy for greenhouse gas emissions from livestock as ruminants are the main sources of anthropogenic emissions of methane (Broucek and Broucek 2014). As indicated SOC stocks ranged from 121.0 to 179.9 tonnes of C ha⁻¹ across the five systems (Table 3). The trees in ILF and ICLF are currently storing 22.9 and 23.7 tonnes of C ha⁻¹, respectively (Table 3).

Table 1 Condition of the soil resource from a Brazilian Oxidic soil under different livestock-based systems.

	Sand %	Clay %	Soil pH -	P mg kg ⁻¹	K mmol _c kg ⁻¹	Ca mmol _c kg ⁻¹	Mg mmol _c kg ⁻¹	Al mmol _c kg ⁻¹
CONT	62	25	5.7	5.4	2.6	15.3	12.4	1.8
ROT	64	25	5.4	4.6	1.7	21.2	12.5	1.3
ICL	60	29	5.7	7.3	2.5	24.1	15.7	0.5
ILF	58	31	5.6	7.7	1.9	28.2	23.5	0.0
ICLF	59	30	5.7	7.3	4.6	29.9	21.9	0.4
	Ksat mm h ⁻¹	BD g cm ⁻³	TP %	MA %	MI %	RP MPa	MWD mm	TOC %
CONT	17.5	1.49	44.2	10.3	33.9	2.87	3.20	1.95
ROT	18.8	1.44	45.9	8.3	37.6	3.16	3.04	2.13
ICL	23.0	1.48	44.8	7.7	37.1	3.10	3.21	2.10
ILF	44.6	1.47	44.8	9.5	35.2	3.52	3.36	2.07
ICLF	69.3	1.56	41.5	5.4	36.1	3.47	2.84	2.38

CONT: continuous grazing system, ROT: rotational grazing system, ICL: integrated crop-livestock system, ILF: integrated livestock-forest system, ICLF: integrated crop-livestock-forest system. Soil pH determined in water (1:2.5 ratio). Soil P extracted using Mehlich-I. Ca, Mg and Al extracted using KCl 1 mol L⁻¹. Ksat: saturated soil hydraulic conductivity, BD: soil bulk density, TP: total soil porosity, MA: soil macroporosity, MI: soil microporosity, RP: soil resistance to penetration, MWD: mean weight diameter of soil aggregates, TOC: total organic carbon. Data from Valani et al. (2022).

Table 2 Soil-based provision of food and fibre from a Brazilian Oxidic soil under different livestock-based systems

	Grass tonnes of dry matter ha ⁻¹ year ⁻¹	Silage	Fibre tonnes of dry matter ha ⁻¹ after 8 years
CONT	5.3		
ROT	11.5		
ICL	10.9	9.6	
ILF	5.2		63.4
ICLF	7.1	10.3	67.4

CONT: continuous grazing system, ROT: rotational grazing system, ICL: integrated crop-livestock system, ILF: integrated livestock-forest system, ICLF: integrated crop-livestock-forest system. Yield data was sourced for grass (Pezzopane et al. 2020b), maize (Pezzopane et al. 2020a) and fibre (Pezzopane et al. 2021) and the impact of added capital (nutrient inputs) was subtracted from the total yield to quantify soil-based yields.

Table 3 Carbon stocks in a Brazilian Oxidic soil (0-100 cm) and in trees from different livestock-based systems

	Soil tonnes of C ha ⁻¹	Trees	Total
CONT	121.0		121.0
ROT	173.1		173.1
ICL	136.4		136.4
ILF	179.9	22.9	202.8
ICLF	160.2	23.7	183.9

CONT: continuous grazing system, ROT: rotational grazing system, ICL: integrated crop-livestock system, ILF: integrated livestock-forest system, ICLF: integrated crop-livestock-forest system. Data for soil organic carbon stocks from Bernardi et al. (2018) and fibre sourced from Pezzopane et al. (2021).

Enteric methane emission from animals in the five livestock-based systems ranged from 2.4 to 4.8 tonnes of CO₂-eq ha⁻¹ year⁻¹ (Table 4). The CONT system had the lowest emission per unit of area due to its low stocking rate, whereas the opposite was true for ROT. Carbon sequestration rate by trees was 29.1 tonnes of CO₂-eq ha⁻¹ year⁻¹ in ILF and 30.6 tonnes of CO₂-eq ha⁻¹ year⁻¹ (Table 4).

Table 4 CO₂-equivalent flows from enteric methane emissions (source) and vegetation (sink) in different livestock-based systems on a Brazilian Oxidic soil

	CH ₄ emission	Carbon sequestration by trees tonnes of CO ₂ -eq ha ⁻¹ year ⁻¹
CONT	2.4	
ROT	4.7	
ICL	3.3	
ILF	3.8	29.1
ICLF	3.0	30.6

CONT: continuous grazing system, ROT: rotational grazing system, ICL: integrated crop-livestock system, ILF: integrated livestock-forest system, ICLF: integrated crop-livestock-forest system. Data for enteric methane emissions sourced from Meo-Filho et al. (2022) and carbon sequestration by trees from Pezzopane et al. (2021).

By combining carbon stocks from soil and trees, the ILF and ICLF are sequestering and storing more carbon than the other systems and these can be used to offset carbon emission to the atmosphere from these systems. For example, carbon stocks from trees (Table 3) in ILF could offset enteric methane emissions (Table 4) for 22 years, while the carbon stock from trees in ICLF could offset enteric methane emissions for 29 years. Combined, these two systems could offset the enteric methane emissions for all five systems for 10 years, before the area in trees would need to be expanded or other strategies would need to be used.

Discussion

Condition of the soil resource

Results from fertility status (Table 1) suggest that nutrient inputs in ROT, ICL, ILF and ICLF are in the maintenance range, as their contents were not always higher than the CONT, which receives no fertiliser inputs. An example of this can be noted from K contents, which according to a regional classification (Cantarella et al. 2022), ranged from “average” (1.6 to 3.0 mmol_c kg⁻¹) to “high” (3.1 to 6.0 mmol_c kg⁻¹) in all livestock-based systems.

By comparing the soil physical condition of these five livestock-based systems with an adjoining area of native vegetation, Valani et al. (2022) found a degree of soil compaction in all five systems, which was attributed to cattle trampling. Grazing is known to cause soil compaction, especially under continuous

grazing systems (Byrnes et al. 2018). In the systems with silage production (ICL and ICLF), wheel traffic during maize sowing and harvesting, as well as the lack of crop residues left over the soil after harvesting, are also factors that would place additional pressure on the soils physical condition.

The ILF integrated system is better able to sustain and critically buffer the provision of services under future climates, which are predicted to be more variable. This is intuitive, based on the organic matter content, along with the physical and chemical condition of the soil, which are all key soil properties regulating the provision of all services (Dominati et al. 2014a). Soil organic carbon stocks down to 100 cm soil depth in the five livestock-based systems (Table 3), also point to the integrated systems storing and retaining more soil organic carbon. Bieluczyk et al. (2020) found that the integrated systems improved the quantity and quality of soil organic matter compared to soil under continuous grazing. Similarly, Tadini et al. (2021) pointed out that soil organic matter in these integrated systems is more chemically stable, with a longer half-life in the soil than soil organic matter in conventional systems, therefore mitigating climate change by avoiding soil carbon decomposition and CO₂ release.

The role of soil in ecosystem services provision

Fibre production in the ILF and ICLF systems lowered the soil-based grass yield by shading and competition for nutrient and water. While reducing grass yields, other studies have reported improved grass quality in terms of crude protein content and digestibility (Pezzopane et al. 2020b) and reduced hours of thermal stress on animals over the summer months (Pezzopane et al. 2019, Barreto et al. 2022). During winter, the dry season in the region, the shading is more pronounced (Bosi et al. 2020a) as is the competition for soil water (Bosi et al. 2020b). Both these impacts translate into an overall lower soil-based grass yield.

Silage production also slightly affected the soil-based grass yield, as maize was grown in two out of six paddocks every year, decreasing the overall grass yield per hectare for the system (Table 2). Despite its lower grass production, ICLF combined the provision of grass, silage and fibre in a single livestock-based system. This is especially important for Brazil as such integrated systems were recommend as a win-win strategy to avoid deforestation, whilst boosting livestock husbandry, sustaining natural resources and delivering more ecosystem services (Feltran-Barbieri and Féres 2021).

In relation to climate regulation, the trees are the primary offset, followed by carbon sequestered in the soil, for the enteric methane emissions from these livestock-based systems. Both these mitigation options

for enteric methane emissions contribute to Brazilian policies such as the low-carbon agriculture plan (2020-2030), also known as the ABC+ plan (Brazilian Ministry of Agriculture Livestock and Food Supply 2021) and the potential marketing benefits associated with carbon-neutral Brazilian beef (Alves et al. 2017a). In the long-term, however, both these mitigation options have a finite capacity to offset enteric methane emissions in these livestock systems. Into the future, options for either direct reductions in enteric methane (e.g., feed additive, animal genetics) and or carbon capture (e.g., biochar) will need to be incorporated into these systems.

Limitations of this study

A more comprehensive study of the ecosystem services in these five livestock-based systems would need to include an analysis of all natural resources and ecosystems services. Data on the soils need to extend to biological activity, while regulating services need to be extended beyond climate regulation to include for example flood mitigation, filtering of nutrients, to name two. A full carbon footprint assessment would include changes in soil organic carbon over time, carbon storage by vegetation, emissions from fertilisers and from machinery use. Guidelines from the Intergovernmental Panel on Climate Change (IPCC 2019) and/or life cycle assessments could be used to address some of these gaps to promote a better understanding of the delivery of ecosystem services in these livestock-based systems, as well as impacts on receiving environments, as part of a more comprehensive assessment. Future studies about the provision of ecosystem services in tropical grasslands should also include cultural services, such as the sense of place and aesthetics.

Different arrangements of integrated systems should also be studied, including the contribution of other species of trees and in different densities and across landscapes beyond flat and easy rolling landscapes and proximity to waterways. The findings in this study can also apply to New Zealand integrated systems, where, for example, poplar and willow are used in low-density tree-pasture systems for slope stability and soil conservation (Dominati et al. 2014b), although other species or arrangements, with different functional traits, may deliver different ecosystem services (Case et al. 2020, England et al. 2020, Dominati et al. 2021).

Conclusions

Complex agricultural systems, such as integrated crop-livestock-forest systems, have multiple trade-offs that need to be considered in farm management plans. Gathering reliable data to compare conventional and integrated livestock-based systems is challenging, especially as it requires a multidisciplinary approach in

the quantification of ecosystem services.

This preliminary study was the first attempt to study soil-based ecosystem services in conventional and integrated livestock-based systems on a Brazilian Oxidic soil. In addition to an assessment of the condition of the soil as a natural resource, three services, provision of food, provision of fibre and climate regulation were assessed. On the face of it, the most integrated system accounted for the highest stock condition and provision of ecosystem services. In systems with trees, the rate of carbon sequestration by trees may offset enteric methane emissions during beef production, which contributes to a more environment-friendly agriculture that includes mitigating climate change.

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