PROJETO
RURAL SUSTENTÁVEL
Fase I

Promovendo o desenvolvimento e a agricultura de baixa emissão de carbono na Amazônia e na Mata Atlântica

LOW CARBON AGRICULTURE PROJECT – Phase I
Promoting development and low carbon emission agriculture in the Amazon and Atlantic Forest

RELATÓRIO DE PRODUÇÃO CIENTÍFICA

Embrapa

RESUMO DO PROJETO

Os sistemas de produção agropecuária são altamente dependentes dos fatores climáticos, por isso a vulnerabilidade dos sistemas de produção aos riscos das mudanças climáticas consiste no problema principal do projeto. Projeto tem como característica principal o fomento as tecnologias de intensificação sustentável em propriedades rurais dos biomas Amazônia e Mata Atlântica com o objetivo de promover, fomentar, implementar e monitorar as tecnologias previstas no Plano de Agricultura de Baixo Carbono (Plano ABC) para mitigar a emissão de gases de efeito estufa (GEE) e aprimorar o desenvolvimento rural, que garantam o desenvolvimento sustentável da terra e das florestas por agricultores. Trata-se de um conjunto de pesquisas, prospecções e descrições relacionadas ao potencial de mitigação de gases de efeito estufa por tecnologias de produção agropecuária visando o desenvolvimento rural.

O OBJETIVO DO PROJETO

"Promover, fomentar, implementar e monitorar as tecnologias previstas no Plano de Agricultura de Baixo Carbono (Plano ABC) para mitigar a emissão de gases de efeito estufa e aprimorar o desenvolvimento rural sustentável da terra e das florestas por agricultores nos biomas Amazônia e Mata Atlântica."

02

OBJETIVOS ESPECÍFICOS

01

Mitigar as emissões de gases de efeito estufa (GEE) de sistemas integrados de produção (ILP; ILPF e IPF), de florestas plantadas e pastagens sob recuperação a partir do monitoramento dos estoques de carbono do solo e emissão de GEE.

02

Desenvolver fatores de emissão dos gases CO2, N2O e CH4 para as diferentes tecnologias do Plano ABC que incluindo o componente vegetal e animal.

03

Indicar os riscos ao desmatamento das propriedades rurais em função das políticas públicas governamentais, da localização relativa às áreas protegidas, malha viária e valor agrícola ou de extração.

04

Determinar o Índice de Desmatamento Evitado (IDE) para as propriedades avaliadas em cada Bioma

A PESQUISA

O TRABALHO DE PESQUISA FOI DIRECIONADO PARA QUATRO VERTENTES: MITIGAÇÃO DAS EMISSÕES DE EFEITO ESTUFA (GEE), MELHORIA DAS BASES DE DADOS DE DESMATAMENTO EVITADO, PERCEPÇÃO DO PRODUTOR RURAL QUANTO À ADOÇÃO E BENEFÍCIOS ECONÔMICOS DAS TECNOLOGIAS E PRÁTICAS AGRÍCOLAS DE BAIXO CARBONO E AVALIAÇÃO DAS PROPOSTAS TÉCNICAS SUBMETIDAS POR INSTITUIÇÕES DE ASSISTÊNCIA TÉCNICA E EXTENSÃO RURAL.

> *O conhecimento e os dados gerados vão contribuir para o trabalho da Plataforma Multi-institucional de Monitoramento das Reduções de Emissões de Gases de Efeito Estufa na Agropecuária, a Plataforma ABC*
>
> Renato Rodrigues

O projeto avaliou também como as tecnologias de baixo carbono contribuem para evitar o desmatamento. Contou com a participação direta da Embrapa Solos, da Embrapa Agrobiologia, da Embrapa Agrossilvipastoril, da Embrapa Soja e da Embrapa Gado de Leite.

A pesquisa obteve diversos resultados interessantes. Como por exemplo os resultados obtidos pelos pesquisadores em três anos de experimentos de 100 hectares no Mato Grosso com adoção do sistema Integração Lavoura-Pecuária-Floresta (ILPF): a emissão de gases de efeito estufa diminuiu 20% quando comparado a um sistema de lavoura tradicional; 10% quando comparado a um sistema de pastagem tradicional; e em até 50% quando comparado a sistemas tradicionais que envolvam floresta plantada mais lavoura e mais pastagem.

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Centro Nacional de Pesquisa de Solos

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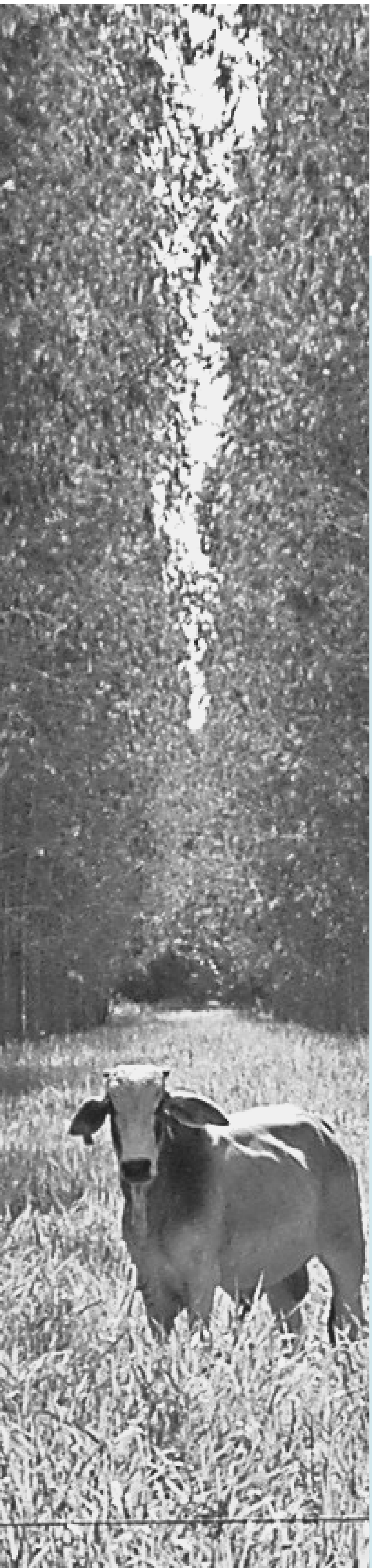
04



RESULTADOS E PUBLICAÇÕES

Listas de documentos anexos:

Anexo 1. Accounting of Greenhouse Gas Emissions Mitigation and Avoided Deforestation in the Low Carbon Agriculture Project.

Anexo 2. Action plan 4: Evaluation of the producer's perception regarding the adoption of low carbon technologies

Anexo 3. Artigos e documentos publicados

ANEXO 1

ACCOUNTING OF GREENHOUSE GAS EMISSIONS MITIGATION AND AVOIDED DEFORESTATION IN THE LOW CARBON AGRICULTURE PROJECT.

Accounting of Greenhouse Gas Emissions Mitigation and Avoided Deforestation in the Low Carbon Agriculture Project.

Authors: Renato de Aragão Ribeiro Rodrigues, Ademir Fontana, Alexandre Nascimento, Bruno José Rodrigues Alves, Cimélio Bayer, Cornélio Alberto Zolin, Eduardo da Silva Matos, Fabiano de Carvalho Balieiro, Laurimar Vendrúsculo, Gracie Verde Selva, and Luiz Tadeu Assad.

Implementação: Apoio Técnico: Realização:

1 Introduction

The agricultural sector is both a major contributor to global climate change, and one of the sectors most affected by the adverse effects associated with it (Tilman et al. 2001; Foley et al. 2005; Foley et al., 2011; Godfray and Garnett, 2014; Kuyper and Struik, 2014; IPCC, 2014; Rockström et al., 2017; Smith and Gregory, 2013).

Agriculture is the strongest sector of the Brazilian economy, contributing 25% of GDP. On the other hand, it exerts pressure for land use and emits large amounts of greenhouse gases (around 32% of Brazil's total emissions, according to the Climate Observatory, 2018).

Increasing agricultural production is necessary to meet the challenge of the UN Sustainable Development Goals of eradicating hunger and securing food for a growing world population, expected to reach 9–10 billion by 2050. This population may require an increase in global food production of between 60 and 110% (Foley et al. 2005; Foley, et al., 2011; IAASTD, 2008; Tilman et al. 2011; Pardey et al. 2014) at a time when the consequences of climate change are affecting agricultural production around the world.

As described by Smith and Gregory (2013) and Foley et al. (2011), whilst ensuring food security, there is an urgent need to reduce the impact of food production on the climate (Smith et al., 2008), and to improve the resilience of food production to future environmental changes (Smith et al., 2013a; Smith, 2015; Foley et al., 2011).

Brazil has developed several agricultural technologies that enable the sector to rise to this challenge. Over the last 20 years in Brazil, crop yields have increased several times without an equivalent increase in agricultural land. The no tillage system has emerged as a technique to minimise erosion and to improve soil fertility, a key factor in the ability of soil to store carbon (Lal, 2003). Nonetheless, a great challenge still facing Brazil is how to deal with the low efficiency of livestock systems.

Between 20 and 30% of Brazil's territory is dedicated to pasture and almost half of this area suffers some level of degradation. Whilst the national mean cattle stocking rate has increased since 1990, it remains under 1 AU ha^{-1} with a cattle extraction rate under 20%, incurring high GHG emission intensity meat production (Cardoso et al., 2016). Approximately 70 million hectares of pasture need to be recovered to increase the productivity and sustainability of livestock systems.

Despite the critical role the agricultural sector plays in current and future emissions, action to reduce emissions related to agriculture has often lagged behind other sectors (Richards, et al., 2018). Brazil is amongst the countries that have undertaken strong measures to reduce emissions from the agricultural sector and land use change (Rodrigues et al. 2019). During COP15, Brazil submitted a voluntary commitment to reduce GHG emissions. Brazil's position in the negotiation motivated other developing countries to also submit voluntary commitments. The Brazilian Nationally Appropriate Mitigation Actions (NAMAs), foresaw a reduction of 36.1% to 38.9% of projected emissions for 2020, thus avoiding the emission of about 1 billion tons of CO2 equivalent (tCO_2e) (Brazil, 2010). This was the largest effort to reduce emissions on the planet (Rodrigues et al., 2019).

The proposals presented in Copenhagen were internalised through Law 12,187/2009, which instituted the National Policy on Climate Change. As part of this national strategy to reduce greenhouse gas emissions, Brazil launched its Low Carbon Agriculture Plan (Plano Nacional de Agricultura de Baixa Emissão de Carbono, ABC Plan) in 2010. At the core of the ABC Plan is a line of low-interest rural credit (the ABC Program) that is specifically intended to fund the implementation of low carbon agricultural practices, or 'technologies', that are likely to contribute to climate change mitigation either by reducing greenhouse gas emissions and/or by sequestering carbon (Newton et al., 2016).

The nationwide ABC Plan has a period of validity from 2010 to 2020. Revisions and updates were planned at regular intervals, not exceeding two years, in order to adapt the plan to the demands of society, the arrival of new technologies and to incorporate new actions and goals if necessary. The Plan is composed of seven programs, six of them related to mitigation technologies, and one program related to climate adaptation (Brazil, 2012):

- Program 1: Recovery of Degraded Pastures;
- Program 2: Integration of Crop-Livestock-Forest (iCLF) and Agroforestry Systems (AFS);
- Program 3: No-tillage System;
- Program 4: Nitrogen Biological Fixation (NBF);
- Program 5: Planted Forests;
- Program 6: Animal Waste Treatment;
- Program 7: Adapting to Climate Change.

The GHG emission reduction potential of the Plan is estimated at approximately 150 million Mg CO_2e, not counting the potential for CO_2 sequestration by forest plantations. Each program proposes the adoption of a series of actions, such as strengthening technical assistance, training and information, technology transfer strategies (TT), field days, lectures, seminars, workshops, the implementation of Technological Reference Units, publicity campaigns and public calls for the contracting of technical assistance and rural extension services (Brasil, 2012).

To reach the objectives set forth in the ABC Plan, in the period between 2011 and 2020, it was estimated that resources of the order of R$ 197 billion would be needed, financed through budgetary sources or agricultural credit lines. According to data on agricultural credit from the MAPA (2019), from 2010 to January 2017, over 34 thousand contracts were executed, with a disbursement of more than R$ 17 billion, totaling an average of around R$ 504 thousand per contract. The total available for the credit line in this period was R$27.67 billion. The number of capacity building events related to the low carbon emission technologies outlined in the Plan carried out between 2011 to 2017 was 40,484, occurring in the 940 Demonstration Units that the Plan has implemented throughout the country.

Changing the mindset and practises of rural producers in relation to their role as providers of environmental goods and services, and creating consumers that are conscious of their choices, is not an easy task, and should not be constructed on an individual basis. Whilst the ABC Plan promotes the dissemination and viability of sustainable technologies by farmers throughout the country, their implementation by farmers faces many barriers. There is lack of knowledge about available technologies, lack of access to technical assistance, as well as lack of incentives and financial support for farmers to invest the time and energy needed to implement new practices. The most affected by these barriers are small and medium producers. At the same time, they suffer most from poverty and are the most vulnerable to the effects of climate change on the productive unit (UNDP et al., 2017). Social inequality and vulnerability are other factors of great concern in Brazil, especially important in the rural areas.

Resolving these issues is absolutely essential to ensure the sustainability of Brazilian agriculture. Strategic partnerships and alliances can play a key role in achieving a large scale shift towards these changes by combining resources and knowledge to address issues that a single organisation would be unable to, especially in an increasingly complex and dynamic world.

To this end the Brazilian government established a partnership, through the Ministry of Agriculture, Livestock and Supply (MAPA) and the Brazilian Agricultural Research Corporation (Embrapa), with the British Government, the Inter-American Development Bank (IDB), the private sector (ICLF Network Association) and the third sector (Brazilian Institute of Development and Sustainability - IABS) to promote low carbon agriculture and sustainable development in rural areas.

The Low Carbon Agriculture Project, fruit of this partnership, aimed to decrease greenhouse gas emissions, reduce poverty and promote sustainable rural development by restoring deforested and degraded land, and by facilitating and promoting the uptake of low carbon agricultural technologies (Projeto Rural Sustentável, 2016).

This research explores the results of the application of some of the ABC Plan technologies in terms of emissions mitigation and avoided deforestation, focusing on technologies aimed at improving practises in the production of livestock and sequestering carbon in soil and tree biomass:

1. RPD – Recovery of Degraded Pasture
2. ICLF - Crop-Livestock-Forest Integration (variations considered - iLF and iCLF).
3. PF - Planted Forest (variations considered - Eucalyptus PF and Agroforestry systems (AFS) + RDP-F + Other PF).

The **Recovery of Degraded Pastures** is closely linked to the science of ecological restoration. A degraded pasture is one that, through disturbance, has lost its natural means of regeneration, presenting low potential to maintain production at sustainable levels. In degraded ecosystems, anthropic action is necessary to recover original condition. The recovery is an intentional activity that initiates or accelerates the restoration of an ecosystem in relation to its health, integrity and sustainability, including a minimum level of biodiversity and variability in the structure and functioning of ecological, economic and social processes.

Crop-Livestock-Forest Integration is a scientifically based sustainable production technology. It integrates different production systems within the same area, so that one culture provides benefits to the other. Implementing iCLF improves land and input use, soil conservation, diversification of production with less greenhouse gas emissions, increased employment and income in the countryside, and reduced pressure on native vegetation. The two variations considered here are:

- Crop-Livestock-Forest Integration: contains in the same area components of agriculture (annual or semi-perennial crops), pasture (grasses associated with animal husbandry) and forestry (arboreal, semi-perennial or perennial, fruit or woody species). It is also known as agrosilvipastoril system.
- Livestock-Forest Integration: a consortium of pastoral components (grasses associated with animal husbandry) and forestry (arboreal, semi-perennial or perennial, fruit or woody species). It is also known as silvipastoril system.

Planted Forests are important not only from a production standpoint, but also from an environmental conservation standpoint. Commercial forests reduce pressure on natural forests, provide raw materials for different industrial and non-industrial uses, and contribute to the provision of various environmental and social services. The three variations considered were: Eucalyptus and agroforestry systems, recovery of degraded pasture with forest and other planted forests.

2 Methodology

2.1 Geographic scope

Municipalities involved in the Low Carbon Agriculture Project and assessed in this study are located in the Amazon and Atlantic Forest biomes, as shown in Tables 1 and 2.

Table 1. Characteristics of municipalities assessed by the Low Carbon Agriculture Project in Mato Grosso and Pará states in the Amazon Biome.

State	Municipality	Fiscal module (ha)	Total area (ha)	Protected areas (ha)	Protected areas %
Mato Grosso	Alta Floresta	100	900,529.09	-	-
Mato Grosso	Brasnorte	100	1,598,528.56	394,545.32	24.68
Mato Grosso	Cotriguaçu	100	948,319.27	300,472.98	31.68
Mato Grosso	Juara	100	2,275,078.88	272,240.36	11.97
Mato Grosso	Juína	100	2,619,643.32	1,666,894.08	63.63
Mato Grosso	Marcelândia	90	1,226,761.85	147,751.12	12.04
Mato Grosso	Nova Canaã do Norte	100	596,061.53	3,126.50	0.52
Mato Grosso	Querência	80	1,781,608.80	749,278.76	42.06
Mato Grosso	Sinop	90	395,462.19	-	-
Mato Grosso	Terra Nova do Norte	90	256,646.43	-	-
Pará	Dom Eliseu	55	525,342.82	-	-
Pará	Ipixuna do Pará	55	521,624.78	5,303.53	1.02
Pará	Marabá	70	1,505,368.99	366,940.60	24.38
Pará	Medicilândia	70	832,690.56	30,929.53	3.71
Pará	Paragominas	55	1,932,076.63	96,925.66	5.02
Pará	Rondon do Pará	55	823,429.62	464.13	0.06
Pará	Santana do Araguaia	75	1,160,130.56	-	-
Pará	Tailândia	50	443,173.87	-	-
Pará	Tomé-Açu	50	514,088.72	1,196.67	0.23
Pará	Tucumã	70	251,479.51	0.012	0.0000047

Table 2. Characteristics of municipalities assessed by the Low Carbon Agriculture Project in Bahia, Mina Gerais, Paranà and Rio Grande do Sul states in the Atlantic Forest Biome.

State	Municipality	Fiscal module (ha)	Total area (ha)	Protected areas (ha)	Protected areas %
Bahia	Camamu	20	87,100	22,646	26
Bahia	Igrapiúna	20	51,229	11,270.38	22
Bahia	Ituberá	20	41,730	15,440.1	37
Bahia	Maraú	20	83,469	19,197.87	23
Bahia	Nilo Peçanha	20	38,624	15,449.6	40
Bahia	Piraí do Norte	20	22,826	1,826.08	8

Bahia	Presidente Tancredo Neves	20	41,577	4,157.7	10
Bahia	Taperoá	20	40,918	9,411.14	23
Bahia	Valença	20	119,118	28,588.32	24
Minas Gerais	Teófilo Otoni	40	324,473	51,915.68	16
Minas Gerais	Setubinha	40	53,531	24,624.26	46
Minas Gerais	Poté	40	63,266	13,918.52	22
Minas Gerais	Padre Paraíso	65	54,307	16,835.17	31
Minas Gerais	Novo Oriente de Minas	40	75,430	14,331.7	19
Minas Gerais	Malacacheta	40	71,991	13,678.29	19
Minas Gerais	Itambacuri	30	141,851	9,929.57	7
Minas Gerais	Franciscópolis	40	71,462	3,573.1	5
Minas Gerais	Capelinha	40	96,660	22,231.8	23
Minas Gerais	Araçuaí	65	223,439	29,047.07	13
Paraná	Renascença	20	42,572	2,980.04	7
Paraná	Realeza	20	35,292	2,117.52	6
Paraná	Primeiro de Maio	16	41,477	0,829.54	2
Paraná	Paranavaí	20	120,291	9,623.28	8
Paraná	Nova Londrina	24	26,829	1,073.16	4
Paraná	Itapejara D'oeste	20	25,663	0,513.26	2
Paraná	Francisco Beltrão	18	73,333	2,933.32	4
Paraná	Dois Vizinhos	20	41,756	1,252.68	3
Paraná	Bandeirantes	18	44,537	1,336.11	3
Paraná	Verê	20	31,239	0,624.78	2
Rio Grande do Sul	Vacaria	25	212,428	40,361.32	19
Rio Grande do Sul	Passo fundo	16	77,946	4,676.76	6
Rio Grande do Sul	Machadinho	20	33,221	1,661.05	5
Rio Grande do Sul	Lagoa vermelha	25	126,089	10,087.12	8
Rio Grande do Sul	Frederico Westphalen	20	26,413	1,584.78	6
Rio Grande do Sul	Erechim	20	43,014	1,720.56	4
Rio Grande do Sul	Ciríaco	20	27,358	1,094.32	4
Rio Grande do Sul	Boa vista das Missões	16	19,434	1,749.06	9
Rio Grande do Sul	Barros Cassal	18	64,788	10,154.36	19
Rio Grande do Sul	Agudo	20	53,444	6,478.8	10

Observation Unit Assessments

A number of properties were selected to be observation units, monitored for productive performance. They were located in the Amazon and Atlantic Forest biomes, according to the Project proposal. In addition, monitoring units were also implemented in these biomes, specifically in the states of Mato Grosso, Pará, Bahia, Rio de Janeiro, Paraná and Rio Grande do Sul, from which parameters and emission factors would be obtained in order to quantify GHG emissions. (Figure 1).

Throughout the project, the costs and risks to the owner with the deployment of the technologies were known, as well as the productive performance. It was also assessed how the techniques could contribute to preventing deforestation and how much mitigation would be achieved in the project area.

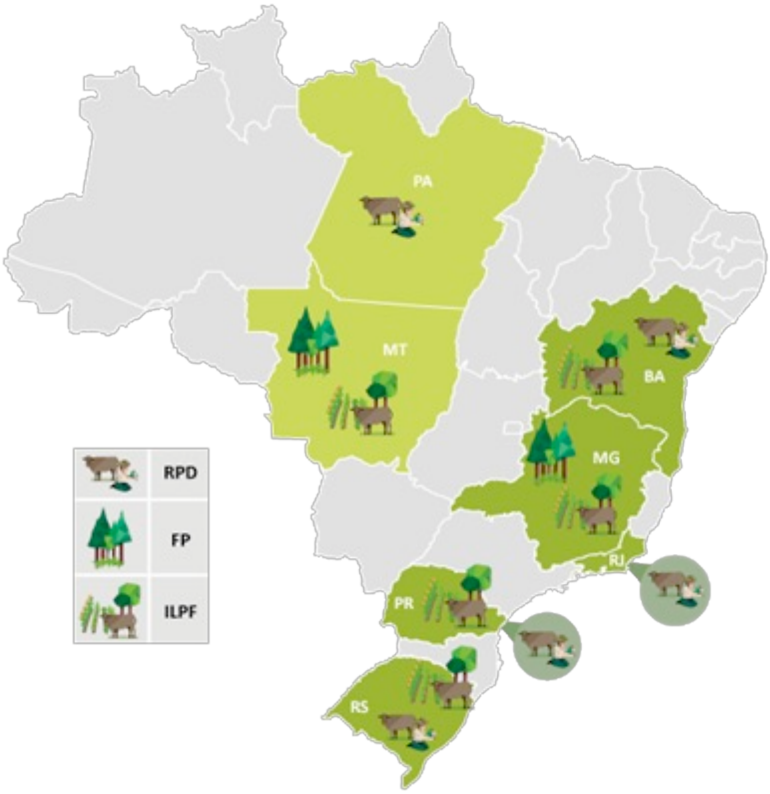


Figure 1. States by region and technologies applied within the scope of the Project

2.2 Methodology for measuring avoided deforestation

The methodology used to quantify the results of the Hectares Indicator related to avoided deforestation in the Amazon and Atlantic forest biomes was performed according to Tipper and Bournazel (2018). Official national cartographic bases were utilised from the following institutions: Brazilian Institute of Geography and Statistics (IBGE), Ministry of Environment (MMA), National Department of Transport Infrastructure (DNIT), National Department of Mineral Production (DNPM, 2015) and Agency National Mining Agency (ANM) of the Ministry of Mines and Energy. The only international base was Global Forest Change (GFC). The following steps are part of the Hectares Indicator methodology:

Step 1 – Scope: This assessment was implemented in twenty (20) municipalities of Mato Grosso and Pará States, Brazil, located in the Amazon Biome and forty (40) municipalities located in Paraná, Rio Grande do Sul, Minas Gerais e Bahia States, within the Atlantic forest biome.

Step 2 - Reference Level: The initial forest cover for the base years of 2016 and 2017 was assessed by the difference between Forest Cover 2000 and Forest Loss products, from 2001 to 2015, and 2001 to 2016, extracted from the global database Forest Change (GFC), produced by Hansen et al (2013), versions 1.4 and 1.5. The classification was based on the FAO criteria (2012) with canopy cover greater than 10%.

The estimate of forest loss in the absence of interventions was determined using the ACEU method (Accessible, Cultivable, Extractable, Unprotected/Protected), also known as the Hectares Indicator, according to Tipper and Bournazel (2018), where the combination of different factors attribute different risk of deforestation to native vegetation (Figure 2):

$$\text{Risk} = (RA + RC + RE) - RU/P \quad \text{(Equation 1)}$$

Where:

Risk = Deforestation risk;

RA = Risk of accessibility (proximity to roads, rivers, etc);

RC = Risk for agricultural suitability or cultivability (slope, soil, climate);

RE = Risk due to the presence of extractable resources (forest or mineral);

RU/P = Risk for unprotected/protected areas due to the absence of mechanisms to protect forest cover. In this case, protected areas have a reduced risk, hence the subtraction. (Official regulation of protected areas).

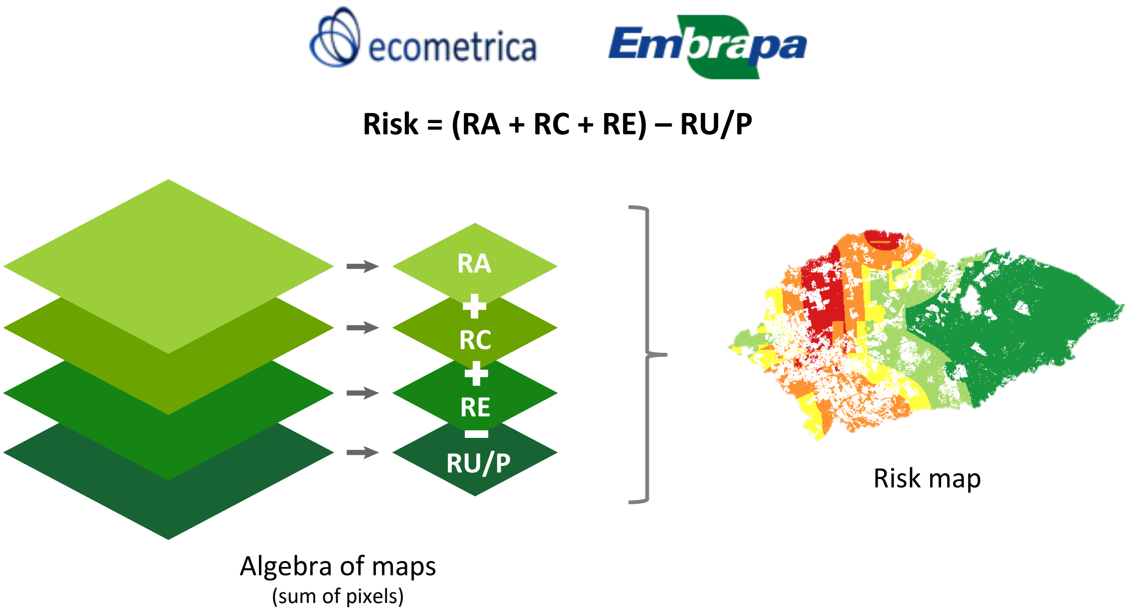


Figure 2. Risk map methodology

Step 3 - Measurement of forest loss: The forest loss measured for the base year 2016 and 2017 produced by Hansen et al. (2013).

Step 4 - Analysis of results: Web mapping applications called *ICF Rural Sustentável, Amazônia Hectares Indicator* and *ICF Mata Atlântica 1* were created for the area analysed throughout the biomes. Those are instances of a mapping platform provided by Ecometrica. In these instances, there are data layers related to municipal boundaries, as well as the forest cover for the years 2016 and 2017. Additionally, forest loss maps were generated and, finally, the risk of deforestation maps, produced using the ACEU (Hectares Indicator) approach were uploaded.

The risk map, as a product of the sum of the factors that contribute or facilitate deforestation and forest degradation, has resulted in approximately twelve (12) qualitative classes. To simplify this amount of risk classes, Tipper and Morel (2018) adopted the Likert scale (Likert, 1932). This type of scale is popularly used in forms that evaluate phenomena with complex causal relationships, including the process of perceiving deforestation (Ali and Khan, 2018; Mareseni and Cadman, 2015). The innovation adopted by the Hectares Indicator methodology, regarding the Likert scale, which uses from 5 to 7 classes, was to quantify the classes through quantiles, in this case 5-quantiles (quintiles) generating the risk map. Each quintile contains 20% of the data.

Expected forest loss, which means forest area that can be lost if no intervention is undertaken, can be obtained by multiplying the area of the deforestation risk class (Very high, high, medium, low and very low) by its probability factor. Then result is then divided by 20 in order to create an estimate for the next 20 years (Equation 2).

Expected Loss (ha) = (Total Class Area *% Expected Loss (in decimals)) / 20 (Equation 2)

It is agreed that very low risk areas have an expected loss of 10% of their total area in 20 years, 30% for low risk areas, 50% for medium risk areas, 70% for high risk areas and 90% for very high risk areas. Finally, avoided deforestation was obtained by the difference between the estimated (expected) value through the ACEU risk and the measured loss extracted from the Forest Loss base.

In addition, bar charts were generated to compare risk classes at the municipal level between 2016 and 2017 reference years. Data distribution of avoided forest losses among states was also performed to investigate trends in this same period.

2.3 Methodology for quantification of greenhouse gas emissions

[1] Available at: Atlantic forest: https://icf-mataatlantica.embrapa.ourecosystem.com/interface/ and Amazon biom: https://icf-ruralsustentavel.embrapa.ourecosystem.com/

Emissions and drain estimates for each technology

For emissions from technologies that include animal production (RDP, iCLF and iLF), in each region average zootechnical indices were considered (stocking rate, entry weight, daily weight gain, slaughter weight, slaughter age). Emissions were estimated considering beef cattle termination, since it was the animal category that predominated.

For the pasture in monoculture in the different regions, the same forage species (*Brachiaria brizantha*) was assumed. In the integrated systems (iCLF and iLF), the same proportion of trees (Eucalyptus), pasture (Brachiaria) and tillage (maize) were assumed.

As for the carbon removal rate (considered as a drain), it was similar in the animal systems and the planted forests for both regions.

Based on information from the monitoring areas and complemented by scientific literature, the GHG emissions from the observation areas (with the implemented technologies) were quantified.

For the quantification in areas with Pasture Recovery, we considered soil and fossil emissions from the use of inputs, and those derived from animals and vegetation, based on the methodology used for inventories based on activity data and emission factors. For the ICLF system, emissions from inputs for grain production and tree planting were also considered; however, emissions were accounted for in proportion to the area occupied by each type of use:

Recovery of Degraded Pasture – emissions and removals

a. **Occupation:**
   Pasture – 100% of area
b. **Emissions (kg CO2e ha-1 year 1 and converted to kg CO_2e kg-1 carcass):**
   CH_4 (faeces and enteric).
   N_2O (excreta e fertiliser)
   CO_2- fossil (liming)
c. **Situations:**
   Degraded
   Recovered
d. **Drain (Mg CO_2e ha^{-1} year^{-1}):**
   Grassland pasture (Brachiaria).
e. **Final results:** Land area required to produce 1 Mg eqCarcass

iCLF - emissions and removals

a. **Occupation:**

Crop - 25% of area

Forest (Eucalyptus) - 25% of area

Pasture - 75% da area

b. Emissions (kg CO2e ha^{-1} year^{-1} and converted to kg CO_2e kg^{-1} carcass):

CH_4 (faeces and enteric).

N_2O (excreta e fertiliser)

CO_2- fossil (liming)

c. Situations:

Degraded

Recovered

d. Drain (Mg CO_2e ha^{-1} year^{-1})

Grassland pasture (Brachiaria).

Mass of biomass (Eucalyptus)

e. Final results: Land area required to produce 1 Mg eqCarcass

iLF – emissions and removals

a. Occupation:

Forest (Eucalyptus) - 25% of area

Pasture - 50% of area

b. Emissions (kg CO2e ha^{-1} year^{-1} and converted to kg CO_2e kg^{-1} carcass):

CH_4 (faeces and enteric).

N_2O (excreta e fertiliser)

CO_2- fossil (liming)

c. Situations:

Degraded

Recovered

d. Drain (Mg CO_2e ha^{-1} year^{-1})

Grassland pasture (Brachiaria)

Mass of biomass (Eucalyptus)

Final results: Land area required to produce 1 Mg eqCarcass

Planted Forest - drain

a. Occupation:

Forest (Eucalyptus) - 100% of area

b. Drain (Mg CO_2e ha^{-1})

Soil + mass og biomass (Eucalyptus)

c. **Final results:** Mg CO_2eq

Planted Forest (AFS+RDP-F + Other PF) - drain

a. Occupation:

Forest - 100% of area

b. Drain (Mg CO_2e ha^{-1})

Soil + mass of biomass (Eucalyptus)

c. **Final results:** Mg CO_2eq

For the project, the implementation of the pasture recovery strategy was oriented to low productivity areas. A survey of producers from the north of the country, in the state of Pará, provided a sample of producers using little technology, however they cannot be considered degraded systems (Table 3). Most of them used *brachiaria* pastures and the worst animal stocking performance averaged 1 AU/ha, with animals slaughtered with 470 kg, a weight reached at 36 months of age, using a mean of males and females.

Table 3. Pasture characteristics and zootechnical indices of fattening herds for slaughter.

Zootechnical indices	Farms					
	Sorriso	Flor da Luz	São Miguel	Assis	São José	Bacabal
Capacity used - Wet (U.A/ha)	1,45	1,66	1,04	1,04	1,66	1,66
Capacity used - Dry (U.A/ha)	1,45	1,45	1,04	1,04	1,04	1,66
Weight at slaughter - Male (kg)	520	500	480	500	530	500
Age at slaughter - M (months)	32	36	36	32	36	32
Weight at slaughter – Female (kg)	340	300	400	350	-	-
Age at slaughter - F (months)	18	30	34	-	-	-

Braq.(*Brachiária brizantha* cv. marandú); Momb. (*Panicum maximum* cv. mombaça); M = male, F= Female; U.A = Animal Unit pesando 450 kg.

In Bahia monitoring areas, degraded pastures had a stocking rate of 0.7 UA/ha, with animals slaughtered at 460 kg, a weight acheived at an age of over 36 months. The pastures had a predominance of *Brachiaria decumbens*. In Seropédica, in Rio de Janeiro state, the monitoring of weight gain of animals from unfertilized systems is 0.2 kg/day, reaching slaughter at 36 months with a weight of 450 kg.

Inputs were not periodically applied in any of the situations considered to be of low technification, especially nitrogen fertilization. Applications of limestone, P and K were rarely made and use of mechanical operation was infrequent.

The productive systems are characterised by the frequent use of inputs, with N rates of 150 kg N ha-1 year-1 on average. Animal stocking exceeded 2 UA ha-1 year-1, with animals slaughtered at 28 to 30 months. For estimation purposes, the following conditions were assumed for poor and recovered pastures (Table 4):

Table 4. Characteristics of prototypic production systems

Variable	**Low productivity pasture**	**Recovered pastures**
Animal Genetics	Nelore or nelore cross	Nelores respective crosses
Pasture	Nominals	Productive
Diet at raising phase	Pasture. Sporadic supply of mineral salt in trough	Pasture. With vitamin-mineral supplementation in trough
Diet at reraising phase	Pasture. Sporadic supply of mineral salt in trough	Pasture. With vitamin-mineral supplementation in trough
Dieta fase engorda	Pasture. Sporadic supply of mineral salt in trough	Pasture. With vitamin-mineral supplementation in trough
Management	Sporadic. Vaccination, marking and weaning.	Breeding, vaccination, marking, weaning and monitoring of delivery
Controle Zootécnico	Sporadic	Present. Identified animals, date of birth, weaning weights, weight gain and other occurrences are recorded.
Animal stocking	0,7 UA/ha	2,2 UA/ha
Weight gain	0,2 kg ha^{-1} dia^{-1}	1,8 kg ha^{-1} dia^{-1}
Slaughter weight	460 kg	480 kg
Slaughter age	36 months	28 months

To assess the impact of mitigation strategies, CO_2 emissions were quantified by the use of inputs and agricultural operations, as well as by the use of urea and limestone and removal by soil. CH_4 emissions were those originated from the enteric process and fecal deposition. N_2O emissions were estimated by the use of nitrogen fertilisers, and by the excreta deposition of the animals in the soil.

CO_2 Emissions

Urea was assumed to be the main source of N applied in production systems. Emissions were calculated by the C content of the molecule, with U being the applied urea dose. The value "0.20" corresponds to the urea CO2 emission factor.

$$C - CO2 = 0{,}20 \times U$$

For limestone, it was estimated the CO_2 emissions that form from the input reaction in the soil, being QC, the amount of limestone applied, and 0.13 the emission factor for dolomitic limestone.

$$C - CO2 = 0{,}13 \times QC$$

Fossil emissions from inputs account for all GHG, from manufacture, transport and application. Emissions were calculated using factors shown in Table 5.

Table 5. Emission factors for inputs used in agricultural areas

	Unit	Emission factor (kg of CO_2 by unit utilised)	Source
Electrcity	kwa^{-1}	0,052	MCTI, 2011
Limestone	1 Mg	36	West, 2001
Urea	1 Mg	858	West, 2001
Phosphorus	1 Mg	165	West, 2001
Potassium	1 Mg	120	West, 2001
Vaccinations	unit	0,005	Estimated*
Mineral salt	1 Mg	120	Estimated*

* Estimated as a function of the average salt emission present in the mineral salt (e.g. potassium and phosphorus) and energy expended for vaccine production/transport.

For pasture restoration systems, it was assumed that each hectare of ground area received liming equivalent to 2 Mg of 100% PRNT dolomitic limestone every four years. The annual fertilisers were 100, 140 and 80 kg of N, P and K ha-1 year-1, respectively. All animals are vaccinated against foot-and-mouth disease and young females against brucellosis. The consumption of mineral salt considered was 40 g per UA, and the consumption of protein mineral salt at 150 g per UA.

For grain production systems, liming was considered every three years and annual application of NPK.

Emissions of CH_4

CH_4 production in animal rumen is the main source of gas in livestock. Research conducted in Brazil determined an average emission factor of 57 kg CH_4 animal-1 year-1 for pastures with better digestibility (Table 5). In the absence of more specific information, it was considered that the most productive, higher quality pastures would have an emission factor of 60 kg CH_4 ha-1 year-1, and the least productive lower quality pasture would be 55 kg CH_4. ha-1 year-1.

It should also be considered that more productive pastures have a higher supply of better quality forage, which contributes to reduced time to slaughter (Ferraz and Felício, 2010).

Table 6. Enteric methane mitigation strategies tested in Brazil, and respective emission factors evaluated using the SF6 technique.

Management and alimentation strategies	Mode of Action	Technology used	Emission factor (kg CH_4 cab-1 ano-1)	Reference
Increased digestibility of the diet	Increases dry matter intake, dilutes emission per kg of ingested dry matter	Exclusive, well-managed pasture in 4 seasons	56,4 ± 18,4	Demarchi et al. (2003a e b)
		Silage, Hay, Stalk and Urea	65,3 ± 19,8	Magalhães et al. (2009)
		Hay with different cutting ages	49,3 ± 0,6	Nascimento et al. (2007) e Nascimento (2007)
		Average	57,0 ± 8,0	

Enteric emissions are calculated by the emission factor product by the number of animals weighing 400 kg (IPCC, 2006). In addition to enteric emissions, CH_4 production occurs with faecal deposition, but in much smaller quantities. For Brazil, a 400 kg cattle is considered to produce 1 kg CH_4 year-1 derived from faeces.

Emissions of N_2O

As pasture recovery implies nutrient replenishment to the soil, with N being one of the most required (Oliveira et al., 2001), higher N_2O emissions from the soil are expected. Studies carried out under the project show higher emission factors for excreta from pastures with higher protein supply (Table 6).

Table 6 shows that the faecal emissions are much lower than that of urine, being important to use the respective emission factors independently. In this sense, a review of data from the international and national literature reinforced the difference and showed that the EF for urine should be 1% while for faeces 0.5%, adopting a conservative view (Bastos, 2018).

Table 7. N_2O emission factor [100 x (g N-N_2O g N-excreta-1)] from cattle excreta in Itabela, BA, deposited in low and high productivity pastures.

Treatments	*B. brizantha* cv Marandu	B. brizantha cv Marandu + N
Dry season	%	
Faeces	0,018	0,008
Urine	0,163	0,447
Wet season		
Faeces	0,075	0,116
Urine	0,370	0,457

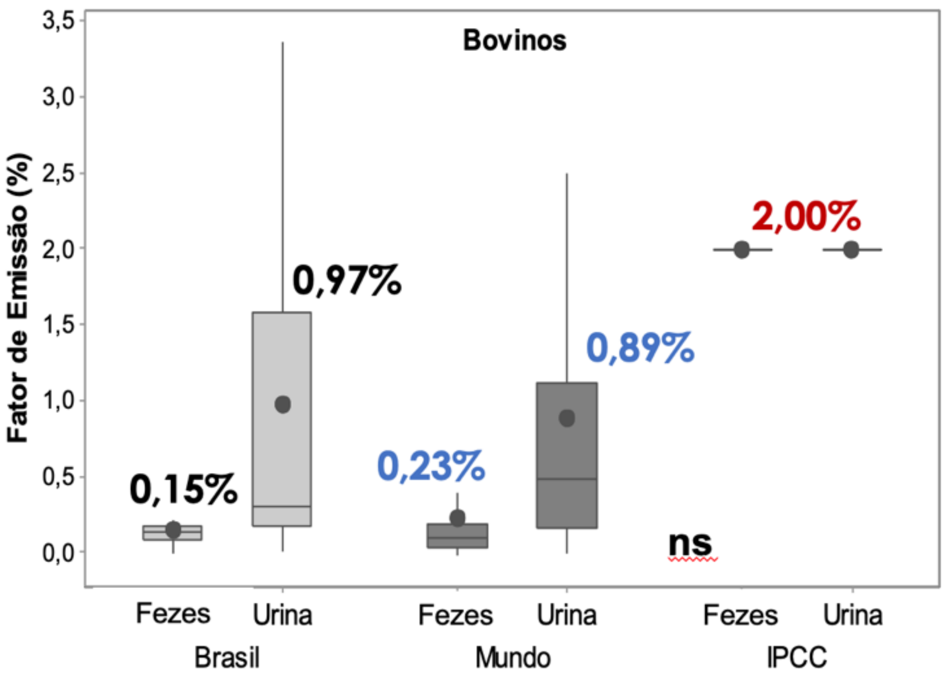


Figure 3. Average emission factors for urine and bovine faeces compiled from national and international studies (Bastos, 2018).

In addition to N_2O emissions from excreta, nitrogen fertilisers for pasture are also a source of this gas. Thus, nitrous oxide emissions were calculated by the formula:

$$N - N2O = (N \times EF1) + (NU \times EFu) + (NF \times EFf)$$

Where N is the amount of N applied as fertiliser and NU and NF are the amounts of N that reach the soil as urine and faeces, respectively. EF1, EFu and EFf are the emission factors for fertilizer, urine and faeces. It should be considered that these factors incorporate indirect emissions. Thus, the factors used were:

EF1 = 1,123 %; EFu = 1,223%; EFf = 0,723%.

Soil carbon removal or sequestration in simulated systems

To account for CO_2 removals, the accumulation of carbon in the soil in the area with the application of the Project technology was considered. For these evaluations, land use in the agricultural model as used as a reference. As for the carbon removal rate (considered as drain), it was similar for both regions in the animal systems, as in the one with PF.

Productive pastures generate a high amount of aerial and underground waste, in the order of 20 to 30 Mg ha-1, with rapid transformation in the soil, which presents one of the highest potentials of C accumulation in the soil. Data obtained in the field suggest that pasture recovery may yield soil C gains between 0.23 and 2.95 Mg C ha-1 year-1 (Table 8).

Table 8. Carbon stocks in the soil of productive and degraded pasture areas, and annual variation of Carbon stocks in the comparison between productive and degraded pastures, for different locations in Brazil.

Location	Depth (cm)	C stock in soil by pasture type Productive	Degraded	Variation in C stock (Mg ha-1 ano^{1})	References
		(Mg C ha^{-1})			
Luz, MG	100	164,7	138,1	2,95	Braz et al. (2012)
Itaporã, MS	100	95,5	84,8	1,78	Braz et al. (2012)
Penápolis, SP	100	62,0	60,5	0,23	Braz et al. (2012)
Chap. do Sul, MS	100	62,3	53,0	1,06	Braz et al. (2012)
Goiânia, GO	40	69,8	69,1	0,62	Freitas et al. (2000)*

MT e RO	30	-	-	0,89	Maia et al. (2009)
Paragominas, PA	100	100,0	108,0	1,60	Trumbore et al. (1995)
Itabela, BA	100	-	-	0,66	Tarré et al. (2001)
Itabela, BA	30	65,5	56,2	0,52	Costa et al. (2009)

* Corrected data for soil mass equivalence reported in Fisher et al (2007).

From Table 8, it is estimated an average rate close to 1.1 (± 0.28) Mg C ha-1 year -1 (or 3.67 Mg CO_2 ha-1 year -1) that could be valid for at least the first 10 years of degraded pasture recovery (Braz et al., 2012).

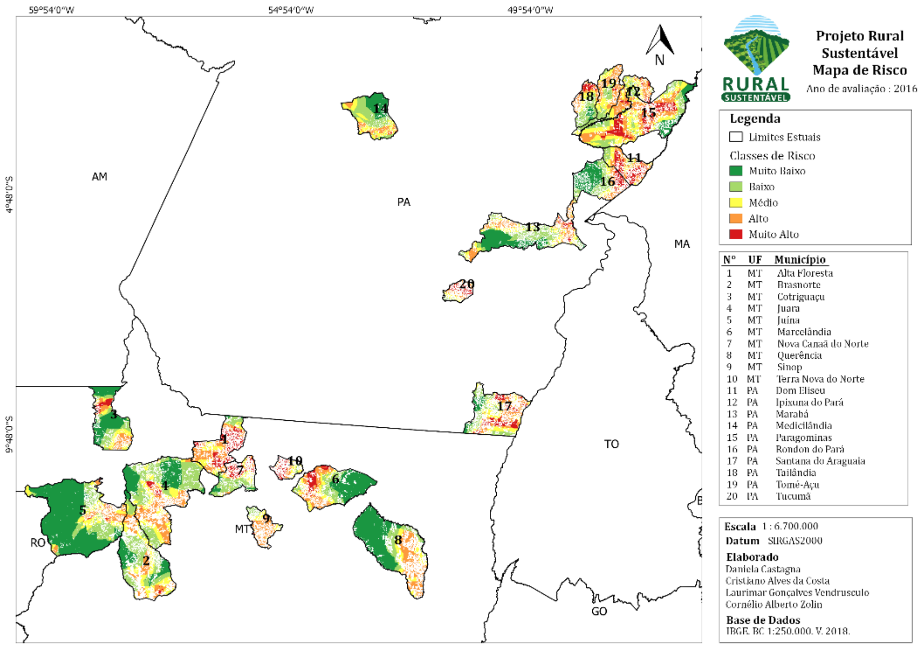
For the purpose of assessing the implementation of Project technologies, emissions and removals were accounted for a period of 20 years. GHG emissions were calculated for one hectare of project area, as well as for one hectare of area managed according to the farmers customary model. With the productivity data, it was estimated the area needed under each system to meet the same demand for meat. The difference in area was considered as the "land-sparing effect" or the gain in efficiency. Emissions per hectare were multiplied by the respective areas required to meet meat demand, allowing for the estimation of the total emissions avoided by project implementation.

Estimates of emissions and removals of CO_2 equivalent in animal-containing systems (RDP, iCLF and iLF) are presented in the form of the area required to produce one Mg in bovine carcass equivalents, and for planted forests, the calculations show the removal of CO_2 achieved as a function of planted area.

3 Results and Discussion

3.1 Avoided Deforestation

The risk map resulting from spatial algebra operations, available on the Ecometrica web platform, is the result of the summation of accessibility maps, agricultural suitability, presence of extractable resources and protected areas (Figure 4).



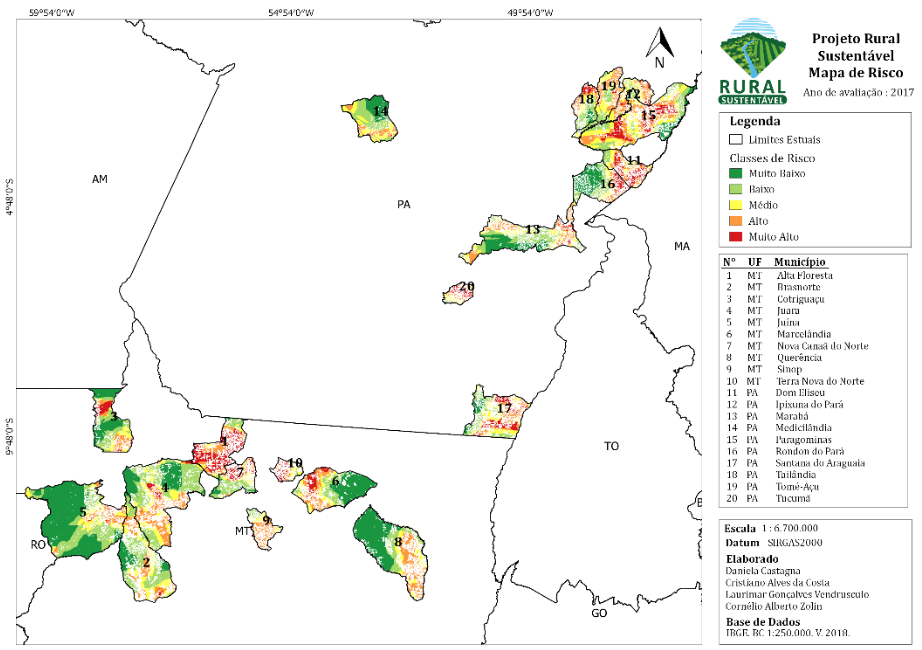


Figure 4 - Maps risk based on ACEU methodology for municipalities covered by the Sustainable Rural project in the states of Mato Grosso and Pará estimated in 2016 (a) and 2017 (b).

Amazon Biome

The influence of large protected areas with very low risk of deforestation are highlighted by ACEU methodology. Those areas are located in the municipalities of Juína (Aripuanã Park, indigenous lands of Serra Morena and Enawenê-Nawê). Querência (Xingu Park and Wawi Indigenous Land), Marcelândia (Xingu Park) and Cotriguaçu (Juruena National Park and Escondido Indigenous Land) in Mato Grosso and Medicilancia (Arara Indigenous Land), Ipixiuna do Pará (Tapirapé National Forest) - Acquiri and Itacaiúnas and Tapirapé Biological Reserve) and Rondon do Pará (Guarani Indigenous Land) in the State of Pará, among others. Conversely, there are municipalities with no such protected areas and large areas with high and very high risk of deforestation in Sinop, Terra Nova do Norte in Mato Grosso and Tucumã in the State of Pará for the 2017 base year.

When observing the spatial distribution of deforestation risk classes in the municipalities of the Amazon biome in 2016 and 2017 (Figure 5), it is clear that there was no expansion or drastic retraction of the classes. We highlighted only an increase in the low-risk area northeast to southwest in 2017 compared to 2016 in the municipality of Juína, possibly due to a road in this area, detected in the analysis.

Avoided forest loss values close to zero means that the ACEU methodology is estimating forest loss close to that observed. Figure 5 shows that, in 2017, more values close to zero were calculated in relation to the same series of municipalities in 2016. Negative values of avoided loss mean higher deforestation values than estimated by the methodology, whereas positive values mean the opposite.

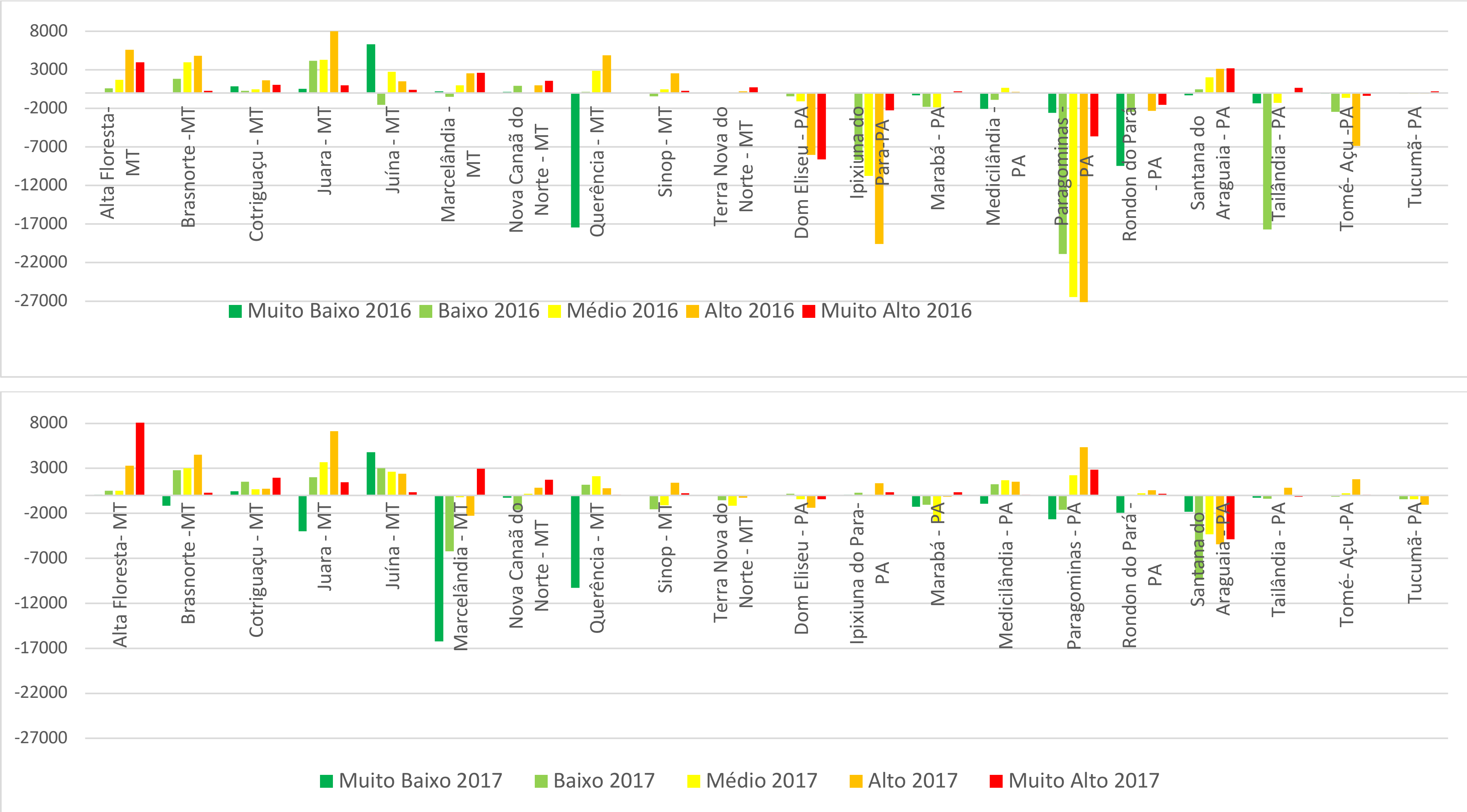


Figure 5. Distribution of risk classes loss in twenty (20) municipalities of the Low Carbon Agriculture Project in the states of Mato Grosso and Pará for the base years 2016 (a) and 2017.

High negative values of avoided deforestation risk at Paragominas were observed in 2016 (average risk = -26,430.5 ha; high risk = -27,112.5 ha and low risk = -20,885.21 ha), Ipixiuna do Pará (high risk = -19,555.6 ha), Tailândia (low risk = -17,673.7 ha) and Dom Eliseu (risk = -8,663.2 ha) in Pará and Querência (very low risk = -17,403 ha) in the State of Mato Grosso. In 2017 negative variations were restricted to Marcelância (very low risk = -16,211.1 ha), Querência (very low risk = -10,284,8 ha), Juara (very low risk = -3,972,4 ha) in the state of Mato Grosso. Factors affecting deforestation and land degradation are not simple to explain and may originate from a variety of sources as discussed in Tipper and Morel (2016). Even though this historical series is not long enough to apply time series statistics, some estimates can be calculated. A box plot illustrated by Figure 6 shows the avoided forest losses.

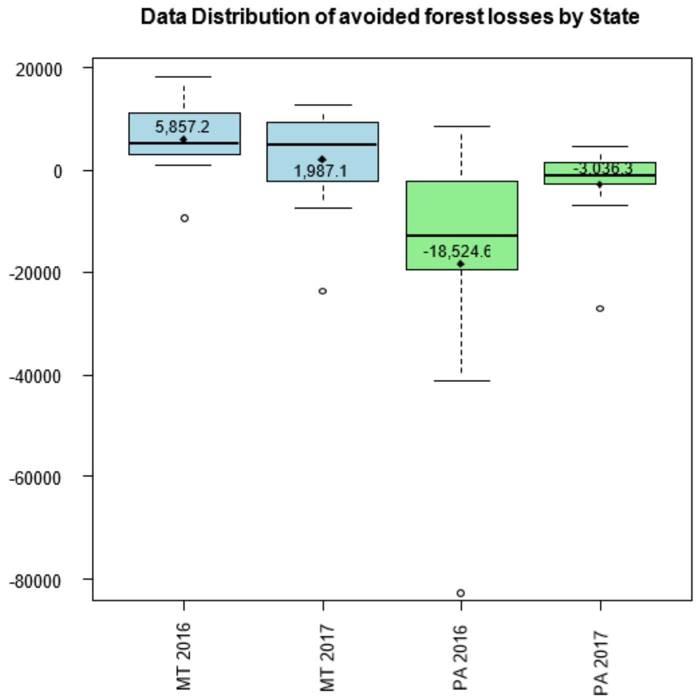


Figure 6. Areas of avoided deforestation considering 2016 and 2017 as the base year from risk maps in municipalities covered by the Low Carbon Agriculture Project in the state of Mato Grosso (blue) and Pará (green).

The average difference between 2017 in the state of Pará is larger compared to the state of Mato Grosso, approximately 15,500 hectares (Figure 6). However, in both states there was a significant reduction in deforestation in 2017 compared to 2016, even in municipalities with a high amount of observed deforestation, such as Paragominas in 2016.

Related to the Amazon biome, the amount of avoided forest loss considering the total area of municipalities in Mato Grosso and Pará, with a few exceptions, has improved. This means that the measured forest loss has been lower than expected by the Hectare Indicator methodology, in particular Dom Eliseu, Ipixiuna do Pará and Paragominas municipalities that are located in the state of Pará. Such findings are based on a comparison of 2016 negative value to 2017 consistently positive values of avoided forest loss. Detailed causes of forest loss decreasing in 2017 were not investigated in this study.

Atlantic Forest Biome

In the 2017 avoided forest loss values illustrated by Figure 7, and considering forty (40) municipalities, we noticed that two (2) municipalities from south Brazil (Paraná and Rio Grande do Sul) stood out. In those areas, the measured forest losses were lower than expected in 2017. They were: Paranavaí (PR), Vacaria (RS). In Bahia State, Maraú municipality has obtained, approximately, 1,600 ha of avoided forest loss in a high-risk area.

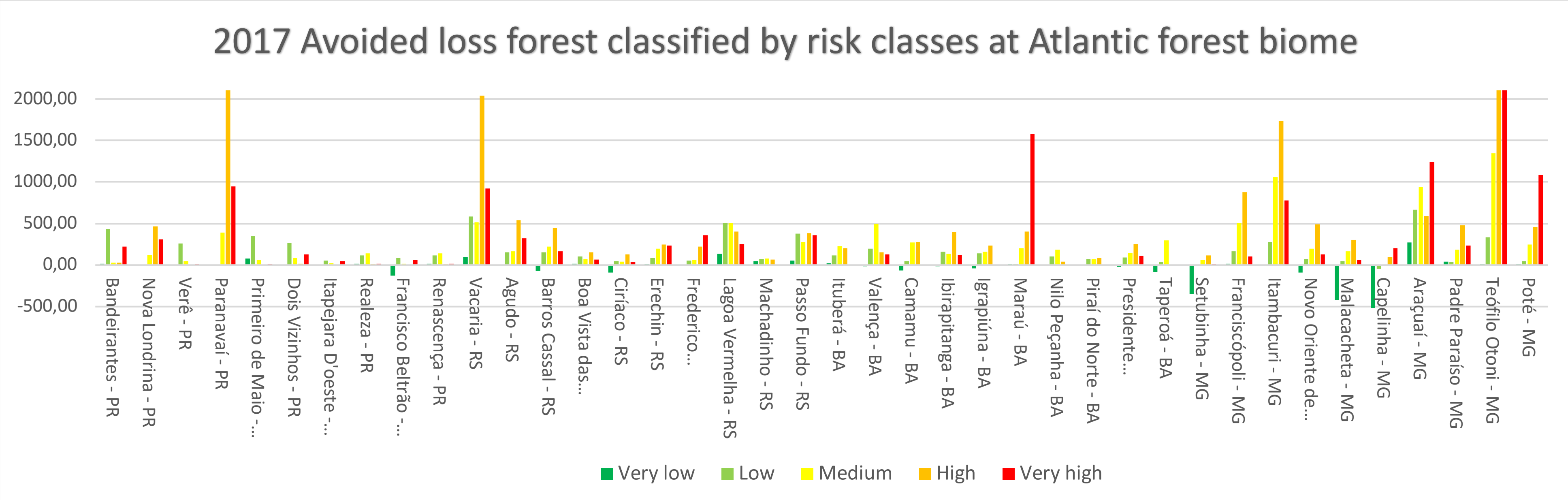


Figure 7. Risk classes distribution of avoided loss forest at the forty (40) municipalities encompassed by the Low Carbon Agriculture Project in the Bahia, Minas Gerais, Paraná and Rio Grande do Sul States, in the Atlantic Forest biome.

In the same direction, a few municipalities in the southeast region of Brazil, (Minas Gerais state) reported the highest positive values of avoided forest loss, such as Teofilo Otoni (From 521 ha in 2016 to 9,100 ha in 2017) and Itambacuri (From 970 ha to 3,800 ha in 2017). A quick news search revealed that water springs restoration took place in this city. However, a non-exhaustive search to explain forest losses discovered that Paranavaí recorded many fire spots in 2017. Another noticeable aspect in Figure 7 was a few negative avoided loss areas classified as very low, for example, Setubinha, Malacacheta e Capelinha, all of them located in Minas Gerais, reaching the total area of 1,800 ha.

Figure 8 shows total avoided forest losses from Atlantic Forest municipalities for a two year time series (2016 and 2017).

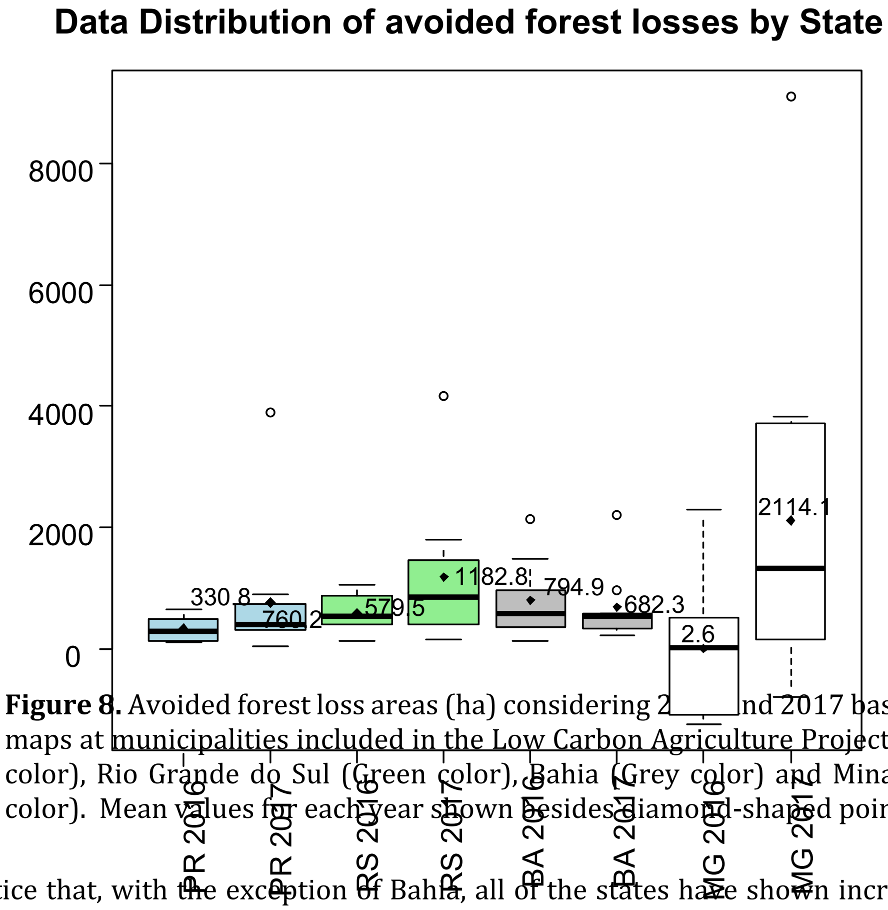


Figure 8. Avoided forest loss areas (ha) considering 2016 and 2017 base year from risk maps at municipalities included in the Low Carbon Agriculture Project in Paraná (blue color), Rio Grande do Sul (Green color), Bahia (Grey color) and Minas Gerais (white color). Mean values for each year shown besides diamond-shaped point.

Notice that, with the exception of Bahia, all of the states have shown increasing values of avoided forest losses. In addition, Minas Gerais, in 2016, had a small value of avoided forest loss (2.6 ha), which means that were many municipalities with high positive and negative values. However, in 2017, those values are consistently positive values of measured forest loss. For this reason, Minas Gerais reached the highest difference between 2017 and 2016 (2,111.6 ha), compared to Paraná (430 ha), Rio Grande do Sul (603) and Bahia (-112.5 ha).

Based on the assessment in 2016 and 2017, the amount of avoided forest losses in Bahia, Minas Gerais, Paraná and Rio Grande do Sul municipalities, with a few exceptions, has improved. This is the consequence of an expectation that loss was higher in 2017 (63,032 ha) than 2016 (35,970 ha) and a decrease of measured forest loss from 23,317 ha in 2016 to 15,526 ha in 2017. The municipalities recording the highest reduction in 2017 forest loss were located in Minas Gerais: Teofilo Otoni, Setubinha, Novo Oriente de Minas and, Capelinha. However, they were also the locations with highest 2016 forest loss, varying from 4,400 to 1,900 hectares.

It is considered that regions of very low risk of deforestation are far from roads, have low agricultural capacity, an absence of natural resource and are located in protected areas. It is correct to conclude that 56% of the municipalities located in the Atlantic Forest biome present a very low risk of deforestation. Regarding to areas classified as very low risk of deforestation, around 50% of the municipalities in Amazon biome had measured losses forest were higher than expected in 2017 (negative values of avoided loss forest). Such findings are based on a comparison of 2016 immense negative value to a 2017 consistently positive values of avoided forest loss.

When considering all the properties involved in the Project and the deforestation risk it is considered that 8,550ha of deforestation was directly avoided (Figure 9).

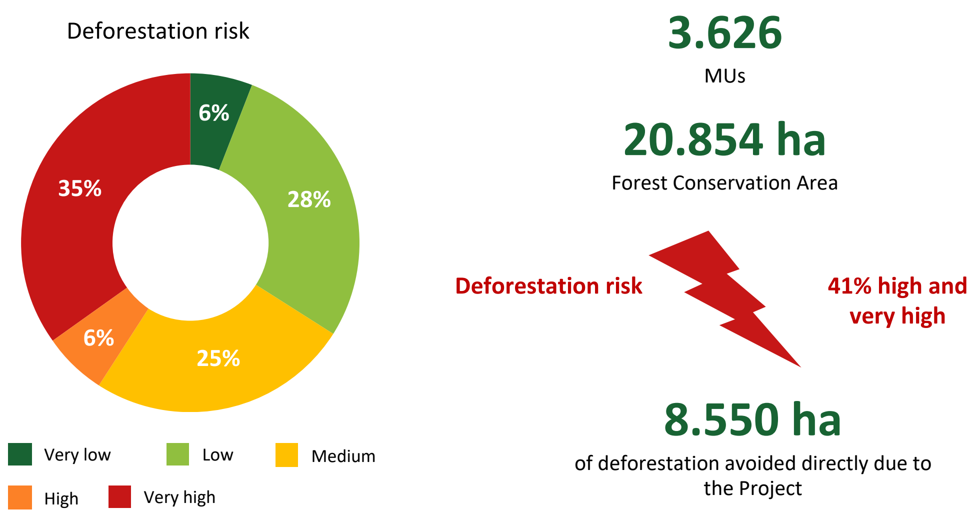


Figure 9. Deforestation directly avoided through Project activities

3.2 Greenhouse Gas Emissions

In general, GHG emissions increased significantly with the adoption of technologies, taking into account the increased use of inputs and the number of animals per unit of area as a result of increased carrying capacity. On the other hand, productivity gains increased at an even higher rate (Table 9). In addition to the efficiency effect, which indicated a reduction in GHG emissions per unit of product, the recovery of plant productivity resulted in soil C gains, contributing to a temporary offsetting of GHG emissions. For systems using trees, the compensation potential was significantly increased (Table 10).

Table 9. Estimates of emissions and removals for recovery systems with animals in each region

Technology **Biome**			RDP Atlantic Forest	RDP Amazon		iCLF Atlantic Forest	iCLF Amazon		iLF Atlantic Forest	iLF Amazon
Total area	ha		3,335.0	18,715.0		787.0	1,141.0		1,892.0	2,370.0
Emissions by area	kg CO2eq/ha/year	DP	1,476.2	2,108.4	DP	1,476.2	2,108.4	DP	1,476.2	2,108.4
		RP	7,019.9	7,472.3	iCLF	4,730.3	4,859.9	iLF	6,264.1	6,458.6
Total emission values (20 years)	Mg CO2eq	DP	98,460.9	789,190.9	DP	23,235.0	48,114.7	DP	55,858.5	99,940.3
		RP	468,225.0	2,796,863.9	iCLF	74,454.7	110,903.5	iLF	237,034.3	306,136.4
Emissions by Carcass equivalent	kg CO2eq/kg carcass	DP	41.5	36.4	DP	41.5	36.4	DP	41.5	36.4
		RP	22.3	21.9	iCLF	25.7	25.3	iLF	22.7	22.4
Reduction in GHG intensity	%		46.3	39.9		38.0	30.6		45.3	38.6
Drainage by removal of CO_2 by soil (20 years)	kg CO2eq/ha	DP	0.0	0.0	DP	0.0	0.0	DP	0.0	0.0
		RP	80666.7	80,666.7	iCLF	46,566.7	46,566.7	iLF	56,650.0	56,650.0
Total CO_2 drain by soil (20 anos)	Mg CO2eq	DP	0.0	0.0	DP	0.0	0.0	DP	0.0	0.0
		RP	269,023.3	1,509,676.7	iCLF	36,648.0	53,132.6	iLF	107,181.8	134,260.5
Compensation for CO_2	Years		11.5	10.8		9.8	9.6		9.0	8.8
Above baseline (DP)	kg CO2eq/ha		5,543.7	5,363.8		3,254.1	2,751.5		4,787.9	4,350.1
Area required to produce 1 Mg carcass equivalent	ha	DP	8.3	5.8	DP	8.3	5.8	DP	8.3	5.8
		RP	2.3	2.2	iCLF	3.9	3.9	iLF	2.6	2.6
Difference	ha		6.1	3.7		4.5	2.0		5.7	3.2
Difference	%		72.8	62.7		53.3	33.3		69.9	55.6

GHG - Greenhouse Gases; DP - Degraded Pasture; RP - Recovered Pasture; RDP - Recovery of Degraded Pasture; iCLF - Crop-Livestock-Forest Integration; iPF - Livestock-Forest Integration

Table 10. Estimates of removal for systems with trees in each region

Technology Biome		PF - Eucalyptus Atlantic Forest	PF - Eucalyptus Amazon	AFS + RDP-F + Others PF Atlantic Forest	AFS + RDP-F + Others PF Amazon
Total area	ha	69	12	3,859.0	2,793.0
Drainage by removal of CO_2 by soil + biomass (20 years)	kg CO2eq/ha	170,256.1	170,256.1	342,486.5	342,486.5
Total drainage (20 years)	Mg CO2eq	11,747.7	2,043.1	1,321,655.3	956,564.7

PF - Planted Forest; AFS - Agroforestry System; RDP-F - Recovery of Degraded Pasture with Forest

For grazing systems, the area needed to produce 1 Mg of carcass in degraded pasture (DP) was larger in the Atlantic Forest than in the Amazon, being 8.3 and 5.8 ha, respectively, with no difference by technology (Table 9). This contrast is due to the fact that degraded pasture in the Amazon has a higher forage supply, capable of maintaining more animals compared to degraded pastures of the Atlantic Forest. However, in the evaluation within the recovered pasture (RP), the opposite was seen, with similarity between the regions, but with difference between the technologies, with the necessary area being smaller in the RDP (around 2,3 ha) and larger in the iCLF (3.9 ha) (Table 9).

In the overall assessment in terms of area required to produce 1 Mg of carcass, the application of degraded pasture recovery technologies leads to increased productivity, with greater area savings ("land-sparing" effect) in the Atlantic Forest (72.8%). Application of iLPF in the Amazon generated a saving of 33% (Table 9). If we consider systems that involve integral animal comfort, characterised by decreased sun exposure due to tree surplus, the differences are small when compared to monoculture grazing (RDP), and thus the iLF seems to be the most promising technology with a sparing of area of 69.9%. in the Atlantic Forest and 55.6% in the Amazon (Table 9).

The improvement of zootechnical indices, in particular for the Atlantic Forest area, was the key factor in the large difference and thus land economy. In this sense, investments in the expansion of this technology are effective in broad ways, involving aspects of both the control emissions and balance of GHG, as well as animal comfort. In this biome, pasture areas in various stages of degradation occupy a considerable area, replacing sugarcane and coffee cycles throughout Brazil's occupation history.

In addition to the area savings and reduction of CO_2e emissions through pasture recovery technologies with systems involving animal production, these areas also show potential to stock carbon and thus can become a carbon drain within each region. The iLF systems, were significant in the Atlantic Forest, reaching more than 3,800.00 ha, generating a carbon accumulation of over 1.3 million Mg CO_2e over 20 years.

Co-benefits

In addition to the direct effect on productivity and mitigation of GHG emissions, the techniques tried in the project brought a change in the landscape, especially with the introduction of trees, which certainly had or will have benefits for local ecology (Figure 10).

Figure 10. View of degraded and recovered pastures in iFP and iLPF system.

In terms of Planted Forests, the Project saw the implementation of 6.733ha, responsible for the sequestration of 2,3MtCO_2 (Figure 11)

6.733 ha

of forests planted through the Project

2,3MtCO2

sequestered

Figure 11. Carbon sequestered by forest planted through the Project.

Gain in efficiency

The gain in efficiency in the productive systems indicates that the producer will be able to expand his production area without implying deforestation or even using the surplus for environmental adaptation, as is the case with many existing properties in the Atlantic Forest Biome. As demonstrated in the figure below, the area required to produce one ton of meat was drastically reduced with the implementation of agricultural technologies.

Figure 12. Area required to produce meat in degraded and recovered pastures.

Technology diffusion from Demonstration Units

Considering boundaries of Demonstration Units (DU) centroid points were created (medium point of the property shape) and from these it was estimated distances to Multiplier Units (MU). The hypothesis was that DU's worked as a showcase encouraging nearby farmers to adopt low carbon technologies. Distances were estimated of 1,114 MU to their nearest DU's. Table 11 shows the amount of MU's according to a 10 km interval. The major finding for the four states of the Atlantic Forest Biome was that around 98.5% of the UM´s are within 15 kilometres of a DU.

Table 11 – Distance analysis to MU's from DU placed at Bahia, Minas Gerais, Paraná and Rio Grande do Sul States.

	Distance from DU (km)				
	< 5	**5-10**	**10-15**	**>15**	**Total**
# MU	1263	431	83	34	1,811
Total %	69.	23.	4.6	1.5	
Cumulative %	-	93.5	**98.5**	100	

Where DU=Demonstrative Units and MU = Multiplicative Units

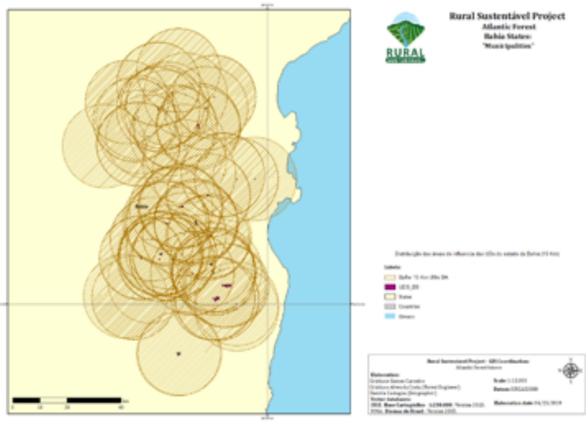
In the Amazon biome (Mato Grosso and Pará states), the same exercise demonstrated that around 82 % of the MUs are within 30km of a DU.

In terms of future impacts of the Demonstrative Units of the Low Agriculture Project, we have determined the optimal distance as 15 km for Atlantic forest and 30 km for Amazon biome. A buffer was then generated around each DU area and the total area estimated. For Atlantic Forest, the total buffer area was 3,681,569.20 ha and for Amazon biome 9,399,583 ha. A very conservative scenario, considering only 1% of the buffer area being transformed into technology, would result in around 37,000 ha and 94,000 ha of technology implemented, for Atlantic forest and Amazon biome, respectively (Table 12, Figure 12).

Table 12. Buffer area in Atlantic Forest states

Total buffer Area*	
State	Area (ha)
Rio Grande do Sul	137,200.94
Bahia	70,685.21
Paraná	979,900.07
Minas Gerais	1,258,981.98
TOTAL	3,681,569.20

* Total buffer area of 15 kilometers around Demonstrative Units.

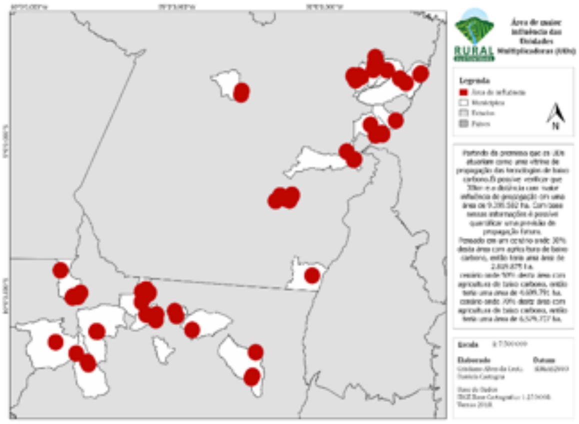


	Distance from DU (KM)		
	< 5	5-10	10-15
MUs implanted	1.263	431	83
Total %	69,7%	23,8%	4,6%
Accumulated %	-	**93,5%**	98,5%

If 1% of this area is transformed in ABC technology we will have a further

37 mil ha

In the Atlantic Forest



	Distance from DU (KM)			
	< 10	10-20	20-30	30-40
MUs implanted	468	299	144	130
Total %	42%	27%	13%	12%
Accumulated %	-	69%	**82%**	93%

If 1% of this area is transformed in ABC technology, we will have a further

94 mil ha

In the Amazon

Figure 12. Potential for technology diffusion in each biome

Final project numbers

The final results of the Project, as related to the KPIs are displayed in Table 13.

Table 13. Final Project results

ICF KPI	Initial target	Final results
ICF KPI 3: Number of people benfited	11.100	• **57.891** • **18.570** (directly) • **39.321** (indirectly)
ICF KPI 6: Tons od GHG avoided or mitigated	10.71 MtCO2e of reduced emissions	• **8,9 MtCO2e** of reduced emissions
	6.97 MtCO2e of reduced emissions	• **57 MtCO2e** of avoided emissions
ICK KPI 8: Area of deforestation and/or degradation avoided	41.560 ha	**219.676 ha** **36.038 ha** of avoided degradation (ABC technologies) **8.550 ha** of direct deforestation avoided **175.088 ha** of indirect deforestation avoided

4 Conclusion and next steps

Natural capital is the basis of agricultural production; the sector depends on preservation. The destruction of native vegetation, loss of biodiversity and climate change have great potential to directly damage the agricultural sector, affecting, for example, the rainfall regime and the presence of pollinators and pests.

The Project targeted small and medium scale producers, those most vulnerable to climate change and with fewer opportunities to operationalize investments needed to increase income, not only in the short term, but with resilient and efficient production, even in the face of medium and long-term climate adversities. By supporting the implementation of technologies that not only increase resilience to climate change, but also reduce the negative impacts of agricultural activities, the Low Carbon Agriculture Project provides concrete evidence of how the necessary transformation of small and medium-sized agriculture can be achieved.

Disentangling conventional agricultural production from environmental problems remains a major challenge, but initiatives such as the Low Carbon Agriculture Project show that it is possible. The Project has proven that combining efforts by institutions at various levels, acting in conjunction with rural producers can bring about major changes. The path towards rural poverty reduction, sustainable intensification of production and mitigation of greenhouse gas emissions can be pursued through strategic partnerships. We need a sustainable rural environment that embraces knowledge, connectivity, technology and innovation, only possible with alliances. Only in this way will we be able to produce and preserve.

In this sense, initiatives such as The Low Carbon Agriculture Project should be increasingly encouraged. This Project brought two very important countries together on the world stage and through the work of the participating institutions, has enabled the first phase to benefit thousands of people, reduce greenhouse gas emissions and expand the adoption of sustainable production technologies.

One of the main challenges of the transition to a sustainable world is to achieve the coordination of policies, programs and instruments that lead to a articulation of the set of explicit and implicit incentives and disincentives towards sustainable development. Since the Project's inception, institutional arrangement has been a key aspect. This made it possible to implement an initiative that, in addition to conducting research to advance knowledge of low carbon agriculture, addressed, jointly and in an integrated manner, the main barriers encountered in implementing sustainable agricultural models on small and medium-sized properties.

Based on its success and using the lessons learned in the execution of its first phase, the Project will enter its second phase, in two new biomes in Brazil, the Cerrado and Caatinga. Phase 2 provides for the implementation of iCLF systems on over 2,600 properties, with an expected result of over 200 thousand hectares with this technology in place. In addition, it advocates the introduction of more sophisticated concepts, with a focus on marketing, the role of associations in management and technical training, access to markets and credit for sustainable property management, enabling the increase in the income of producers.

With this, Brazil and the United Kingdom have further strengthened ties and are prepared for a new and exciting challenge: to build a better world. The Project is helping to rewrite the history of Brazilian agriculture and contributing to a fairer society, with more equality, more preservation and more sustainability.

ANEXO 2

ACTION PLAN 4: EVALUATION OF THE PRODUCER'S PERCEPTION REGARDING THE ADOPTION OF LOW CARBON TECHNOLOGIES

Action plan 4: Evaluation of the producer's perception regarding the adoption of low carbon technologies

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Introduction

The global process of climate change imposes itself as a challenge to be faced today due to its effects on ecosystems and its consequent economic and social impacts. Immediate actions to mitigate the effects and adapt the agents to climate change are necessary and, in this sense, the sustainable Rural Project (SRP) is positioned as an important tool in promoting sustainable rural development, reduction of rural poverty, biodiversity conservation, and climate protection.

The SRP comprises a set of actions aligned with the Sectoral Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low Carbon Economy in Agriculture (in Portuguese, *Plano Setorial de Mitigação e de Adaptação às Mudanças Climáticas para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura – Plano ABC*) and the United Nations Framework Convention on Change Climate, being divided into three scopes: i) financial subsidy to small and medium-sized farmers for the acquisition of low carbon technologies, ii) technical training of producers and providers of agricultural and environmental services, and iii) implementation, monitoring, and evaluation of the activities of technical cooperation.

This document is related to the third specific objective of the project, the evaluation of the agricultural producers' perception regarding the adoption of low carbon technologies. Understanding the producer's perception of the use of sustainable production techniques, such as those encouraged by SRP, is fundamental to the success of the program, being a reference to new stages of the project or even to other public policies. In this sense, this action plan sought to evaluate the levels of environmental producers' perception of the demonstrative units (DUs) participating in SRP and how the perception relates to their product choices and their socioeconomic profile.

The initial research involved the elaboration of questionnaires for application to the producers of the DUs, the instructional tutorial video to the applicators of the questionnaires, the socio-economic analysis of the biomes and municipalities selected by the program, the tabulation of primary and secondary data, the descriptive analysis of the results collected, and the generation of synthesis indicators to evaluate the producers' perception. The questionnaire applied to the DUs was elaborated according to the methodological assumptions of the Principal Component Analysis (PCA) and the Cluster Analysis. In this sense, five groups of variables were established: i) Adopting producers' socioeconomic profile, ii) Production level and market integration, iii) Technologies used, iv) Environmental perception degree, and v) Political and legislative institutional relationship degree. The generated data, in a cross-sectional format for 278 individuals or DUs at a given point in time, have these groups as reference.

The study adopts the PCA as a methodology to understand the agricultural producers' perception in relation to the low carbon (CO_2) technologies adoption. From the PCA, it was possible to create the Climate Change Perception Indicator (CCPI) and the classification of producers at different perception levels. Following this distinction, it was carried out the characterization of the producer profiles regarding the used technologies, allowing the analysis of the producers' perception regarding the low CO_2 emission technologies adoption promoted in the SRP. This executive summary presents the main results obtained in this study in terms of socio-economic analysis, characterization of producers, and perception regarding the low CO_2 emission technologies adoption.

1 – Socio-economic analysis of the Amazonian and the Atlantic Forest biomes

The socio-economic analysis of the municipalities in the Amazonian Biome (AMB) and in the Atlantic Forest (in Portuguese, Mata Atlântica) Biome (AFB) aims to capture economic and social information that characterize the regions where the SRP was implemented, with the agricultural producers as reference. Such information is relevant to guide and contextualize the obtained data from the participating rural producers and, therefore, is fundamental to the quality of the study on the perception of rural producers regarding the low CO_2 emission technologies adoption. Table 1 presents the used variables and indicators.

Table 1 – Variables and indicators for municipalities in SRP and for municipalities in AMB and in AFB

1. Socio-demographic characterization	Municipalities of the SRP/AM	AMB Municipalities	Municipalities of the SRP/MA	Municipalities of the AFB
Population (2018, IBGE estimate)[1]	1.534.060	22.701.954	1.399.033	148.521.029
Growth rate pop. (2010-2018)	15,52%	13,17%	6,60%	8,74%
HDI (2010, average)[2]	0,647	0,608	0,663	0,684
HDI Income (2010, average)	0,655	0,592	0,660	0,671
HDI Longevity (2010, average)	0,798	0,776	0,807	0,816
HDI Education (2010, average)	0,520	0,495	0,550	0,586
2. Economic structure	**Municipalities of the SRP/AM**	**AMB Municipalities**	**Municipalities of the SRP/MA**	**Municipalities of the AFB**
GDP at current prices (2015 million reais)[3]	30.000,97	393.450,50	32.440,14	4.803.537,06
GDP per capita (2015 in reais)	20.291,30	17.967,81	23.231,20	32.906,26
GDP Share in Biome (2015)	7,63%	100%	0,68%	100%
Participation of the GVA of agriculture in total GVA at current prices (2015)[4]	27,70%	23,20%	9,84%	3,75%
Portion of formal employment in the primary sector (2016)	13,70%	5,30%	7,13%	3,07%
Portion of formal employment in the secondary sector (2016)	19,30%	15,20%	22,89%	21,93%
Portion of formal employment in the tertiary sector (2016)	67,00%	79,40%	69,98%	75,01%

[1] Brazilian Institute of Geography and Statistics.
[2] Human Development Index.
[3] Gross domestic product.
[4] Gross Value Added.

Locational agricultural Quotient (2016)	2,560[5]	[6]1,410[7]	2,612[8]	0,818[9]
Land Properties Scale Index (2006)	7,920	11,190	37,046	28,150
Higher agricultural activities (2017)	Soy, corn, cocoa, cassava, and coffee	Soy, maize, cassava, cotton, and Banana	Soy, apple, corn, cassava, and tobacco	Soy, sugar cane, corn, coffee, and tobacco
3. Infrastructure	**Municipalities of the SRP/AM**	**AMB Municipalities**	**Municipalities of the SRP/MA**	**Municipalities of the AFB**
Share of households with water supply by general network or source at the property (2010)	91,70%	81,80%	86,51%	89,66%
Share of households with general sewer or or septic tank (2010)	11,10%	14,10%	48,31%	52,33%
Share of households with electricity (2010)	93,60%	91,10%	95,33%	98,73%

Source: Own elaboration based on data from the IBGE system of automatic Recovery-SIDRA (2018); of the United Nations Development Programme – UNDP (United Nations-UN), the João Pinheiro Foundation (Minas Gerais) and the Institute for Applied Economic Research – IPEA (2013); Of the annual Social Information Relationship (RAIS) of the Ministry of Labor (BRAZIL, 2018); And the SOS Mata Atlântica Foundation and INPE (2018).

Infrastructure: The municipalities of the SRP/MA presented a slightly better performance in the socioeconomic and infrastructure indicators evaluated in comparison to the municipalities of the SRP/AM.

Rural profile: Agricultural production-oriented profile of the municipalities of the SRP, of both biomes. Such characteristic may support the implementation of the project due to the greater aptitude in adopting the techniques and guidelines proposed by the SRP.

Locational Agricultural Quotient (LAQ): The LAQ calculated for the municipalities of the SRP is 2.56 for those located in AMB and 2.61 for the AFB. The index compares two sectoral-spatial structures and measures the importance of the sectors in the regional productive structure, the calculated value indicates a high specialization of agriculture in the municipalities of the SRP, a specialization greater than the other municipalities in their biomes.[10]

Heterogeneity: The region where the SRP municipalities are located presents heterogeneity in terms of economic and climatic dynamics, A factor that should be taken into consideration in the elaboration of public policies.

Environmental vulnerability: The strategic location of the selected municipalities highlights the focus on the environmental sustainability of SRP, as it seeks to promote productive sustainability in areas vulnerable to biome degradation, notably Those located on the frontier of agricultural expansion.

[5] This value is based on the relationship between municipalities of the SRP/AM and municipalities in AMB.

[7] This value is based on the relationship between municipalities in AMB and Brazilian municipalities.

[8] This value is based on the relationship between municipalities of the SRP/But and municipalities in the AFB.

[9] This value is based on the relationship between municipalities in AFB and Brazilian municipalities.

[10] THE LAQ is given by: EAPRSETPRSEABETB Where: EAPRS Represents the Agricultural sector in the municipalities of the SRP In the biome in analysis; ETPRS The total employment in the municipalities of the SRP; EAB The employment of the agricultural sector in the municipalities of the biome in question; ETB The total employment in the municipalities of the investigated biome. (A) literature considers that values of LAQ greater than 1 (one) indicates sectorial specialization (BRAZIL, 2008).

2 – Characteristics of the producers of the DUs

i) socioeconomic profile

The analysis of the socioeconomic characteristics of the DUs participating in SRP is essential to understand both the profile of rural producers who adopt low CO2 technologies and concern about environmental aspects. The results presented here may be a reference for future SRP stages or even for other similar public policies since they characterize the producers regarding schooling (Figure 1), gender (Figure 2), age (Figure 3), consumption and Profile of the workforce used in the property.

Decision-making: 67% of producers make decisions related to ownership together with their spouse, half of which also include their children in the process. 26% of producers make decisions on their own.

Family Farming: Family farming characterizes the profile of the producers. 53% do not have contracted employees, and of these, 93% have at least 1 relative working in the production. Of those who have contracted workers, the number of family workers exceeds that of contractors in the vast majority of properties.

ii) Production level and market integration

Investments: High percentage of owners who target more than half of their gross income for the realization of investments (31%). Among the investments, we highlight those carried out for the acquisition of new permanent crops, new pastures, new and used machines, and implements, besides the purchase of animals for reproduction and/or work.

Technical assistance: a factor relevant to the productive success of the participating DUs is access to technical assistance. In this sense, it is verified that 91% of the properties received technical assistance recently, with 52% receiving, on average, once a month. Of those who did not receive assistance, some indicated that they did not have financial conditions to hire or did not need assistance. The low integration of the DUs into the industries is also verified. About 70% are not integrated, that is, they do not produce and sell according to standards established by the industries.

Rural credit: Access to rural credit is another important factor for the development of rural properties and its lack can represent a serious obstacle to the adoption of sustainable technologies. Table 1 shows that, among the properties participating in SRP, there is a balance between the number of properties that use some type of rural credit (57%) And those that do not use (43%). Among those using, the average value acquired is just over 52,000 reais in the last 12 months, with strong participation of PRONAF, the national program for strengthening family Farming.

iii) technologies

The producers indicated that access to technical assistance and training are the decisive tools for the implementation of the technologies listed. The level of use of such technologies can be seen in table 2.

Table 2 – Use of technologies supported by SRP

Technology	Use	Not Use
iLPF/SAFs	62%	38%
Planting of commercial forests	30%	70%
RDA-P	53%	47%
RDA-F	29%	71%
Sustainable management of native forests	19%	81%
No-tillage system (SPD)	26%	74%
Biological nitrogen fixation (FBN)	15%	85%
Animal manure Treatment	13%	87%
Adapting to climate change	12%	88%
Other	2%	98%

Source: own elaboration based on the results of the research.

The results indicate a remarkable split between technologies that present a straight and perceptive connection with production of goods to be commercialized and those that, even having undeniable contribution to increasing production, can be associated more closely with building conditions to increase production in the middle or long term. Moreover, these results can be viewed as part of a changing in the agriculture production since there is a strong association among the technologies supported by SRP. Thus, positive results of those technologies focused on commercialized goods tend to create opportunities for adoption of technologies that will generate a huge impact in the relationship between agriculture and environment in the long term such as no-tillage systems, animal manure treatment and biological nitrogen fixation (FBN).

iv) environmental perception degree

Producer Impact: The performance of the rural producer directly impacts the phenomenon of climate change, either positively or negatively, depending on the practices adopted. It is important that each producer understands the impacts caused by its productive activities. In this sense, the owners of the DUs interviewed answered questions that sought to capture such type of perception. Thus, 58% of the owners affirmed believing that the way they conduct activities can collaborate with climate change, while 42% said they did not believe (Figure 4). Thus, approximately 96% of respondents would be willing to change personal habits (not related to production) to contribute to the fight against climate change (Figure 5), and 93% would be willing to change the production techniques, even without Financial support for this (Figure 6).

Heterogeneity of impacts: The producers perceive the effects of climate change, even if they lack specific technical knowledge to deal with such phenomenon. Since the studied DUs are located in municipalities, states and even different biomes, the variability of responses, especially related to perceived impacts, is high, evidencing the heterogeneity of effects when one thinks in terms of different regions of Brazil.

v) Political and legislative institutional relationship degree

Most of the owners participate in government programs, with emphasis on PRONAF, and do not rely on direct income transfer policies. As for environmental legislation, there is a clear perception regarding the non-compliance of environmental laws by producers in general and a visible ignorance about all the regimental aspects of the legislation. However, the producers were extremely conscious about the limits of economic development when considered "at all costs", evidencing the importance of the environment in the development process.

3 – The producer's perception of the adoption of low CO_2 emission techniques

The producers' perception in relation to climate change was used as a parameter to evaluate their perceptions regarding the adoption of low CO_2 emission techniques as encouraged by SRP. In this sense, an index was established – the Climate Change Perception Index (CCPI) – elaborated based on questions present in the questionnaire applied to the producers of SRP DUs. The questions that compose the index refer to Group IV of the questionnaire, namely, environmental perception; and seek to verify how aware the producers are in relation to climate change.

The elaborated CCPI sought to segment the producers of the DUs participating in the SRP in relation to their degree of perception regarding the issues related to climate change. The index ranged from 0 to 1. The high, medium and low degrees were delimited considering the responses of the producers to the six questions used for the elaboration of the CCPI, listed in table 3.

Table 3 – Questions used to elaborate the CCPI

1) What is your degree of concern about climate change?
2) Do you think that changes are occurring in the rainy season of your region in the last ten years (decreased; increased; change of the season and diminished; changed of the season and increased; not changed)?
3) Do you think there are changes in the temperature of your region in the last ten years (No; Yes: increased; Yes: decreased)?
4) Would you be willing to change some of your personal habits (unrelated to production) to contribute to combating climate change?
5) Would you be willing to change some of your productive techniques, even without receiving financial support for this, to contribute to combating climate change?
6) When choosing someone to vote for, do you consider the environmental proposals of the candidate?

Source: own elaboration based on the results of the research.

The AFB presents the CCPI slightly higher than that referring to the AMB (Not Significantly different), indicating that the average producers' perception of the DUs in relation to climate change is similar between the biomes (Figure 7). This result can be said to be unexpected, given the best socioeconomic parameters and the best quality of the infrastructure presented by the municipalities of the SRP/MA, which they also show better performance in income and education indicators in relation to SRP/AM municipalities.

The socio-economic analysis presented in section 2 of this document indicates that the social and economic infrastructure of the regions can influence the performance of SRP since producers oriented by the environmental issue tend to adopt techniques or be an example for other producers in the region. Moreover, it is verified a considerably larger number of DUs in the AFB, an average of 46 DUs per state, against 30 DUs per AMB state, evidencing that the socio-economic infrastructure is a differential for the dissemination of sustainable production techniques. Table 4 shows the ranking of the average CCPI per state.

Table 4 - Ranking of states with municipalities participating in SRP

State	CCPI average (CP1)
Rio Grande do Sul	0,72
Mato Grosso, Brazil	0,68
Minas Gerais	0,64
Stop	0,57
Paraná	0,52
Rondônia	0,50
Bahia	0,42
Total average	0,57

Source: own elaboration based on the results of the research.

The aggregate result of the indicator is quite representative as to the effect highlighted earlier. However, the result by state from Table 6 surprises, when considering those socioeconomic and infrastructure parameters, due to the positions, for example, of Mato Grosso and Pará figuring ahead of Paraná.

Age Profile: The producers with the highest environmental perception degree indicated by the CCPI are older, about 66% of the producers are in the range of 45 to 65 years, whereas, among the producers with low perception level, 54% are in the range of 35 to 55 years.

Education: There is a positive relationship between the years of study and the environmental perception degree. Of the classified with high CCPI, there is a higher participation of producers with higher education and high school degree, completed and incomplete, compared to those classified with low CCPI. The latter, with a greater presence of illiterate and only literates.

Technologies: The producers of DUs with a high degree of CCPI use more RAD-P and RAD-F technologies, no-tillage system, biological nitrogen fixation and treatment of animal manure (table 5). The last is still little used by producers with low CCPI, which stand out by the use of ILPF/SAFS systems. It is noteworthy that, among the 8 (eight) technologies, the producers with a high degree of CCPI stand out as the largest producers adopting in five (5) of them, evidencing a greater diversification in relation to other producers. When the variable of interest is the time of use, the producers with high CCPI showed a higher percentage of DUs using at least one of the techniques for more than 20 years, and most of the producers of this Group use for 10 years or more.

Table 5 – use of the technologies supported by SRP by CCPI degree

Technologies	CCPI		
	High	Middle	Low
RDA with Pasture	64,9%	49,1%	48,2%
RDA with Forests	44,6%	24,6%	21,2%
iLPF and/or SAFs	55,4%	55,3%	63,5%
No-tillage system	33,8%	22,8%	23,5%
Biological nitrogen fixation	21,6%	11,4%	12,9%
Planted forests	28,4%	30,7%	30,6%
Animal manure Treatment	14,9%	14,0%	08,2%
Natural forest management	20,3%	21,1%	16,5%

Source: own elaboration based on the results of the research.

4 – Typology of producers

Producer Type 1: The first group, containing 109 DUs, is the one with the producers who perhaps have not yet perceived in a profound way climate change. Most of the interviewees in AMB are part of this group (just over 52%), as well as almost half of the women interviewed. 75% of the illiterate producers interviewed are type 1. More than 60% of the DUs without a family worker is led by a type 1 producer. In addition, only in this first group, it is possible to find more than half of the producers as non-unionized. More than half of the interviewed producers who are unaware of the ABC Plan (52.46%) or low CO2 emission technologies (72.22%) or Brazilian environmental legislation (56%) is part of this group. The Type 1 producer is still the one who most reports that none or few of the producers with whom he/she has more contact adopt low emission technology. Most of those who do not perceive changes in precipitation (66.67%) or temperature (80.95%) are also in this first group. As for the CCPI, the type 1 producer tends to present a low value for this index of perception.

Producer Type 2: The second group, in turn, brings the 97 most conscious owners in relation to global climate change. Approximately 75% of this group is in the AFB. Most type 2 producers have internet access or television. Undoubtedly, the use of low CO_2 emission technologies was more widely found among the type 2 producers. Also, in this group are those producers who most reported that all or many of their peers adopt some or even the same low emission technology adopted. Approximately 64% of this group always takes the candidate's environmental policy into account when voting (against only 2% never doing so). The type 2 producers are those who are most willing to change their practices, whether technical or personal, to adapt or mitigate climate change. Finally, type 2 producers, in general, have high values of CCPI.

Producer Type 3: The third group of producers is composed of 67 owners of DUs who, despite realizing the changes in terms of precipitation and temperature and thus worrying about climate change; have not yet succeeded expressing such perception and concern. Manifestation in terms of personal provisions of change (either personal or technical) or even in terms of practice, when in electoral periods. It is important to emphasize that almost 30% of the producers in this group never take into account the candidate's environmental policy when voting, while only a little more than 2% of them always.

5 – International Climate Fund Key Performance Indicator # 3: Number of forest-dependent people whose livelihoods were protected or improved due to ICF projects

The Key Performance Indicator (KPI) focuses on the socio-economic impacts of forest-sector interventions and seeks to understand “the number of forest-dependent people whose livelihoods were protected or improved” by a programme spending International Climate Finance (ICF), as the Sustainable Rural Program (SRP).

The SRP was implemented in areas whose advancement of land use over the native forests of the Amazonian and Atlantic Forest (Mata Atlântica) biomes is growing. That is, areas sensitive to deforestation. In this sense, the people affected by the program are directly or indirectly dependent on activities that relate to the native forests of the respective biomes. It is also reiterated that one of the objectives of the project is to establish sustainable technologies for the maintenance of these areas.

To measure the number of people who had their livelihood maintained or improved by the program (Table 6), two categories of benefits provided by SRP were established: **i) financial benefits** and **ii) in-kind benefits** or not financial. The first category includes people who have benefited directly from the program through the payment of resources for participation such as DUs, MUs or Technical Assistance Agents (TAAs). The second category refers to people who have benefited directly or indirectly by some program activities, such as field days, family workshops, thematic seminars and training, being measured by the participation number. In addition to the DUs, MUs, and TAAs, which may have participated in more than one event, the category counts other individuals who also participated in such events, even if they were not participants of the SRP. The second category encompasses the first.

Table 6 – *Number of forest-dependent people whose livelihoods were protected or improved due to the ICF project*

Benefits	Total
i) Financial	18.570
ii) In-kind	39.321

Source: own elaboration based on the results of the research.

Box 1 – Core Concepts Central to this Special Report

Perception:	Producers participating in SRP perceive the effects of climate change even if they lack the specific technical knowledge to deal with the phenomenon.
Key Factors:	Technical assistance is indicated as an essential factor for the adoption of low CO2 technologies. Rural Credit allows the implementation of technologies through the hiring of technicians and inputs required. It is also indicated as a determinant factor.
Technologies:	The greater the perception of the producer in relation to climate change, the more diverse is the use of sustainable technologies. iLPF/SAFs are the most widely used technologies. Most used technologies are those that use more manpower and/or are those that are directly geared towards the production of good marketable.
Infrastructure:	Social and economic infrastructure contributes to the environmental producers' perception and to the dissemination and use of technologies.
Impacts on people - KPI 3:	39,321 people were directly or indirectly impacted by the SRP.

Source: Own elaboration based on the results of the research.

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ANEXO 3

ARTIGOS E DOCUMENTOS PUBLICADOS

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ORIGINAL ARTICLE

GRASSLAND SCIENCE
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Nitrous oxide emissions and forage accumulation in the Brazilian Amazon forage-livestock systems submitted to N input strategies

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Abstract
In the Brazilian Amazon, nitrogen input strategies are required to maintain forage–livestock systems productivity. However, greenhouse gases (GHG) emissions mitigation from tropical soils is also a global demand. This research aims to assess productivity and nitrous oxide (N_2O) emissions from Oxisol cultivated with Marandu palisade grass (*Brachiaria brizantha* [Hochst. Ex A.Rich.] Stapf) submitted to nitrogen (N) input strategies (N fertilization and biological N fixation) in the Brazilian Amazon. The treatments were the following: control (unfertilized); U40 (fertilized with 40 kg N/ha as urea); U80 (fertilized with 80 kg N/ha as urea); AS40 (fertilized with 40 kg N/ha as ammonium sulfate); AS80 (fertilized with 80 kg N/ha as ammonium sulfate); and IAB (inoculated with *Azospirillum brasilense*). From January to March 2016, soil N_2O emission, forage accumulation (FA) and relative emission (RE) were assessed during two 28-day cycles. The FA was greater in the U80 and AS80 than in control and IAB. The highest peaks of soil N_2O flux occurred from 4 to 7 days after N fertilization, primarily in the highest N rates treatments. Overall, 40 kg N/ha resulted in higher N_2O flux than control and IAB, which were lower than 80 kg N/ha regardless of the N source. The lowest fluxes occurred in the control and IAB (below 20 μg $N\text{-}N_2O\ m^{-2}\ hr^{-1}$). All of the emission factors (EF) calculated for both fertilizers and rates were lower than 0.35%, which is below the 1% established by the IPCC. Our results indicate the need for discussion of the EF in the pasture intensification to contribute to avoid deforestation and mitigating emissions. The inputs of 40 kg N/ha per application with urea or ammonium sulfate, due to the low EF and RE, are recommended as a pasture N input strategy in the Brazilian Amazon.

KEYWORDS
climate change, fertilization, livestock, mitigation

1 | INTRODUCTION

The beef cattle production in Brazilian Amazon is a pasture-based system that uses forage plants of high productive potential; however, due to inadequate management and low fertilization input, forage plants lose productivity a few years after pasture establishment (Dias-Filho, 2011). In addition, the current lack of management in livestock systems conducted under Amazon's edaphoclimatic conditions may result in advanced pasture and soil degradation (Macedo 1999).

The production systems intensification has been highlighted as an alternative to avoid pasture degradation while focusing on sustain forage productivity and improving system efficiency (Pedreira & Pedreira, 2014). This strategy involves nutrient replenishment in soil via fertilization or biological agents responsible for extracting more nutrients from the soil and biological nitrogen (N) fixation that may became available for plants (Hungria, Nogueira, & Araujo, 2016). Due to the low natural fertility of Amazon soils, frequent nutrient replenishments are imperative for soil maintenance and improvement (Dias-Filho, 2015), and the fertilization strategies impact should be constantly evaluated, as well as their effects on the environment (Peters et al., 2012).

Fertilization using N sources, mainly urea and ammonium sulfate, is considered an important strategy to increases forage accumulation(FA) in pasture-based systems (Martha Júnior, Vilela, & Sousa, 2007). On the other hand, N fertilization is responsible for increasing soil nitrous oxide (N_2O) emission, which contributed, in 2011, for 14% of the total greenhouse gases (GHG) emissions from the agricultural sector worldwide (Tubiello et al. 2014). Nitrous oxide has a global warming potential 298 times greater than carbon dioxide (CO_2) and is involved in deleterious chemical processes to the ozone layer (IPCC 2013). Among the mitigation strategies for the soil N_2O emissions, the N fertilizer sources with low emission potential and with more efficiency, and/or the biological agents to N fixation, can replace or decrease N fertilizers application and reduce N_2O emission (Smith et al., 2008).

Biological N fixation using *Azospirillum brasilense* inoculation in grasses has become a promising practice for increasing forage productivity (Pedreira et al., 2017). Unlike biological N fixation in leguminous plants, in which there is a mutualistic relationship, N fixation in grass is intermediated by endophytic bacteria, which provide part of the N fixed to the associated plants (Hungria et al., 2016). Although less efficient, N fixation in grasses can mitigate N_2O emissions by reducing the need for mineral fertilizers (Hungria et al., 2016; Smith et al., 2008).

Overall, when evaluating only the N_2O emissions, fertilized agricultural systems have emitted more N_2O than unfertilized systems (Soares et al., 2016; Uchida & Clough, 2015), indicating that system intensification could generate a greater environmental impact. For this reason, the productivity should be considered when analyzing the influence of N input strategy on the GHG emissions (Burney, Davis, & Lobell, 2010).

Based on that, we hypothesize that N input strategies will enhance FA, although each strategy will present a different N_2O emission factor, and this knowledge contributes to developing sustainable forage-based systems. In order to test this hypothesis, we assessed FA and N_2O emissions from Oxisol cultivated with Marandu palisade grass (*Brachiaria brizantha* [Hochst. Ex A.Rich.] Stapf) pasture submitted to N input strategies (N fertilizer and biological N fixation) in the southern Brazilian Amazon.

2 | MATERIAL AND METHODS

2.1 | Field experiment

The experiment was carried out in the Amazon Biome at Embrapa Agrossilvipastoril, Sinop, Mato Grosso (latitude: 11°50'53" S - longitude: 55°38'57"W). The soil of the experimental area was classified as Oxisol (Hapludox) occurring in a flat relief (Soil Science Division Staff, 2017). The climate was classified according to the Koppen Climate Classification System as an Am monsoon climate, which alternates between a rainy and a dry season (Alvares, Stape, Sentelhas, Moraes Gonçalves, & Sparovek, 2013), with an average annual temperature of 25.5°C (20.2 °C minimum and 33.0°C maximum average temperatures). Average annual relative air humidity is 70%, with 2,250 mm of annual precipitation (Embrapa, 2017). Weather data were obtained from a record station located 500 m from the experiment site.

The experimental area was established with Marandu palisade grass intensely grazed during 2 years without fertilization to achieve a moderate degradation stage. Besides that, the area was divided into 18 plots (3 x 3 m), in a randomized complete block design with six N inputs strategies (treatments) and three replicates. The treatments were the following: control (unfertilized); U40 (fertilized with 40 kg N/ha as urea); U80 (fertilized with 80 kg N/ha as urea); AS40 (fertilized with 40 kg N/ha as ammonium sulfate); AS80 (fertilized with 80 kg N/ha as ammonium sulfate); and IAB (inoculated with *Azospirillum brasilense*).

To evaluate the N input strategy effect, two cycles of 28 days in the middle of the growth season were evaluated: cycle 1—from January 13 to February 10 and cycle 2—from February 11 to March 10, 2016. The urea (45% N) and ammonium sulfate (21% N) were applied manually on January 15 and February 12, on soil surface using the granular formula. The inoculation was sprayed on the post-harvest sward, at the same dates, using *Azospirillum brasilense* (2×10^8 colony forming unit/ml, strains AbV5 and AbV6) at a rate of 300 ml/ha diluted by a volume of 200 L/ha.

2.2 | Forage accumulation and relative forage accumulation

At the beginning of the experiment, all plots were harvested at 15 cm sward height. In each cycle, forage mass (FM) was quantified at pre-harvest by sampling the forage inside two quadrats (0.5 × 1 m) at 15 cm height. Forage mass harvested above 15 cm at the end of each cycle was used to calculate FA. Samples were dried at 55° C in a forced-air dryer until constant weight and weighed. The relative forage accumulation (RFA) was obtained by deducting control FA from the U40, U80, SA40 and SA80 values.

2.3 | Soil N_2O emissions

Gas samples were collected using rectangular vented static chambers (Parkin & Venterea, 2010). The metal chamber bases (5 cm height x 40 cm width x 60.5 cm length) were installed in the soil at a depth of 5 cm. The tops were constructed using polypropylene trays (9.2 cm height x 40 cm width x 60.5 cm length) coated with a double-sided thermo-reflective blanket to reduce the internal temperature of the chamber. Samples were collected over a 60-min period, with

4 samplings (0, 20, 40 and 60 min) between 8 and 10 a.m. (Parkin & Venterea, 2010). For sampling, 20 cm^3 polypropylene syringes were used with three-way couplings to avoid atmospheric air contamination. Samples in the syringes were transferred to 20 cm^3 glass bottles (vials), previously evacuated in the laboratory. Gas samples were collected daily during the first 15 days of each cycle, starting 2 days prior to fertilization. After 15 days, samples were taken every 5 days.

The sample gas concentrations were determined in a gas chromatograph (GC-2014, Shimadzu®) using an electron capture detector (ECD), for nitrous oxide quantification. The chromatograph system is fitted with Hayesep 80/100 mesh (1/8 "x 2.1 mm), T, D and *N* (two) series columns of 1, 2 and 1.5 m, respectively, and maintained at 75°C. Ultrapure nitrogen was used as the tracer gas at a flow rate of 25 ml/min, and injector pressure was maintained at 300 kPa. The injection volume was 1 ml, and the total analysis times were 5 min. In order to quantify the N_2O concentrations, three known standard concentrations of 382, 808 and 2,027 ppb were used in the chromatograph.

Based on the analytical results, it was possible to adjust the linear model by relating the variations in N_2O concentrations within the chamber as a time function (0, 20, 40 and 60 min). These data were then used to calculate N_2O flux from the soil to the atmosphere following the equation proposed by Hutchinson and Livingston (2001): Flux (µg N m^2 hr^{-1}) = (dC/ dt) x V/ A x (m/ vm), where dC/ dt = change in gas concentration in the chamber as a function of time; V = chamber volume (L); A = area of the chamber (m^2); m = molecular weight (g); and Vm = molecular volume of the gas (L). Flux results were used to estimate the cumulative gas emissions over the evaluation period using the trapezoidal integration principle (Klein et al., 2015).

The EF, which considers the amount of N_2O emitted from the soil in relation to the amount of N applied, was calculated for urea and ammoniac sulfate treatments, as follows:

$$\frac{\text{EF}\ (\%) = \text{kg of N} - \text{N}_2\text{O in treatment} - \text{kg of N} - \text{N}_2\text{O in the control}}{\text{kg of N applied} \times 100}$$

To determine the relative emission (RE), which is the ratio between total N_2O emissions and FA, RFA (previously described) was divided by accumulated emissions.

2.4 | Soil analysis

Disturbed soil samples from each treatment were collected from the 0–5 and 5–10 cm layers on the days 0, 2, 4, 6, 10, 14, 19, 24 and 28 of each cycle to determine the following attributes: gravimetric humidity, pH and inorganic forms of *N* (exchangeable ammonium and nitrate). Half of the sample volume collected in the field was stored in a freezer at −16°C to avoid transformations of mineral N in the soil until analysis (Li et al., 2012). Thereafter, 25% of the sample was used to determine gravimetric moisture and another 25% was air-forced dryer and sieved through 2-mm mesh, which was used for pH determination and for initial soil characterization.

Undeformed soil samples were collected in cylinders (98 cm^3) at the beginning of each cycle to determine soil bulk density, which, together with gravimetric moisture and particle density data, was used to calculate the water-filled pore space (WFPS) of the soil (Linn & Doran, 1984). Since soil particle density is a stable short-term attribute, it was determined at the onset of the experiment in triplicate at each studied depth (Embrapa, 2011), which revealed a result of 2.40 g/cm^3 and 2.69 g/cm^3 at depths of 0–5 and 5–10 cm, respectively. The pH was determined in water (deionized) using a soil:water ratio of 1:2.5. The 0–5 cm layer had 37%, 8% and 55%, while the layer of 5–10 cm had 37%, 7% and 56% of clay, silt and sand, respectively, resulting in a clayey texture for both layers (Santos et al. 2013). Cation exchange capacity, base saturation and aluminum saturation were determined according to Embrapa (2011) and presented 7.01 $cmol_c$/kg, 55% and 0% for the 0–5 cm layer, and 7.28 $cmol_c$/kg, 48% and 0% for the 5–10 cm layer, respectively. Total soil carbon (C) and N was determined using a dry combustion element analyzer (®Elementar Analysensysteme, GmbH) and revealed 3.24% C and 0.22% N for the 0–5 cm layer, and 2.10% C and 0.13% N for the 5–10 cm layer, respectively.

For the mineral N extraction (NH_4^+ and NO_3^-), 1 mol/L KCl solution was used at a soil:solution ratio of 1:5, stirred for 30 min and centrifuged at 3,800 *g* rpm for 5 min and then at 18,700 *g* rpm for 5 min, thus obtaining a limpid extract (Cantarella & Trivelin, 2001; Li et al., 2012). Centrifugation was used instead of filtration following recommendations of Cantarella and Trivelin (2001), which pointed out N contamination in extracts due to the use of filters. One day prior, samples were removed from the freezer to thaw in a refrigerator at 4°C. The determination of NH_4^+ and NO_3^- was performed using the colorimetric method (Sattolo, Otto, Mariano, & Kamogawa, 2016).

2.5 | Statistical analysis

Forage accumulation data were analyzed using a mixed models method with parametric structure in the covariance matrix, through the MIXED procedure of the statistical software SAS (SAS Studio, v. 9.4) (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006) with repeated measurements and using the maximum likelihood-restricted method (REML). Block and block × treatment interaction was considered as random effect, treatment and cycle as fixed effect. The covariance matrix used was the Akaike information criterion (AIC) (Wolfinger, 1993), and the correction of degrees of freedom was made using the method of Satterthwaite (1941) (DDFM = SATTERTHWAITE). The treatment means were estimated by least squares mean (LSMEANS), and comparison was performed using the probability of the difference (PDIFF) of Student's *t* test ($p < .05$).

The average and standard error was determined for daily N_2O flux, average N_2O flux of each cycle and for the entire experimental period, as well as for the RE, inorganic N and WFPS, since these data did not exhibit a normal distribution. Emission factor data were submitted to the variance analysis and, when significant, the Tukey test was applied at 5%.

3 | RESULTS AND DISCUSSION

Forage accumulation differed for strategies (p = .0114; Figure 1), but there was no cycle (p = .8248) or cycle × treatment interaction (p = .5025) effects. Once the essential nutrients do not limit the grasses growth potential, the N available will contribute to increasing FA. The greater N rate contributed to increased leaf area index, leaf and canopy photosynthesis rates and FA (Yasuoka et al., 2018). It occurs because N is a component of chlorophyll, an enzyme responsible for photosynthesis (Rubisco) and proteins (Taiz & Zeiger, 2013), which drives the process of energy capture and CO_2 fixation of by plants. Thus, biomass enhancement depends on leaf area development driven by cellular expansion and photosynthetic efficiency (Martins, Monteiro, & Pedreira, 2015).

In this scenario, FA was greater in the U80 and AS80 than in control and IAB. The U40 and SA40 presented FA intermediated to all N inputs strategies. Fertilization with higher rates may result in greater FA; however, the N source could also drive this process (Bourscheidt, Pedreira, Pereira, Zanette, & Devens, 2019). Although we would expect more FA using AS source, once it has sulfur (23%) in addition to *N* (Chien, Gearhart, & Villagarcía, 2011), in our study, there was no N source effects on FA at the same rates. Furthermore, the values obtained in this experiment are similar than those reported by Pedreira et al. (2017) in Marandu palisade grass pasture inoculated with *A. brasilense* or fertilized with 40 kg N/ha using urea in Oxisol dystrophic soils.

The foliar application of *Azospirillum brasilense* did not contribute to increase FA, which presented values similar to the control. Lower nitrogen availability can affect root development, photoassimilate production and, consequently, reduce the growth rate (Gimenes et al., 2017). Probably, the bacteria would need longer period to colonize and offers nitrogen inputs to the plant.

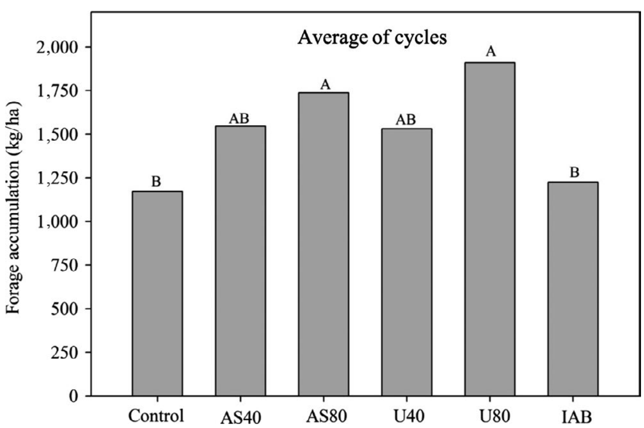

FIGURE 1 Forage accumulation (kg/ha, average of cycles) in pastures under N input strategies in the Brazilian Amazon. U40 (40 kg N/ha as urea); U80 (80 kg N/ha as urea); AS40 (40 kg N/ha as ammonium sulfate); AS80 (80 kg N/ha as ammonium sulfate); and IAB (Inoculated with Azospirillum brasilense). Means followed by a common uppercase letter in the bar are notdifferent by t test (p < .05)

Marandu palisade grass under pasture intensification strategies highlights the contribution to the N_2O emissions from Oxisol in the edaphoclimatic conditions of the Brazilian Amazon. Average soil N_2O flux (μg N m^2 hr^{-1}) in cycle 1, cycle 2 and in the average of the two cycles was higher in pastures fertilized with 80 kg N/ha as urea (Figure 2). Average soil N_2O flux in other treatments with N fertilization (U80, AS40 and AS80) did not differ in cycle 1. In cycle 2 and in the average of the two cycles, soil N_2O flux differed between AS40 and AS80. The flux in all cycles, including the average of both cycles, were similar in AS80 and U40, with values between 15 and 30 μg N m^{-2} hr^{-1}. The flux in U40 or AS40 did not differ in either cycle or in the average of the two cycles. The high N_2O fluxes from N fertilized soils are because the denitrification pathway, which would not be possible without soil moisture (precipitation) during this period. The difference in N_2O emissions between U80 and AS80, which was similar to AS40 and U40, is an important point that needs to be clarified. As the edaphoclimatic conditions were similar to both N rates, the different N_2O fluxes at the same N rate may be due to the fertilizer reactions in soils. Urea has an alkalizing hydrolysis which increases the nitrite accumulation, leading to higher N_2O emissions if compared to AS (Tierling & Kuhlmann, 2018).

The lowest average flux was measured in the control and inoculation treatments, with all values below 10 μg N m^{-2} hr^{-1}. Although, in cycle 1, the AS40 soil N_2O flux (14.4 μg N m^{-2} hr^{-1}) was similar to the control (8.4 μg N m^{-2} hr^{-1}). The low soil N_2O fluxes in control and IAB are due to the absence of the mineral N application. It highlights the low N mineralization in Oxisol, decreasing N availability to follow the nitrification/denitrification processes responsible for N_2O formation in soils (Butterbach-Bahl, Baggs, Dannenmann, Kiese, & Zechmeister-Boltenstern, 2013).

In the two cycles, the highest peaks of soil N_2O flux occurred a few days after N fertilization (Figure 3), and largely in the treatments with the highest N rates. The highest N_2O flux peaks were measured in U80, with values up to 140 and 90 μg N-N_2O m^{-2} hr^{-1} for cycles 1 and 2, respectively. In the AS80, the maximum peaks were up to 50 and 40 μg N-N_2O m^{-2} hr^{-1}, in cycles 1 and 2, respectively. At the rate of 40 kg N/ha, flux dynamics were similar for both fertilizers sources. The lowest fluxes were measured in the control and IAB, with values predominantly below 20 μg N-N_2O m^{-2} hr^{-1}.

The emissions were greatly until 10–12 days post-fertilization. In cycle 1, on the first day after fertilization, the flux increased for all N fertilization treatments; however, in cycle 2, this only occurred after the second day. The highest in N_2O flux increments started to occur at days 2 and 3 post-fertilization. Twelve days after fertilization, the fluxes were similar among treatments, which were equal to those on pre-fertilization period (values below 20 μg N-N_2O m^{-2} hr^{-1}). Similar to other studies, the duration of high soil N_2O flux and the flux level depend on the N rate which affects, with the environmental conditions, the inorganic N availability (Soares et al., 2016; Tierling & Kuhlmann, 2018). It demonstrates that under Brazilian Amazon

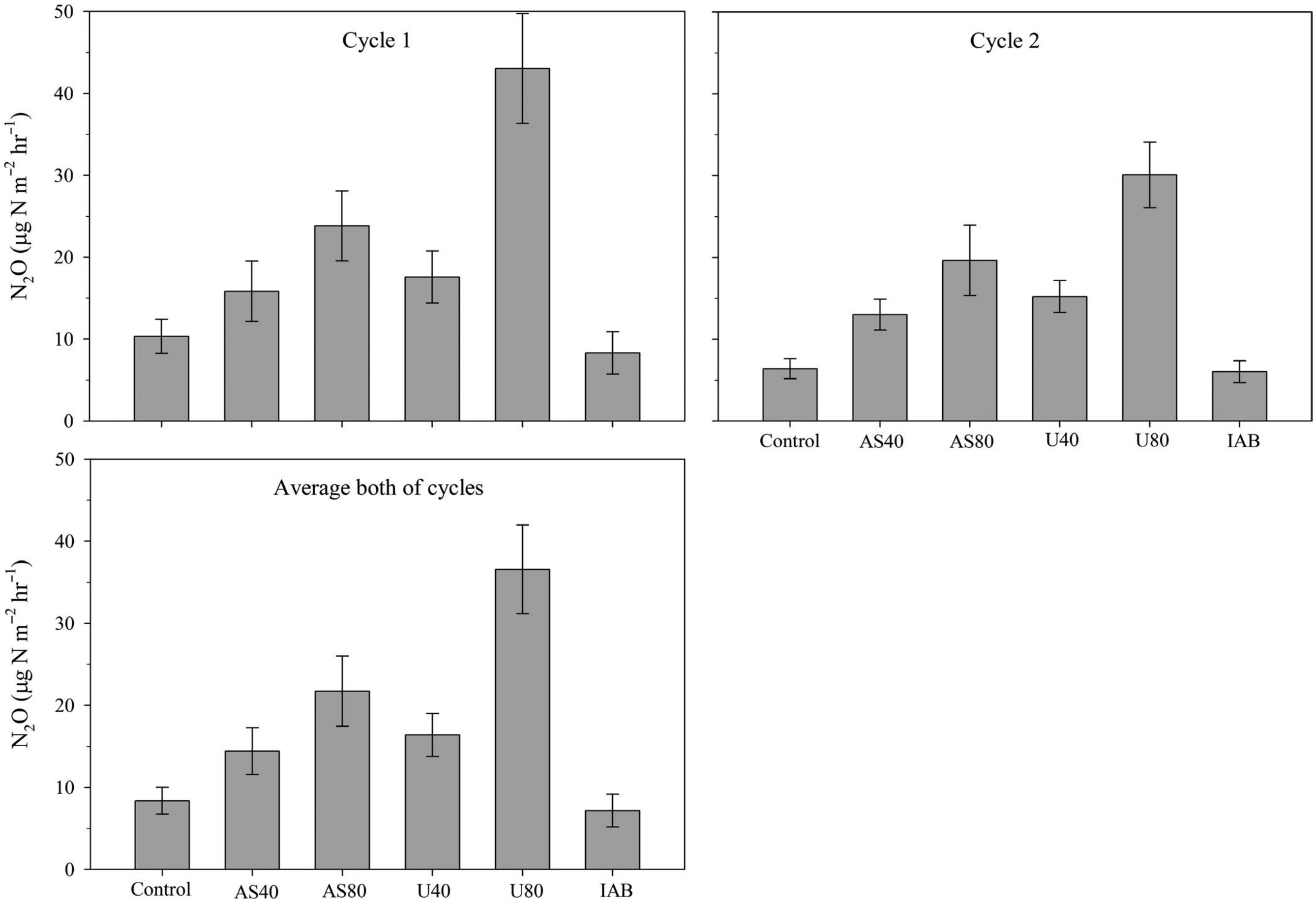

FIGURE 2 Average soil N_2O flux (µg N-N_2O m^{-2} hr^{-1}) under N input strategies in cycle 1, cycle 2 and the average of cycles in the Brazilian Amazon. Vertical bars correspond to the mean standard error. U40 (40 kg N/ha as urea); U80 (80 kg N/ha as urea); AS40 (40 kg N/ha as ammonium sulfate); AS80 (80 kg N/ha as ammonium sulfate); and IAB (Inoculated with Azospirillum brasilense)

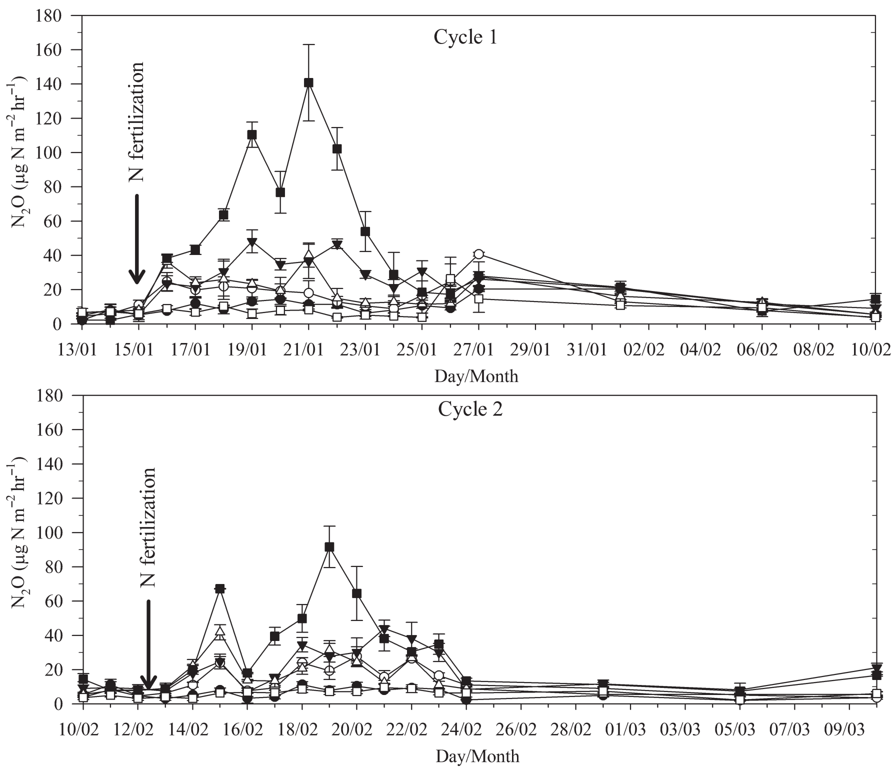

FIGURE 3 Soil N_2O flux (µg N-N_2O m^{-2} hr^{-1}) under N input strategies in the Brazilian Amazon

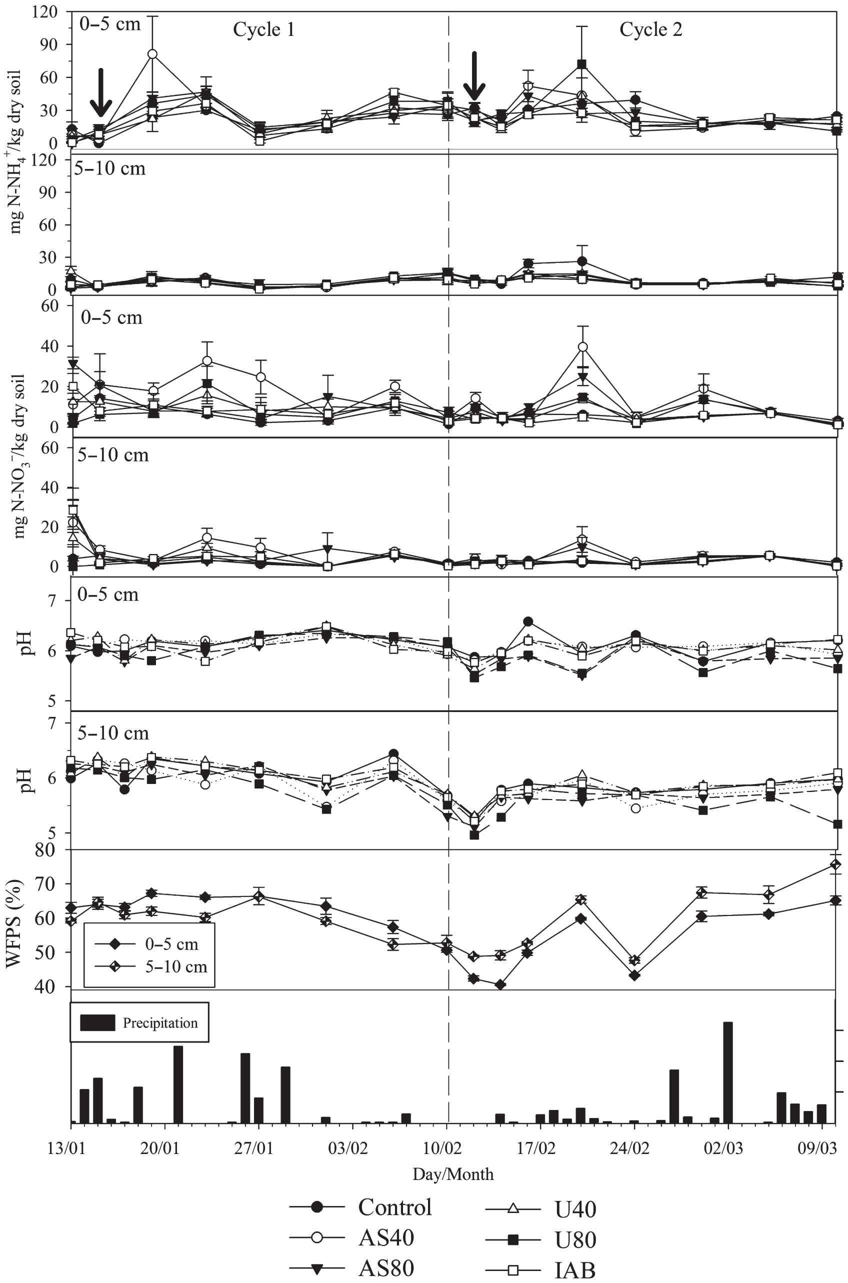

FIGURE 4 Mineral nitrogen availability (nitrate and ammonium), pH and water-filled pore space (WFPS) in the soil layers at 0–5 and 5–10 cm, and rainfall in pastures N input strategies in the Brazilian Amazon.U40 (40 kg N/ha as urea); U80 (80 kg N/ha as urea); AS40 (40 kg N/ha as ammonium sulfate); AS80 (80 kg N/ha as ammonium sulfate); and IAB (Inoculated with Azospirillum brasilense)

edaphoclimatic conditions, the influence period of the N fertilization would be up to 2 weeks, depending of the precipitation.

In treatments receiving higher N rates (AS80 and U80), the highest flux peaks in cycle 1 may have been caused by higher rainfall (233 mm) than in cycle 2 (191 mm). The higher rainfall during cycle 1 provided, on average, a higher and more constant WFPS than during cycle 2 (Figure 4), suggesting a greater influence of denitrification on N_2O flux, which occurs when the soil has less oxygen (Van der Weerden, Kelliher, & Klein, 2012). However, this process only occurred following the fertilization input, which indicates that even in soil with more oxygen (as in the end of cycle 2), no soil N_2O emission occurs without mineral N being available.

The mineral N availability in the soil was similar among treatments (Figure 4). Although the availability of NH_4^+ and NO_3^- in the 0–5 cm layer was higher than in the 5–10 cm layer. In the AS40, the higher N availability in the 0–5 cm layer was observed 4 days after fertilization. In fact, the highest N rates treatments (80 kg N/ha) did not present a greater mineral N availability, a phenomenon that should be studied further. Since the present study fertilizers were manually distributed on the soil surface, partial surface runoff could have occurred, resulting in nutrient removal from the pasture (Burkitt, 2014). Furthermore, low N content may be related to its fast processing rate by microorganisms once the humidity and temperature conditions become adequate for nitrification and denitrification processes (Butterbach-Bahl et al., 2013). Future studies should elucidate N changes in the soil, enhancing the soil sampling frequency to improve the understanding of the N dynamics processes.

In cycle 1, the 0–5 cm soil layer in pastures fertilized with AS40 presented the highest NH_4^+availability of approximately 70 mg N/kg on January 19 and, after 4 days (January 23), exhibited a greater

TABLE 1 Ammonium sulfate (AS) and urea (U) emission factors at rates of 40 and 80 kg N/ha in cycle 1, cycle 2 and the average of both cycles of Marandu palisade grass pastures in the Brazilian Amazon

Treatment	Cycle 1	Cycle 2	Average
	%		
AS40	0.100b	0.088b	0.108b
AS80	0.173b	0.205ab	0.189b
U40	0.086b	0.088b	0.126b
U80	0.318a	0.286a	0.321a

Note: Averages followed by the same letters in the column of each cycle do not differ by Tukey's test at 5% probability.

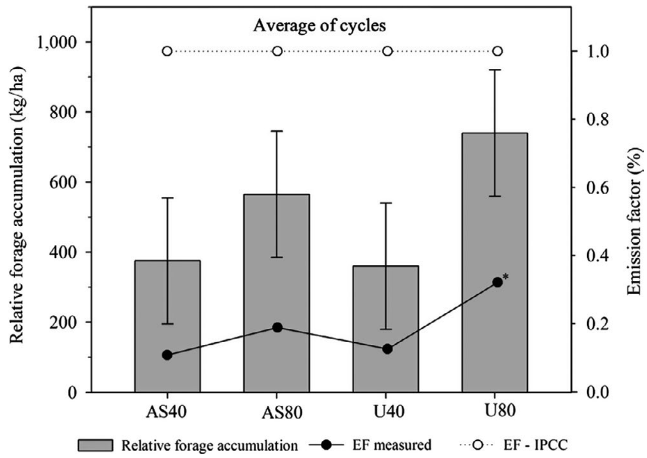

FIGURE 5 Relative forage accumulation (kg/ha) and emission factors (EF, %) in pastures under N input strategies in the Brazilian Amazon (* differs by Tukey's test at 5% probability). U40 (40 kg N/ha as urea); U80 (80 kg N/ha as urea); AS40 (40 kg N/ha as ammonium sulfate); AS80 (80 kg N/ha as ammonium sulfate); IAB (Inoculated with Azospirillum brasilense); and IPCC (Intergovernmental Panel on Climate Change)

availability of NO_3^- (30 mg N/ha). This was not expected, since there was greater N rate; however, it indicates the occurrence of the nitrification process, which transforms N-ammoniac into N-nitric and must have been incorporated in N_2O emission via denitrification. This process is driven by the favorable conditions identified in cycle 1 (e.g., high WFPS), leading to microsites under anoxic soil conditions (Van der Weerden et al., 2012). The nitrification process was also observed in cycle 2, since the NO_3^- availability increased only after fertilization, and exhibited higher NH_4^+ availability, which was primarily due to enhanced rainfall. However, the nitrification process can be inhibited by grasses (Byrnes et al., 2017; Subbarao et al., 2012), which do not discard the low levels of N-nitric affected by Marandu palisade grass, especially with the ammoniacal fertilizers application that stimulates the production of biological nitrification inhibitors in grasses (Peters et al., 2012; Subbarao et al., 2012).

Notably, the WFPS values support an important role of moisture in N_2O emissions (Van der Weerden et al., 2012). In cycle 1, with higher WFPS in the 0–5 cm layer compared to the 5–10 cm layer, the emissions were higher than in cycle 2. In cycle 2, in which the layer underlying the surface exhibited higher WFPS, lower N_2O emissions were measured, indicating that the N_2O emissions occurred mainly in the superficial layer due to the greater mineral N availability.

The pH of the two soil layers was also similar among treatments. The 0–5 cm layer presented a slight acidification a few days after fertilization, with the highest rates in cycle 2, regardless of the nitrogen source (Tierling & Kuhlmann, 2018). The treatments effect on soil pH in the 5–10 cm layer was also small; however, a decrease in pH occurred a few days after the reduction in the overlying layer.

Soils with the pH range measured in our study allowed for higher N_2O emissions than those with lower pH, since they presented greater nitrite (NO_2^-) accumulation (Tierling & Kuhlmann, 2018). This is due to the higher ammonia (NH_3) availability during the nitrification process, which impairs the microorganisms development (Nitrobacter) responsible for nitrite oxidation to nitrate (Venterea et al., 2015). Under these conditions, the ammonium oxidation processes occur; however, due to the microorganisms sensitivity to the NH_3 presence in a higher proportion than in a lower pH soil, nitrite accumulates and leads to a N_2O emission via nitrifier denitrification (Tierling & Kuhlmann, 2018; Wrage, Velthof, Beusichem, & Oenema, 2001). This explains, in the cycle 2, a flux peak of up to 70 µg N m^{-2} hr^{-1} occurred 3 days after fertilization in pastures fertilized with U80 despite low rainfall and subsequently lower WFPS (Figure 4). With the return of the rainfall between 4 and 7 days after fertilization (Figure 3), a greatest N_2O flux peak occurred, which was probably due to the denitrification process since soil WFPS increased to over 60%, supporting the environmental conditions for this process (Butterbach-Bahl et al., 2013).

The highest EF was calculated to the U80, in the cycle 1, 2 and in the average of the two cycles (Table 1). In cycle 2, with lower rainfall, the rate of 80 kg N/ha for both sources (AS80 or U80) presented the similar EF, with values of 0.2% and 0.3%, respectively. In the others treatments (AS40, AS80 and U40), the EF were similar regardless of source, rate and cycle. The greatest EF was measured in our study to the U80 (0.321%) represents about 30% of the default EF suggested by the IPCC (2006), which established a factor of 1%. Thus, for the national inventories, we suggested that the contribution of nitrogen fertilization to the soil N_2O emissions under Brazilian Amazonia's edaphoclimatic conditions should be lower than 0.35%. The Brazilian inventory could achieve even lower reported emission values if was possible to also takes into account the N fertilizer source and rate.

Moreover, it is important to highlights the link between EF and RFA. Overall, as rate was increased from 40 to 80 kg N/ha, the RFA and EF also were enhanced (Figure 5). However, the ratio between the amount of emitted N-N_2O (g/ha) and FA (kg/ha) during the study period allows the evaluation of the optimal strategy to increase FA while resulting in lower N_2O emissions from soil. In all cycles, including the average of the two cycles, U80 resulted in higher RE when compared to the U40 and SA40 (Figure 6). This

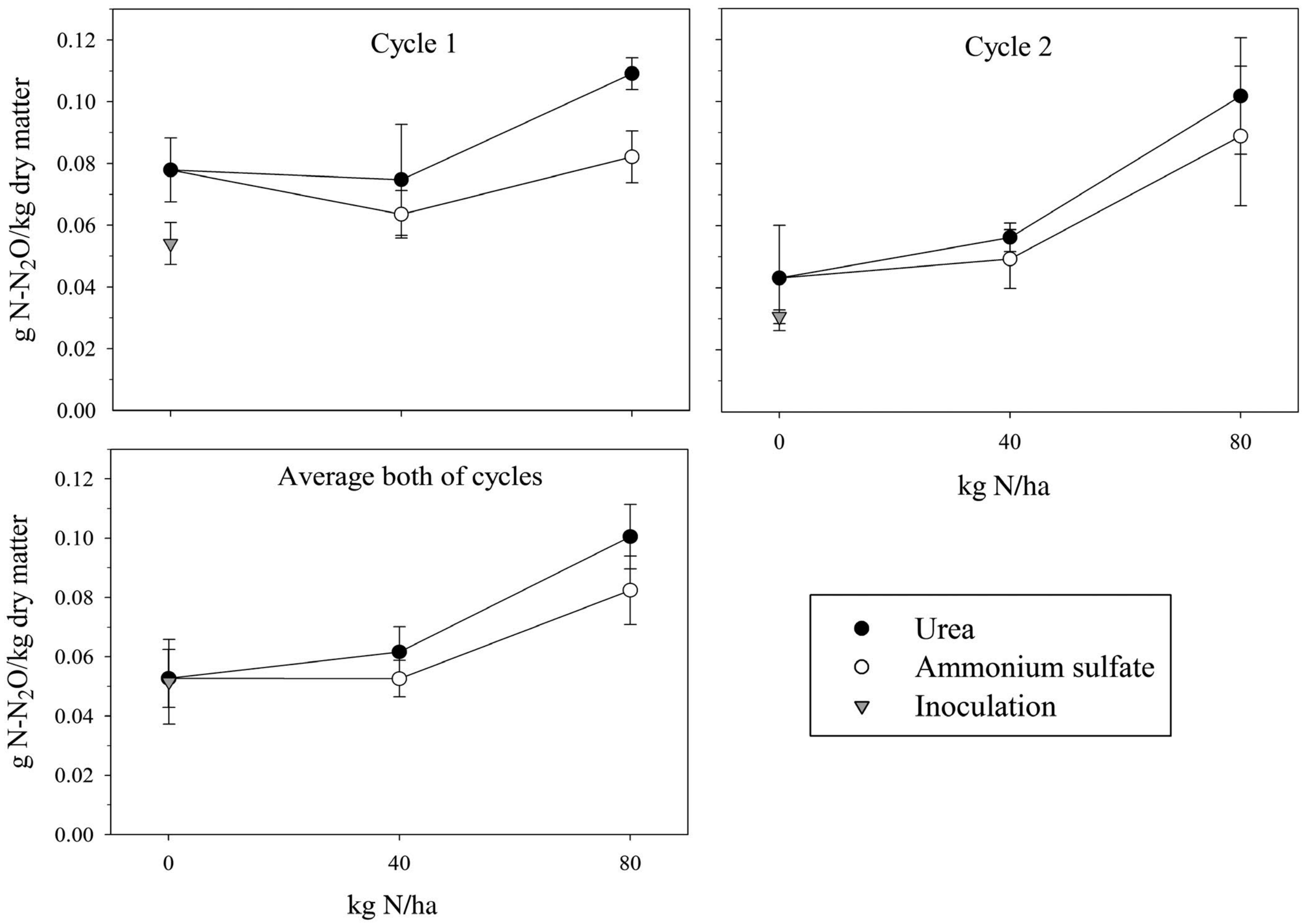

FIGURE 6 N_2o emission (g $N\text{-}N_2O$) per ton of dry matter produced in cycle 1, in cycle 2 and in two cycles (average) evaluated in an experiment of Marandu palisade grass submitted to N input strategies in the Brazilian Amazon

demonstrates the lowest efficiency of urea as nitrogen source at highest rates, because to accumulate a determinate amount of forage, the rate of 40 kg N/ha as urea or ammonium sulfate results in lower N_2O emission than 80 kg N/ha as urea. However, in the first cycle and on average of both cycles, AS80 resulted in the RE compared with the control. Thus, if high and well-distributed rainfall is expected, the application of AS80 could offer low N_2O emission and high productivity. This suggests that ammonium sulfate fertilization represents the best option, since it reflects greater FA in relation to control, specially at high rates. Profitability analyses should be performed to allow N input strategies decision-making in a production system.

The similar RE among the control and the 40 kg N/ha treatments in cycle 1, cycle 2 and the average of the two cycles suggests the application of both sources at this rate. This indicates that pasture fertilization strategy is highly recommended due to the greater potential to produce animal protein when compared with the control.

Excepted in the cycle 1, IAB resulted in the same RE as the control. In the cycle 2, IAB presented a lower RE than all N fertilizers; however, in cycle 1 and in the average of both cycles, RE IAB was similar to AS40 and U40. The IAB could be a N input strategy due to the similarity with the control; however, we should emphasize that foliar inoculation may not be the best application form for this technology (Pedreira et al., 2017). The seed inoculation during the pasture establishment should be tested for N_2O emissions and its relationship with grass productivity.

Based on the N_2O flux average and dynamics, EF, and RE, we affirmed that the optimal N input strategy for intensification of Marandu palisade grass pastures in the Brazilian Amazon would be at rate of 40 kg N/ha per application, using ammonium sulfate or urea. This would allow for increased FA with lowest N_2O emissions per unit of product when compared with highest fertilization rates. For the pastures management, a rate of 60 kg N/ha is the maximum recommended per application (Martha Júnior et al., 2007), which supports the results obtained by the our study focused on N_2O emissions. However, economic analyses were not included, it is recommended for each potential producer in each region, since prices can vary greatly according to the fertilizer industry distance (Pedreira, Pereira, & Paiva, 2013). For this reason, in some regions with even higher N_2O emissions, urea could be more economically advantageous than ammonium sulfate.

The adoption of 40 kg N/ha per application as a technologic tool could help mitigate GHG emissions, improving FA and, consequently, forage quality and animal production when compared to systems without fertilization (Tesk et al., 2018). Thus, sustainable pasture intensification will avoid new areas of natural vegetation being opened and incorporated as areas for agricultural production. Our data suggest that Brazilian Amazon has potential to support to forage–livestock systems with relatively high pasture productivity and low emissions that may minimize negative environmental impacts.

4 | CONCLUSION

The input of 80 kg N/ha using urea results in higher N_2O flux average and peak from soil, as well as a higher emission factor than 80 kg N/ha using ammonium sulfate and the 40 kg N/ha using urea and ammonium sulfate.

The application of 40 kg N/ha (urea or ammonium sulfate) is recommended as a pasture N input strategy in the Brazilian Amazon due to the lower emission factor and relative efficiency.

Further studies on inoculation should be performed, particularly with seed inoculation, to better examine this technique as a viable pasture N input strategy in the southern Amazon biome.

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Assessing the economic viability of integrated crop–livestock systems in Mato Grosso, Brazil

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Abstract

Population growth and rising incomes have led to increasing global demand for meat products. Meeting this demand without converting remaining natural ecosystems or further degrading ecosystems is one of the largest global sustainability challenges. A critical step to overcoming this challenge is to increase the productivity of livestock grazing systems, which occupy the largest land area of any type of agriculture globally. Integrated crop–livestock systems (iCL), which re-couple crop and livestock production at the farm scale, have been considered a promising strategy to tackle this challenge by restoring degraded pasturelands and providing supplemental nutrition to livestock. However, few studies have analyzed the economic viability of such systems, especially in Brazil, an important player in global food systems. This paper presents an economic analysis of iCL in Mato Grosso, Brazil, the largest grain and beef producer in the country, which spans the ecologically diverse Amazon, Cerrado and Pantanal biomes. We compare the economic performance of an integrated soybean/corn and beef cattle system to a continuous crop (soybean/corn) system and a continuous livestock (beef cattle) production system from 2005 to 2012. We use empirical case study data to characterize a 'typical' farm for each production system within the study region. We find that the integrated crop–livestock system has a higher annual net present value (NPV) per hectare (ha) than continuous cropping or livestock under a range of discount rates. However, under a scenario of substantially higher crop prices, the continuous cropping outperforms iCL. While iCL is not feasible in all regions of the Amazon and Cerrado, our results indicate that in places where the biophysical and market conditions are suitable for production, it could be a highly profitable way to intensify cattle production and potentially spare land for other uses, including conservation. Nevertheless, additional credit and technical support may be needed to overcome high upfront costs and informational barriers to increase iCL areas as a sustainable development strategy for agriculture in the Amazon and Cerrado regions.

Introduction

Agriculture is the main economic activity in many low-to-moderate income countries (World Bank, 2017; FAOSTAT, 2018) and employs a large number of workers worldwide (UNEP, 2011; ECLAC, 2017; FAOSTAT, 2018). In Brazil, crop and livestock production contributes substantially to economic growth—roughly 23% of the gross domestic product (GDP) as of 2016 (USD 336.9 billion) (MAPA, 2017*a*; 2017*b*). However, it has also been associated with high levels of greenhouse gas emissions (GHGs) and environmental degradation (Graziano da Silva, 2010; Vilela *et al*., 2011; MAPA, 2017*a*; 2017*b*), as well as increasing income inequality in rural areas (Abramovay, 2000; Graziano da Silva and Campanhola, 2004; Balsan, 2006). Beef cattle production, in particular, has been associated with very low incomes and high levels of land degradation, abandonment and deforestation (Margulis, 2004; Fearnside, 2005; Garrett *et al*., 2017*a*). In this context, there has been a growing impetus to develop alternative agricultural models that achieve higher productivity and incomes, while reducing environmental impacts, most notably deforestation and GHGs (Nair, 1991; Porfirio-Da-Silva, 2007; Graziano da Silva, 2010; Lemaire *et al*., 2014; Reis *et al*., 2016). Improving the sustainability of agriculture in Brazil is a key component of the country's plan to achieve their emissions reduction targets.

Considering this challenge, two agricultural models that have been encouraged by the Brazilian government, mainly in the Amazon and Cerrado region, are integrated crop–livestock systems (iCL) and integrated crop–livestock–forestry systems (iCLF)[a] (Brasil, 2012). These types of production systems aim to improve the sustainability of agriculture production through the integration of various types of agricultural production (i.e. crops, livestock and forestry) in the same area, via intercropping, or rotations, to obtain synergies among agroecosystem components (Nair, 1991; Macedo, 2009; Balbino *et al*., 2011; Lemaire *et al*., 2014).

Integrated systems represent a strategy to intensify resource uses—labor, land and capital, to increase productivity, while also diversifying production and sparing land for conservation or other uses (Franzluebbers, 2007; Herrero *et al*., 2010; Lemaire *et al*., 2014; Reis *et al*., 2016). Production diversification has the additional benefit of reducing market risk, since farmers have opportunities to manage their product portfolio to take advantage of agricultural market price fluctuations (Herrero *et al*., 2010; Lazzarotto *et al*., 2010).

A key feature of integrated systems, mainly iCL, is that they can be used to recover degraded pastures (Kluthcouski *et al*., 2003; Macedo, 2009; Vilela *et al*., 2011; Salton *et al*., 2014) by using residual fertility from the crop rotation to restore soil quality and finance further system improvements (Vilela *et al*., 2011; Costa *et al*., 2012). Prior studies in Brazil, especially in the Cerrado, have also shown that iCL systems can increase production efficiency since they contribute to: (i) improvements in soil quality; (ii) water conservation; (iii) an increase of animal performance; and (iv) a reduction in GHGs per unit of food produced (Kluthcouski *et al*., 2003; Macedo, 2009; Vilela *et al*., 2011; Salton *et al*., 2014). What is less understood is how economically viable these productions systems are in the Legal Amazon region of Brazil, particularly in light of their potentially high initial investment costs (Gil *et al*., 2018) and (Appendix 1). This lack of generalized information about the economic performance of iCL in the country's largest cattle and crop production region may help explain its low adoption rates, despite fairly high levels of government support (Martha Júnior *et al*., 2011; Vilela *et al*., 2011; De Oliveira *et al*., 2013; Salton *et al*., 2014; Reis *et al*., 2016).

The aim of this paper is to conduct a comprehensive economic viability analysis of iCL vs a 'typical' (as defined below) continuous crop or livestock farm in the Brazilian Legal Amazon state of Mato Grosso, which is the country's largest producer of soybean and cattle. The evaluation process focuses on assessing the return on investment (ROI) of these systems to inform both producers' decision-making processes as well as bank financial evaluations for funding iCL projects. The integrated system evaluated in this study pertains to soybeans double cropped with corn, followed by pasture and beef cattle grazing, which is the most common integrated system in the Brazilian Amazon and Cerrado (Nair, 1991; Macedo, 2009; Balbino *et al*., 2011; Lemaire *et al*., 2014). Our analysis relies on experimental data for a period of 7 years: 2005–2012. In addition to conducting a specific assessment of the case of Mato Grosso, the methods used here can inform future efforts to evaluate the economic viability and returns of iCL at broader scales.

Material and methods

Case selection

Our analysis focuses on two representative crop and livestock regions in the state of Mato Grosso, Brazil, one of the largest agricultural frontiers in the world (IBGE, 2017; IMEA, 2019; MAPA, 2017*a*, 2017*b*). Pastures occupy a majority of the area, followed by soybeans, which are often followed by corn during the course of a single year. Our livestock data were acquired from the municipality of Alta Floresta, in the North region of the state (Fig. 1b), which had the fifth largest cattle herd of the state (706,500 animals) in 2016. Our cropping data were acquired from the municipality of Santa Carmem, in the Mid-North region of the state (Fig. 1a), where about 40% of the soy production occurred in 2016.

The great concentration of agricultural production in the focal livestock and crop regions makes these cases globally important. Yet, they may not be generalizable to all regions within the state, which contains a great deal of climate, soil and institutional variability. The state spans three ecological biomes: the Amazon, Cerrado and Pantanal. Since colonization of the region did not begin in earnest until 1960, it is still a highly dynamic environment characterized by agricultural systems across a range of farm sizes and technology levels.

Defining a 'typical' crop and livestock farm in Mato Grosso

We defined the 'typical' crop and livestock systems for the North and Mid-North regions of Mato Grosso for the year 2005[b] using farm observations, meetings with local agricultural experts, including farmers, retailers, technicians, consultants, trading managers and data from the Mato Grosso Institute of Agricultural Economics (IMEA). IMEA carries out a comprehensive yearly economic survey focusing on the main agricultural commodities in Mato Grosso: soybean, corn, cotton and beef cattle. These surveys are performed in all Mato Grosso regions using focus group meetings that include farmers and representatives from agricultural organizations and businesses. The purpose of these meetings is to gather up-to-date information about costs, revenue, productivity, investments, farm size, management practices, labor and infrastructure for each commodity across farms in the state.

Based on these data we determined that the typical farm size in Mato Grosso is 700 ha of cultivated land area. The typical crop farm is defined by an intensive and specialized production system with two crop seasons per year: soybean (*Glycine max*) (October–February) and corn (*Zea mays*) (February–June/July). The initial investment required for the operation of this continuous soybean/corn system was USD 765.63[c] ha^{-1}, excluding the land acquisition cost.[d] This farm possesses a high level of technology in all production stages with high investment in infrastructure and inputs. As a consequence, it has high soybean productivity levels (av. 3.12 MT ha^{-1}), as well as high production costs (av. USD 530.45 ha^{-1}) (Table 1). Most soybean production in the region is exported through multinational traders. As of 2005, corn area in the state was still limited, but most production is marketed through domestic channels.

In contrast, the typical livestock farm is characterized by traditional cattle ranches with a low level of technology, low productivity

[a]In this paper we will concentrate our analysis in integrated crop and livestock systems because this is the integrated system most adopted in Brazil, mainly in Brazilian Cerrado and the Amazon region.

[b]This year was selected to allow comparison of economic results given that the integrated system experiment started at 2005.

[c]2005 prices. Conversion using exchange data from official Brazilian Govern database provided by Research Institute of Economic Applied (IPEA): http://www.ipeadata.gov.br/Default.aspx.

[d]The perspective of the analysis was to evaluate the productive activity performed in the area.

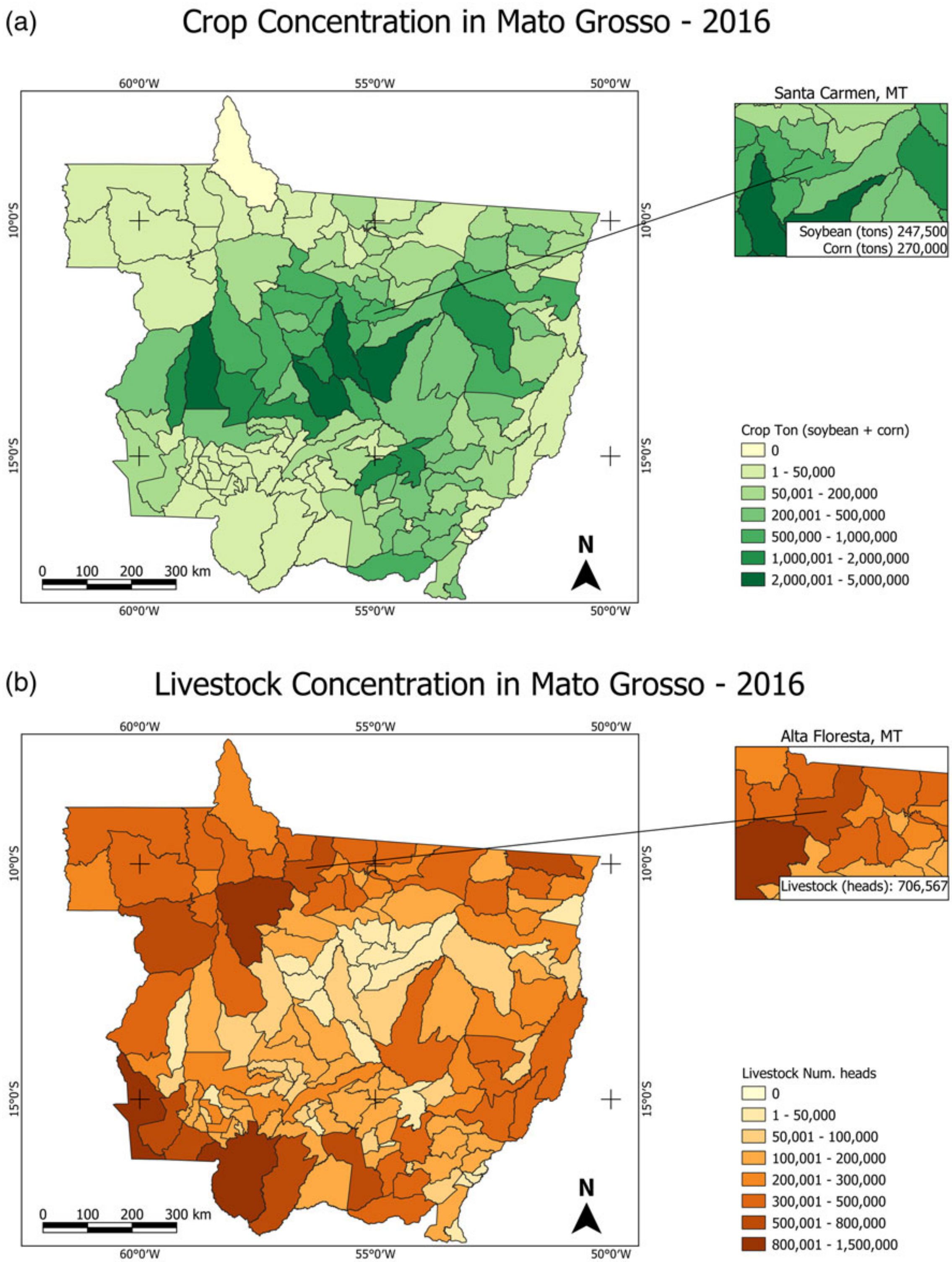

Fig. 1. (a) Crop concentration in Mato Grosso, 2016. (b) Livestock concentration in Mato Grosso, 2016.

and large areas. Farmers do not invest in sophisticated infrastructure, only basic equipment, such as a corral, troughs and fences. Also, farmers do not invest in pasture management. As a consequence, in the dry season, they have difficulties providing adequate nutrition to their herd. The most common cattle breed is Zebu cattle (*Bos taurus indicus*) and pasture is *Urochloa brizantha* cv. Marandu. In contrast to soybeans, the cattle are mainly sold for internal markets and this activity is less responsive of international prices and exchange rates. The initial investment required for the operation of a continuous traditional livestock system was USD 173.73 ha^{-1}, excluding the land acquisition cost.

Integrated crop and livestock systems are still somewhat rare in the study region, so it was not possible to use observations and expert knowledge to characterize these systems. Instead, we draw

Table 1. Productivity, operating and inputs cost for a typical integrated crop-livestock, continuous crop and continuous livestock farm in Mato Grosso from 2005 to 2012

	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012
Soybean							
	Soybean productivity (MT/ha)						
iCL typical farm	3.58	3.72	3.34	3.63	3.70	3.77	3.56
Crop typical farm	3.14	3.14	3.14	3.03	3.07	3.33	3.01
	Operational cost (inputs, work force and machinery) (USD/ha)						
iCL typical farm	274.94	149.77	194.26	408.10	233.59	271.58	282.71
Crop typical farm	375.19	432.65	520.91	631.64	440.84	532.49	779.46
	Input cost (USD/ha)						
iCL typical farm	165.19	98.83	128.53	280.70	157.49	172.76	180.62
Crop typical farm	319.29	368.18	443.29	537.52	340.94	435.80	704.73
Corn							
	Corn productivity (MT/ha)						
iCL typical farm	2.19	5.04	4.08	2.82	–	1.95	4.80
Crop typical farm	4.63	4.63	4.63	5.07	4.00	3.99	6.22
	Operational cost (inputs, work force and machinery) (USD/ha)						
iCL typical farm	26.19	57.56	61.82	69.06	64.61	61.52	109.52
Crop typical farm	225.10	259.57	312.52	378.96	309.30	408.05	459.87
	Input cost (USD/ha)						
iCL typical farm	16.30	37.63	39.28	48.79	47.21	50.96	79.88
Crop typical farm	183.43	211.52	254.67	308.80	246.29	338.25	400.28
Cattle							
	Cattle productivity (kg/ha)						
iCL typical farm	162.00	372.00	360.00	216.00	402.00	399.00	411.00
Livestock typical farm	324.00	–	–	–	–	336.00	–
	Operational cost (inputs, work force and machinery) (USD/ha)						
iCL typical farm	897.01	1181.71	1376.48	1003.18	2353.35	2495.65	3679.37
Livestock typical farm	92.39	108.68	127.78	142.87	138.07	164.78	182.24

[a]Meetings to collect data on the livestock typical farm were accomplished every five years.
[b]iCL typical farm operating cost includes animal acquisition, which is the most important input cost of livestock. In the livestock typical farm, this value is not computed because farmers produce their herds.

our data from the first iCL experiment established by the Brazilian Agricultural Research Corporation (Embrapa) on a farm called Dona Isabina in the municipality of Santa Carmen in 2005. The farm has 2000 ha cultivated with soybean, corn and rice (*Oryza sativa*) in rotation and crop sequences. However, the iCL experiment occurred on just 100 ha of the site. The soils in the test site are yellow Oxisols and the topography is flat, with very little slope. The average altitude is 386 m, average annual rainfall of 2064 mm with a dry season from June to September and average temperatures of 27.6°C. To establish pasture rotations and crop sequences, the area of 100 ha was divided into five parcels of 20 ha, bounded by fences. The area in which the experiment was implemented had already been cultivated with soybeans in the summer and pearl millet (*Pennisetum glaucum*) as a cover crop after the soybean harvest. Scaling this area up to 700 ha (to match the size of typical crop and livestock farms in the region) we calculated an initial investment of USD 863.38 ha^{-1}, excluding land acquisition costs.

Each parcel was cultivated with pastures (*Urochloa brizantha* cv. Marandu and *Urochloa brizantha* cv. BRS Piata). The land use of the iCL system followed an annual rotation of crops: soybean or rice in the summer (October–February) and corn or beans (*Phaseolus vulgaris*) immediately following (February–June). The second crop was intercropped with grass pastures. After the second crop harvest, the cattle were allowed to graze on the pastures that remained, which provided them with additional nutrition during the dry season (June to September) when there is low forage availability.

In the first five years of the experiment the herd was a mixture of male and female Zebu cattle acquired in the region. These animals were sold for slaughter when they reached weight of 480 kg. In the last two years, only males were raised, but still slaughtered when they reached 480 kg. The only supplementation used all year long was mineral salt with an average consumption of 90 g day^{-1} during the rainy season and 120 g day^{-1} during the dry season. In the dry season, the cattle also received sorghum silage (*Sorghum bicolor*), soybean residues, corn and rice produced in the farm processing unit. In all modules, mangers for supplementation and watering were available.

Economic indicators

We used an economic viability analysis approach to compare the economic results of the three agricultural systems (Buarque, 1984; Gitman and Zutter, 2014). This method is established in the economic literature as an instrument to evaluate the economic potential of any investment decision (Buarque, 1984; Lapponi, 2013; Gitman and Zutter, 2014). We used data from IMEA to generate typical crop and livestock farm and survey data to generate the iCL farm. Taking into account the lack of available economic performance data for agriculture systems, the use of IMEA and experimental data are the only feasible approaches for establishing the time-series data required to carry out the economic viability analysis presented. The results can be useful for farmers, helping them compare different investment options, as well as for funding agents since they can evaluate different complex agriculture systems using comparable indicators. Since prior studies have identified that a lack of technical information on the economic performance of iCL for both farmers and financers is a key constraint for farmer adoption (Martha Júnior *et al*., 2011; Vilela *et al*., 2011; De Oliveira *et al*., 2013; Salton *et al*., 2014; Reis *et al*., 2016; Cortner *et al*., 2019), our approach may help enable wider scale adoption of this technology. The financial accounting approach used here, which is based on observed outcomes, is also a useful complement to process models, which predict outcomes based on inputs (e.g. Gil *et al*., 2018 for the same region).

We used the following five indicators to assess economic viability and potential economic returns of the iCL system, continuous soy/corn system, and continuous beef cattle system over 7 years (2005–2012): (i) internal rate of return (IRR), (ii) net present value (NPV), (iii) return on investment (ROI), (iv) profitability index (PI) and (v) payback (Gitman and Zutter, 2014).[e]

Cash flow: To calculate each of these five indicators we first needed to estimate the real cash flow (CF) based on 2005 prices. Following (Lapponi, 2013):

$$\mathrm{CF}_t = \mathrm{FCO}_t + \Delta I + \Delta \mathrm{CG}_t \quad (1)$$

In which: FCO_t = Operating cash flow; ΔI = Net investment in assets; $\Delta \mathrm{CG}_t$ = Net investment in working capital.

Apart from the relationship between costs and revenues, cash flow results take into account interest deductions, taxes and labor charges to demonstrate the cash generation potential of each system.[f] As a measure of yearly profitability, we used the net operating profit after income tax (NOPAT).[g] It represents the net profit that the system generates to remunerate both the funding entity and the producer (Assaf Neto, 2011; Lapponi, 2013; Gitman and Zutter, 2014). As an inflation indicator, we used the broad consumer price index (IPCA) provided by the Brazilian Institute of Geography and Statistics (IBGE), which is the official inflation index in Brazil.

[e]Annual results from indicators NPV (annual net present value- NPVA) and ROI (annual return of investment—ROIA) were calculated and displayed to become easier the comparison between the three systems.

[f]The share of working capital was disregarded and the assets' flow was incorporated into the operating result observed in the last year of assessment.

[g]For construction of the NOPAT, see the supplementary material.

Investment value: Except for the land value, which was not incorporated into the cash flow, all other infrastructure elements required for production activities were considered as if they had been purchased in the initial year of all production systems, 2005. A market survey was conducted with consultants and equipment retailers to collect prices data in the Mid-North region in 2005, taking into account the infrastructure needed to set up each farm system.

Discount rate: The discount rate defines the present value of future returns (Buarque, 1984; Gitman and Zutter, 2014). Choosing a discount rate is one of the most controversial points in economic investment analysis because the choice of incorrect values can lead to suboptimal results and decisions (Buarque, 1984; Lapponi, 2013). The project economic evaluation literature defines the discount rate as the opportunity cost of investment, which means that it should reflect the expected return value for alternative available investments with similar risk to the activity being analyzed (Buarque, 1984; Lapponi, 2013; Gitman and Zutter, 2014). This approach, although it incorporates correctly the perspective of the discount rate to be used, is limited by the lack of investment alternatives that can serve as a reference (Buarque, 1984).

As a result, the official savings rate is more commonly used in many agricultural investment evaluations, since it represents a low-risk and low return alternative investment option (Buarque, 1984; Gitman and Zutter, 2014). In other cases, the economy basic interest rate or long-term interest rates has been used, also indicating low-risk investment alternatives, but with higher returns. An important issue regarding the use of these rates as a reference is no consideration of the investor's profile for defining the interest rate to be used.

Given these drawbacks, our study uses the weighted average cost of capital (WACC), to adjust the variables that make up the investment opportunity cost based on the agent's profile, as well as the level of risk associated with the business being evaluated[h]. The WACC is more appropriate for this evaluation since it considers an agent's decision about which percentage of investment will be funding as well as incorporates market risks of alternative investments (Buarque, 1984; Lapponi, 2013; Gitman and Zutter, 2014). The WACC rate was built taking into account the financial market conditions in Mid-North region in 2005.

Incorporating changing land use and market dynamics

Since our study analyzed the economic viability of the three systems over a 7-year period it was necessary to incorporate changes in land use and markets that were occurring over that period. These dynamics include the growing importance of corn as a second crop[i] (resulting in an increase in the on-farm area allocated to integrated crop–livestock systems), changes in the marketing arrangements used by farmers, and a dynamic macroeconomic environment in which real prices for soybean, corn and beef were changing frequently due to growth in demand and exchange rate variations.

Data from IMEA show that corn as a second harvest crop grew by 14.87% per year in the period 2008–2012. To simulate dynamics of land use in the integrated crop–livestock farm, the growth of corn second harvest area in the typical continuous crop farm was used to define the growth of the integrated

[h]For construction of the WACC, see the supplementary material.

[i]According to IMEA, for the 2007/2008 crop year the corn area in Mato Grosso was 1,670,800 hectares and 796,500 hectares for Mid North region. In the 2009/2010 this area increasing to 1,948,020 hectares in the state and 964,000 hectares for Mid North region. The crop year with a more expressive planted area was 2012/2013, in which were planted 3,702,053 hectares in the state with 1,830,318 hectares in the Mid North region.

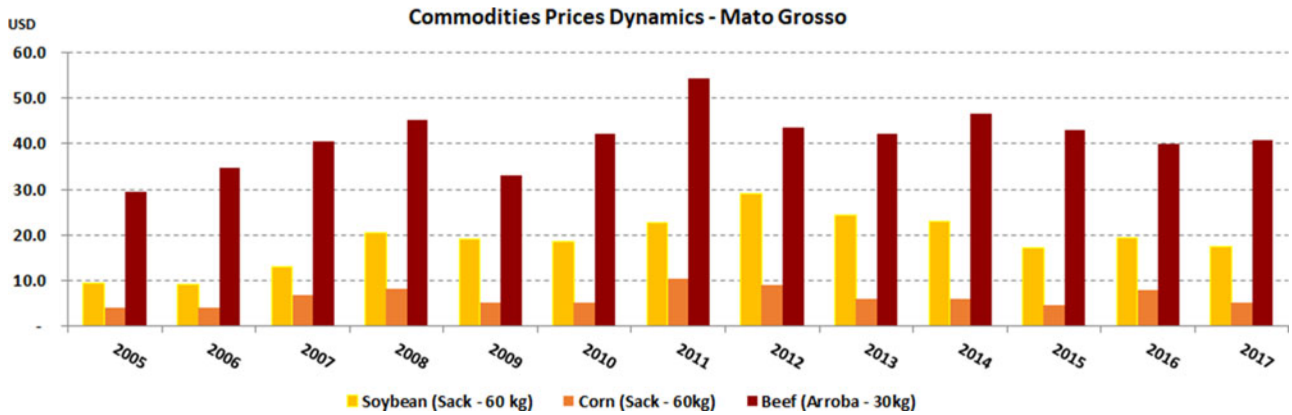

Fig. 2. Average commodity prices in Mato Grosso from 200 to 2017.

system area[j] (Kluthcouski *et al.*, 2003; Macedo, 2009; Balbino *et al.*, 2011; Vilela *et al.*, 2011).

Interviews with farmers and specialized consultants who worked in the North and Mid-North regions in 2005 identified that the most common soybean marketing practice used during that time was to sell their harvest over three periods: (i) 25% of production was sold in advance, from August to October, (ii) 50% of production was sold from November to April, during the harvesting and immediate post-harvest period and (iii) 25% of production was sold from May to July, the period of preparation for another harvest. To adjust the revenue dynamics to the trading practices of that period, the crop sales process was adjusted according to the moment of the soybean harvest[k]. Soy sale prices for each period are calculated as the average of the prices observed during the months of soy trading. Similarly, corn sale prices are calculated as the average of the prices observed from September to November, the main months for corn trading.

Of particular importance, soybean prices were very low in 2005 and 2006, while production costs remained high (CEPEA, 2007). However, after 2007 the soybean price steadily increased, a trajectory influenced by China's consolidation as the main Brazilian soybean importer (Fig. 2). In 2012, the soybean price in the Mid-North of Mato Grosso—USD 28.94 per sack (60 kg), was three times higher than the value observed in 2005—USD 9.55 per sack; (IMEA, 2016). Nonetheless, in 2009, the financial crisis complicated production and trading. The devaluation of the Brazilian currency during this period (9% in one year), led to increased crop production costs (10% in 2009), largely as a result of fertilizer imports, while soybean prices remained low (IMEA, 2019).

In contrast, corn prices increased during 2010–2012 as a consequence of financial crisis of 2009, since corn production is oriented toward domestic consumption and is not as influenced by global commodity markets. The same domestic market orientation and price dynamics can be seen in the prices for beef, which achieved a historic high price in 2011, USD 54.40 per "arroba" (30 kg of live weight). However, a considerable portion of Mato Grosso's beef production is exported, 22.1% on average in the last 5 years (MAPA, 2017*b*), destined mainly for EU, Russia, China and Middle East (MAPA, 2017*b*; IMEA, 2019).

[j]The most common practice is to plant corn intercropping with pasture to recover soil quality and provide food for cattle during the driest period of the year in the region, from June to September.

[k]Only the soybeans trading process was taken into consideration, once the corn, at that moment, did not present the economic relevance observed currently.

Results

Productivity

The average cattle productivity in the iCL farm (331.71 kg ha^{-1}) was 5 times higher than the typical livestock farm (63.3 kg ha^{-1}) (IMEA, 2019) due to the availability of higher quality pasture during the dry period of the year. The productivity of soybean in the iCL farm was also on average 16% higher than crop typical farm during the whole study period (Table 1). On the other hand, the input cost of iCL system was 62% lower than the continuous crop farm. Taking into account the high contribution of fertilizers to input costs, this association between higher productivity and lower input cost is likely related to the positive influence of the integrated systems on soil nutrient availability (Carvalho *et al.*, 2010; Garrett *et al.*, 2017*b*). Further systematic measurement of soil nutrient availability is needed to confirm this hypothesis. A different result was observed with corn. Since corn had little economic importance at the time that the iCL experiment was started at the Dona Isabina farm and the main objective was to provide agronomic benefits for pasture, low productivity corn seeds were used. Moreover, in 2009 and 2010 there was an intense dry period at the crop germination stage which affected productivity.

Cash flows[l]

The iCL system had the largest investment costs (negative cash flow in years one and two), but also had the largest positive cash flows throughout the remainder of the study period, achieving a positive result of USD 654.04 ha^{-1} in 2012 compared to USD 460.85 ha^{-1} for continuous cropping and UDS 27.59 ha^{-1} for continuous livestock (Fig. 3). Macroeconomic fluctuations explain most of the changes in cash flows over the study period. In particular, soybean and beef prices increased during the study period (Fig. 2).

During June to September most continuous livestock farms have to sell off part of their herd, since they do not have conditions to feed them (IMEA, 2016; Valentim, 2016; Gil *et al.*, 2018; Reis *et al.*, 2019), which is thought to cause declines in the local cattle price. The higher pasture productivity obtained in the iCL system on the Dona Isabina farm, translated to higher cattle productivity (331.71 kg ha^{-1} annual average) (Table 1), and enabled this farm to keep their animals during the annual dry

[l]For a detailed cash flow description, see supplement material.

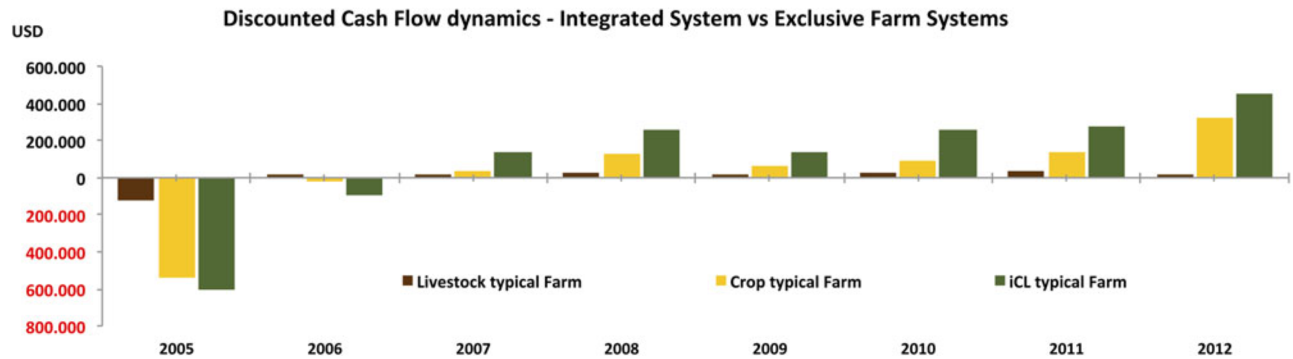

Fig. 3. Discounted cash flow of a typical integrated crop-livestock, continuous crop and continuous livestock farm in Mato Grosso from 2005 to 2012.

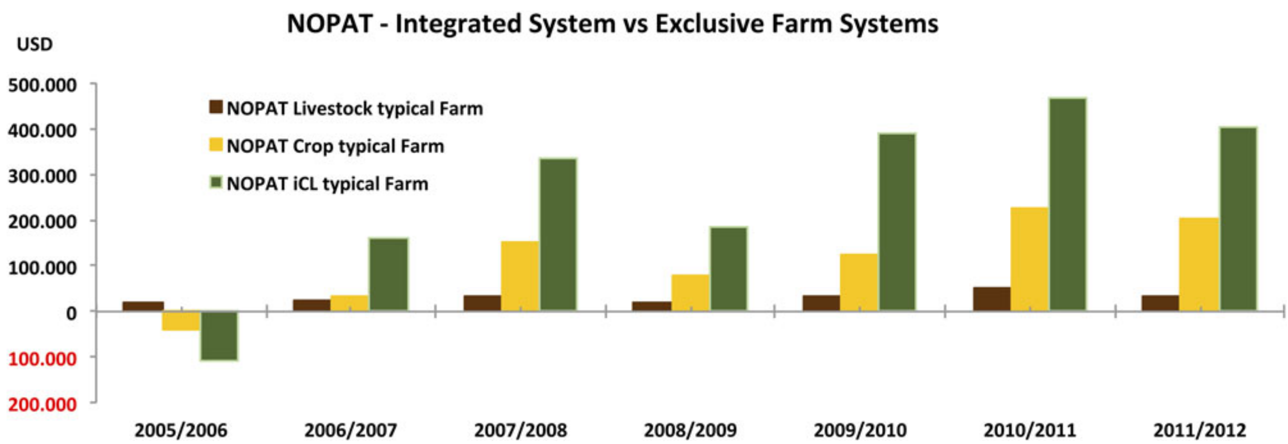

Fig. 4. NOPAT of a typical integrated crop-livestock, continuous crop and continuous livestock farm in Mato Grosso from 2005 to 2012.

season. Indeed, the pasture management strategy implemented at Dona Isabina provided an annual increase of 14% in cattle productivity over the seven years. Moreover, in 2012, the annual cattle productivity was 2.5 times higher than its cattle productivity in 2005 (Table 1). The seasonal dilemma of traditional cattle ranches also enabled the Dona Isabina farm to acquire animals at a low price during the dry season and sell them in periods when prices were high. The seasonal advantage and the high cattle productivity largely explain the better economic results of iCL vs continuous cattle (Fig. 3).

The iCL farm also resulted in higher cash flows than the continuous crop farm (Fig. 3), due to the combination of higher productivity and, on average, 62% lower production costs and 51% lower operating costs (Table 1). The large reduction in production costs can be attributed to lower fertilizer needs due to improved soil fertility from both manure and nitrogen fixing legumes in the pasture.

The economic fragility of traditional livestock is evidenced by the smaller cash flow throughout the study period (on average USD 23,131.62 vs USD 109,164.24 for continuous cropping and USD 204,318.97 for the integrated system).

The iCL farm also outperforms the continuous cropping and continuous livestock systems in terms of the NOPAT (Fig. 4). This indicator, which can be interpreted as the annual system capacity to provide economic return after taxes and financial expenses (e.g. interest on debt), indicated that the iCL farm provided a greater money supply than the continuous crop and livestock systems throughout the study period, aside from the initial year.

Another economic indicator widely used in the project analysis approach is the recovery period of the investment (the number of years of positive cash flows it takes to repay the initial investment and negative cash flows), known in the literature as the payback period. The iCL farm recovered the investment after 4 years (Fig. 5) while the continuous crop did not recover their investment until year 6. The livestock system recovered the investment after 5 years. In the end of seventh year, the continuous crop and livestock farms had an accumulated cash flow of USD 228,207.46 and USD 40,313.76, respectively. However, the iCL farm had accumulated USD 825,868.81.

Economic viability indicators

The cash flow of all systems provides useful information to elaborate the set of economic viability indicators displayed in Table 2. Across all indicators (NPV, internal rate of return, payback, profitability index and ROI) the iCL system performs substantially better than the continuous crop and livestock farms. The exception is the higher upfront investment cost per hectare. The livestock farm has the worst performance across all indicators.

Scenario Analysis

Different Interest Rates

All the results presented above are quite sensitive to the discount rate. Here, we used the Center-West Constitutional Fund rate,

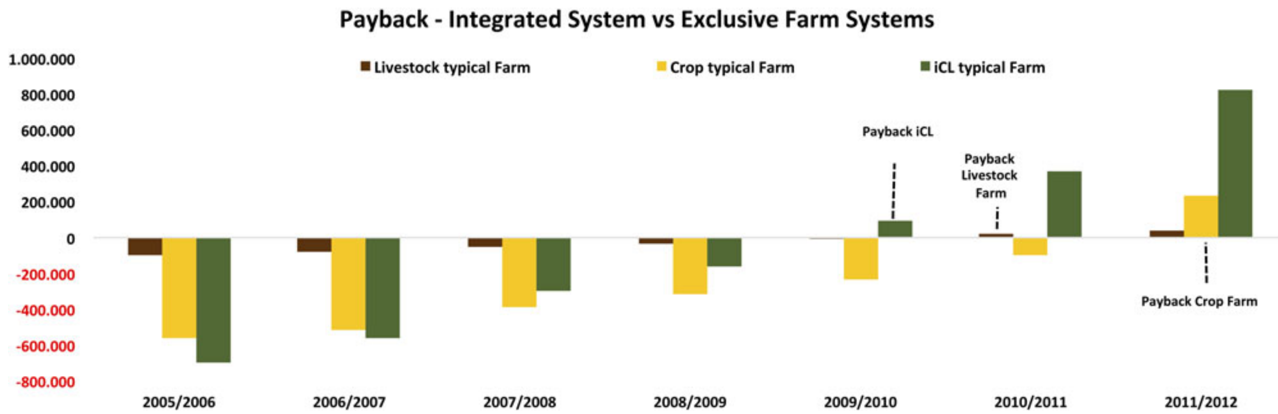

Fig. 5. Payback of a typical integrated crop-livestock, continuous crop and continuous livestock farm in Mato Grosso from 2005 to 2012.

Table 2. Economic viability indicators for a typical integrated crop—livestock, continuous crop and continuous livestock farm in Mato Grosso from 2005 to 2012

Indicators	Crop typical farm	Livestock typical farm	iCL typical farm
WACC	9.66%	9.18%	9.53%
Investment (USD) ha^{-1}	USD 765.63	USD 173.73	USD 863.38
NPV (USD) ha^{-1}	USD 66.73	USD 5.22	USD 674.17
NPVA (USD) ha^{-1}	USD 13.56	USD 1.04	USD 136.25
IRR	11.32%	10.01%	22.16%
ROI	10.98%	9.64%	18.94%
ROIA	1.2%	0.42%	8.58%
Profitability index	1.09	1.03	1.78

8.75%, to construct the WACC, as well as the entire set of economic viability indicators because in 2005 there was no specific government loan program to encourage iCL in Brazil. However, in 2010, Brazilian Government implemented the low carbon agriculture plan (ABC plan) with incentives and low interest rates for more sustainable agricultural systems, including iCL. The ABC plan offered interest rates of 5.5% in 2010 (Brasil, 2012). However, the performance of iCL relative to the other systems does not change if we use the ABC plan rate or the basic interest rate of Brazilian economy (SELIC) in 2005 (19.24%), a rate used to evaluated investments in stock market (Table 3).

Different Prices

Between 2005 and 2006, soybean prices were very low in the global market (Fig. 2). Both soybean and corn prices peaked in 2010 and then again in 2016. To capture the effects of these higher prices we used the average soybean and corn prices observed in the Mid-North region between 2013 and 2017. For consistency, the cattle prices were also adjusted to the average prices in the Mid-North region between 2013 and 2017. Moreover, the corn planted area was increased, to match the growth in the average farm-level planted area in the Mid-North in the last 10 years (2007–2017: 46.44%). All other conditions were kept unchanged. As a result of these scenario adjustments the continuous crop system overtook iCL as a better investment (Table 4).

Discussion

High profitability and greater profit stability of iCL under a range of scenarios offsets its high upfront costs

Despite its low uptake compared to continuous cropping system or traditional extensive ranching, our results indicate that iCL is a substantially better land use investment than continuous crop or livestock systems from a financial perspective under existing crop price scenarios. It both increases the productivity of pasture areas and reduces reliance on external inputs in cropping areas, contributing to higher overall profitability. One reason for the low uptake of iCL is that farmers accurately perceive the system to have high upfront costs and they are uncertain as to how long it will take for the system to pay back this investment (Martha Júnior *et al.*, 2011; Costa *et al.*, 2012; Cortner *et al.*, 2019). However, our results show that the payback period is only 4 years for the iCL system, less than that of continuous cropping—6 years, or continuous livestock—5 years.

If payback time is considered as an investment risk indicator (Assaf Neto, 2011; Gitman and Zutter, 2014), then iCL actually demonstrates lower economic risk than continuous crop or livestock systems (Muniz *et al.*, 2007; Lazzarotto *et al.*, 2010). The iCL system also shows lower variations in profit and NPV under different price and interest rate scenarios. Given the high fluctuations in prices that have occurred in grain commodity prices over the 2000s and their inverse relationship to domestic beef prices, iCL allows farmers the opportunity to buffer their losses when one system suffers due to major price changes. However, the positive returns on continuous cropping are likely a market barrier to the adoption of iCL in regions that are highly suitable for soybean and corn production.

Economic performance of continuous cropping is highly dependent on exchange rates and world prices

Due to its dependence on external markets for both sales and fertilizers, the performance of continuous cropping was strongly influenced by the prevailing exchange rate and international commodity prices, the same main drivers of deforestation in the Amazon (Rodrigues-Filho *et al.*, 2015). When the currency was devalued, Brazilian crops became more competitive in global

Table 3. Simulation with different interest rates—economic viability indicators for a typical integrated crop-livestock, continuous crop and continuous livestock farm in Mato Grosso from 2005 to 2012

	Crop typical farm		Livestock typical farm		iCL typical farm	
Indicators	SELIC (19.24%)	ABC plan (5.5%)	SELIC (19.24%)	ABC plan (5.5%)	SELIC (19.24%)	ABC plan (5.5%)
WACC	13.86%	8.36%	19.24%	5.5%	13.73%	8.24%
Investment (USD) ha^{-1}	765.63	765.63	173.73	173.73	863.38	863.38
NPV (USD) ha^{-1}	(89.98)	124.33	(45.18)	31.52	393.73	776.62
NPVA (USD) ha^{-1}	(20.89)	24.17	(12.27)	5.55	91.07	150.38
IRR	11.31%	11.31%	10.01%	10.01%	22.15%	22.15%
ROI	11.84%	10.71%	14.22%	8.04%	19.99%	18.61%
ROIA	(1.77%)	2.17%	(4.21%)	2.41%	5.50%	9.58%
Profitability index	0.88	1.16	0.74	1.18	1.45	1.89

Table 4. Simulation with different crop prices—economic-financial viability indicators for a typical integrated crop-livestock, continuous crop and continuous livestock farm in Mato Grosso from 2005 to 2012

Indicators	Crop typical farm	iCL typical farm
WACC	9.66%	9.53%
Investment (USD) ha^{-1}	765.63	863.38
NPV (USD) ha^{-1}	761.38	52.70
NPVA (USD) ha^{-1}	154.66	10.66
IRR	30.54%	10.86%
ROI	21.01%	10.46%
ROIA	10.35%	0.84%
Profitability index	1.99	1.06

markets, but, also faced higher production costs (Table 1). In 2008 and 2011, when the exchange rate increased substantially, production costs were particularly high.

Moreover, the high profitability of cropping under current price scenarios may explain why the most common strategy of iCL in this region has been the 'third harvest', in which a farmer produces soybean in the first harvest and plants corn intercropped with pasture. Recent research by Embrapa found that 83% of integrated systems in Brazil are iCL and the same pattern can be observed in Mato Grosso (Embrapa; Rede iLPF, 2017). Furthermore, the 'third harvest' strategy represents around 50% of iCL in Mato Grosso (Embrapa; Rede iLPF, 2017). As the results show, iCL can reduce external input dependence and improve the economic viability of farming in the region.

Extensive livestock ranching traps farmers in a cycle of low income due to dry season losses

The cash flow restrictions faced by traditional extensive livestock producers make it difficult for ranchers to take advantage of the livestock market. These farmers have few alternatives than selling part of their herd in the dry season, which limits their cash flow and, as a consequence, their capacity to generate revenue. The lack of economic competitiveness of extensive livestock relative to cropping or iCL explains why over the last decade in Mato Grosso many pasture areas have been overtaken by cropland (Macedo *et al.*, 2012; Lapola *et al.*, 2014).

Given the existing low returns of continuous livestock systems, and future potential changes in climate that will further reduce pasture productivity in Mato Grosso (Gil *et al.*, 2018), it will be even more imperative to help farmers adopt improved pasture management practices, such as iCL to maintain their livelihoods, or else abandon production entirely. iCL would also help reduce the GHGs from livestock (Gil *et al.*, 2018) and provide new funding opportunities, which have been connected with use and adoption of sustainable practices such as ABC plan.

Low interest loans are key to the viability of establishing all three systems

Using the SELIC interest rate scenario of 19.24%, only iCL was still economically viable. Using the ABC interest rate of 5.5% doubled the NPV of iCL. Continuous cropping showed a huge deficit in the SELIC interest rate scenario, indicating the relationship between technological levels and financial obligations. These results underscore the importance of public policies to provide attractive funding plans with low interest rates to agriculture. However, in recent years, because of economic and political crises, the interest rates provided by the ABC program increased to 8.5% in 2016/2017 and 7.5% in 2017/2018 (MAPA, 2017*b*).

Conclusion

The challenge of protecting the environment, while generating income and reducing social inequality, requires the identification of agricultural strategies that enable the sustainable intensification of production. Given the growing international concern about the environmental impacts of agricultural activities in the Brazilian Amazon and Cerrado, as well as the importance of Brazilian agriculture in world food systems, the promotion of sustainable agricultural practices in Brazil is of global relevance.

This work, in addition to presenting an alternative to the current model of agriculture, sought to advance understanding of the economic performance of iCL as a sustainable intensification strategy compared to traditional continuous crop and livestock systems. Our results showed that iCL had higher levels of productivity, profitability and ROI and lower payback periods and economic risk than the continuous crop and livestock systems under existing prices and exchange rates over a 7 year period between 2005 and 2012. However, under higher crop prices, continuous cropping provides better economic results than the integrated system.

The case study approach used here is necessary and useful in the absence of a large sample of iCL farms from which to draw data, but does not guarantee that the results are representative of all potential iCL farms in the region. In order to assess how generalizable our results are to northern Mato Grosso and the rest of the Legal Amazon, a wider sample of farms across the region needs to be considered. As iCL continues to be adopted, these types of surveys will become increasingly possible.

Finally, the financial performance of iCL, though potentially important for decisions to adopt or not adopt these systems, are not the only outcomes that are relevant to farmers and policy makers. Systematic measurement of environmental indicators, such as soil fertility, GHGs and water consumption on iCL farms in the study region are needed. Further research should also explore the tradeoffs between economic and environmental outcomes in integrated systems (e.g. Gil *et al*., 2018). Since farmers are often motivated by non-monetary objectives and integrated systems entail major changes in management complexity, debt financing and farm aesthetics, better understanding of their cultural appropriateness is needed (Garrett *et al*., 2017*b*; Cortner *et al*., 2019). Given the multifaceted and dynamic reality associated with agriculture, it is vital to assess the social and environmental benefits across a wider range of farms and regions, as well as climate and macroeconomic scenarios. The evaluation of any agricultural system's potential to promote sustainable development must be based on models and assessments that capture the interrelations between different system components—economic, social and environmental—at broader spatial scales beyond the farm (Garrett and Rausch, 2016).

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Appendix 1 Summary Literature Review: Economic analysis of integrated crop and livestock systems in Brazil

Authors	Focus of the analysis	Productive Systems	Period	Indicators	Main results
Muniz *et al.* (2007)	Economic viability and minimizing market risks	iCL in Goias, Brazil	3 years, using simulations	NPV and IRR	The iCL was economically viable in all scenarios considered
Lazzarotto *et al.* (2010)	Economic viability and minimizing market risks	iCL, continuous crop system (soybeans and corn in the summer and wheat in the winter) and continuous livestock (beef cattle) system in Paraná, Brazil	13 years, using simulations	NPV and IRR	In both situations (real and simulated) the iCL presented better economic results: NPV 103% higher than the crop system and 19.6% higher than the livestock system. Furthermore, the iCL presented lower probabilities to display negative NPV considering investment and prices fluctuations
de Oliveira *et al.* (2014)	Economic viability	iCL and continuous crop system (soybean) in Rio Grande do Sul, Brazil	12 years	Productivity and Gross Margin	The iCL presented better results, especially in years when the rainfall volume in crop development time was insufficient
Costa *et al.* (2012)	Economic viability, cash flows dynamics and higher investment requirements	iCL; iCLF with eucalyptus trees on simple lines (227 trees/ha) and iCLF with eucalyptus on simple lines (357 trees/ha), in Mato Grosso do Sul, Brazil	12 years, with real data for the first two years	NPV	The lower necessity of investing on the iCL to both iCLF in addition to a return on capital invested in a shorter period, indicate that system iCL tends to be a more suitable alternative to producers who deals with financial constraints and/or risk averse.
Martha Júnior *et al.* (2011)	Economic viability	iCL; continuous livestock system (beef cattle) and a continuous crop system (soybean) in Goias, Brazil	1 year	Net Revenue, Productivity and Entrepreneur Return Rate	The iCL was more economically attractive than the livestock system, but did not show better results than the soybean crop system. The ERR for the livestock system was negative (−1.55%), for the iCL the return rate was 26.7 and 55.9% for the soybean crop system
De Oliveira *et al.* (2013)	Economic viability	iCLF system in Goiás, Brazil	7 years, with real data for the first three years	NPV and IRR	Due to favorable crop prices scenario, the economic results were very positive: NPV annual of USD 269.53 ha to 2009 prices. For the IRR the value was 54.24%, well above the attractiveness minimum rate considered, which was 8.75%.

iCL, integrated crop and livestock system; iCLF, integrated crop, livestock and forest system; NPV, net present value; IRR, internal return rate; ERR, entrepreneur return rate.

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Nitrous oxide, methane, and ammonia emissions from cattle excreta on *Brachiaria decumbens* growing in monoculture or silvopasture with *Acacia mangium* and *Eucalyptus grandis*

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ABSTRACT

We quantified nitrous oxide (N_2O), methane (CH_4), and ammonia (NH_3) emissions from cattle urine and dung patches on *Brachiaria decumbens* growing in a long-term silvopasture (SPS) or in monoculture (MONO) during the annual rainy and dry periods in southwest Brazil. We hypothesized that microenvironmental changes triggered by dense shade and litter, provided by trees, and pasture quality in SPS would affect greenhouse gas emissions from cattle excreta. Two field trials (rainy and dry season) were carried out using manual closed static chambers in a 3 × 2 factorial scheme, corresponding to three excreta types (urine, dung, and control without excreta) and two pasture systems (SPS and MONO), in a block design with three blocks and two replicates per block (n = 6 per treatment). Generally, N_2O and CH_4 fluxes were higher in SPS than in MONO. Notably, N losses in the form of N_2O did not exceed 0.10 %, except for N_2O emissions from urine deposited during the rainy season in SPS (0.39 % of applied N). Cattle dung was also a source of CH_4. The highest fluxes were observed under SPS during the rainy season, but emissions were generally low, with emission rates < 0.1 kg CH_4 head^{-1} yr^{-1}. The highest N losses by NH_3 volatilization were observed for urine under MONO, amounting to 8.3 % of total N applied during the rainy season and 17.1 % during the dry season. Our results demonstrate that N_2O, CH_4, and NH_3 emissions from cattle are influenced by pasture system, excreta type, and season. N_2O and CH_4 emissions increase in long-term SPS, while NH_3 losses reduce.

1. Introduction

Brazil has the largest commercial cattle herd in the world, with approximately 218 million head (IBGE, 2016). The herd is raised in open pastures of tropical grasses (*Brachiaria* and *Panicum*) that occupy almost 170 Mha. Due to the large herd and the extensive area used for beef cattle production, animal excretion and pasture fertilization can lead to significant emissions of greenhouses gases (GHG), such as nitrous oxide (N_2O) and methane (CH_4), and ammonia (NH_3) emissions as an indirect source of N_2O. Therefore, alternative grazing systems to mitigate GHG emissions and NH_3 pollution are required.

N_2O is a potent GHG with a global warming potential 265 times that of carbon dioxide (CO_2) in a 100-year time frame (IPCC, 2019). Emissions of this gas occur mainly from animal excretion and nitrogen (N) fertilization. In countries like Brazil with a large agricultural sector, more than 90 % of N_2O emissions are from this sector (MCTI, 2017). Recently, several authors have shown that N_2O emissions depend on the type of excreta, with urine being the main source in temperate and tropical environments (Van der Weerden et al., 2011; Lessa et al., 2014; Sordi et al., 2014; Cardoso et al., 2019). Climatic season is also another important factor driving N_2O emissions; in grassland ecosystems, emissions are higher during the rainy season (Lessa et al., 2014;

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Mazzetto et al., 2014; Cardoso et al., 2019). Recent studies have also shown that N_2O emissions from bovine excreta are lower than the Intergovernmental Panel on Climate Change (IPCC) emissions factor (EF) of 2% of N excretion emitted as N_2O. In a review of 418 studies, Cai and Akiyama (2016) found an N_2O EF of 0.76 % for urine and 0.27 % for dung; this was updated by Cardoso et al. (2019) who found an EF of 0.84 % for urine and 0.28 % for dung.

These differences in N_2O production are caused by the type of N in the excreta (mainly urea in urine and organic N in dung), soil moisture, and temperature (Van der Weerden et al., 2011; Lessa et al., 2014; Mazzetto et al., 2014; Cardoso et al., 2019). An alternative practice for reducing environmental impacts, by stocking carbon (C) in trees and improving animal welfare and the biodiversity of the productive system, is the inclusion of trees in the grazing system—silvopasture (SPS; Lima et al., 2019). There are differences in soil moisture and temperature (Neel et al., 2016), as well as in the N returns (Lopes et al., 2017; Lima et al., 2019), between SPS and monoculture pasture (MONO). There is an unsolved research question about how N_2O emissions differ between SPS and MONO. The presence of trees and grass in the system can improve N usage by plants and reduce the N available for losses via N_2O. However, the N returns from animal excretion and higher soil moisture may increase N losses. Therefore, we hypothesized that N2O emissions may differ between grazing system and season, with emissions being relatively high in SPS compared to MONO and during the rainy season compared to the dry season.

Ammonia emissions from animal excreta are driven by the excreta as well as soil pH and soil temperature (Nichols et al., 2018). As discussed above, in SPS, it is expected that soil temperature and soil recycling of N may vary, and probably affect NH_3 losses. Recent studies have shown that NH_3 emissions from excreta are lower than the EF of 20 % for bovine excretion of N lost as NH_3 suggested by IPCC (2019) guidelines (Lessa et al., 2014; Cardoso et al., 2019). Thus, differences in NH_3 emissions from excreta between SPS and MONO are expected.

With regard to CH_4 emissions from dung, the amount of C and moisture content at the time of dung deposition drive CH_4 production (Jarvis et al., 1995; Mazzetto et al., 2014; Cardoso et al., 2019). Protein content is higher under the severe shading conditions of long-term SPS than under MONO (Lima et al., 2019). Protein and fiber content of forage can influence the biochemical composition of dung, and, consequently, the available C that can affect CH_4 production. Another important factor that affects CH_4 production from dung is the formation of a crust on the patch of dung that ends CH_4 production (Holter, 1997; Cardoso et al., 2018, 2019). Variation in CH_4 emissions due to season is caused by air temperature and the water content of dung that probably differ between SPS and MONO due to the shaded conditions in SPS, which keep the dung moist for longer. Therefore, grazing system and season may affect CH_4 emissions, which could be relatively high in the rainy season compared to the dry season and in SPS compared to MONO.

SPS is considered an option by Brazil and other countries to deal with climate change. However, studies reporting the nature and magnitude of effects of SPS on GHG and NH_3 emissions from cattle excreta are unknown. In this study, we aimed to quantify N_2O, CH_4, and NH_3 emissions from animal excreta (urine vs dung) during two seasons (rainy vs dry) and in two grazing systems (SPS vs MONO).

2. Materials and methods

2.1. Soil and site description

The present study was conducted at the Embrapa Dairy Cattle unit (Brazilian Agricultural Research Corporation), located in the city of Coronel Pacheco, Minas Gerais State, Brazil, from February to April and July to October 2017. The geographical coordinates of the experimental site are 21°33′S and 43°06′W, and it is 410 m a.s.l. According to the Köppen climate classification, the climate of the region is type Cwa (mesothermal). Average air temperature is 17 °C from April to September and 24 °C from October to March. The soil of the experimental area is a dystrophic Ferralsol (WRB-FAO) with undulating relief. The physical and chemical properties of the soil at the start of the experiment are shown in Table 1. Climatic data for the experimental period were collected at the Meteorological Station of the Experimental Field at Coronel Pacheco, approximately 500 m from the experimental area.

Table 1
Physical and chemical properties of *Brachiaria* pastures soil (0-10 cm depth) under silvopasture system (SPS) or monoculture (MONO).

Properties	SPS	MONO
pH (H_2O)	4.6 ± 0.08	5.2 ± 0.15
P (mg dm^{-3})	5.3 ± 0.63	5.7 ± 1.90
K (mg dm^{-3})	75.0 ± 11.01	71.0 ± 21.00
Ca^{2+} (cmolc dm^{-3})	1.3 ± 0.03	1.6 ± 0.05
Mg^{2+} (cmolc dm^{-3})	0.8 ± 0.25	0.6 ± 0.16
Al^{3+} (cmolc dm^{-3})	0.5 ± 0.30	0.2 ± 0.10
H + Al (cmolc dm^{-3})	7.7 ± 0.11	5.9 ± 0.07
OM (dag kg^{-1})	5.4 ± 0.37	4.9 ± 0.25
P-Rem[a] (mg L^{-1})	25.1 ± 2.40	23.7 ± 1.70
BD[b] (kg dm^{-3})	0.99	0.95
PD[c] (g cm^{-3})	2.65	2.65
Sand (g kg^{-1})	306	337
Clay (g kg^{-1})	495	495
Silt (g kg^{-1})	147	168

[a] P-Rem, Remaining phosphorus, Amount of phosphorus added that remains in the equilibrium solution, after a certain time of contact with the soil.
[b] BD, soil bulk density determined by the volumetric ring method (Embrapa, 1997).
[c] PD, particle density, mean value for this type of soil (Kiehl, 1979).

Evaluations were performed in a long-term SPS and MONO of *Brachiaria decumbens* (syn. *Urochloa decumbens*), both of which were established in November 1997 in an eight-hectare area of mountainous topography with ~ 30 % slope. The SPS consisted of *B. decumbens* cv. Basilisk and the legume tree *Acacia mangium* as well as *Eucalyptus grandis*, arranged in alleys comprising parallel rows with an intrarow spacing of 3.0 m and an interrow spacing of 3.0 m. The two tree species were planted alternately in each of the rows, which reduced the incidence of photosynthetically active radiation (PAR) by approximately 70 % compared to monoculture (open pasture), thus characterizing an intensely shaded environment.

The total study area of 611 m^2 was subdivided into 36 plots of 4 m^2 (18 plots in each system) distributed in three blocks (Fig. 1), and fenced off to avoid animal disturbance. In SPS, the experimental plots were placed between the rows of trees, since the on-farm tropical conditions led the animals to usually select shady areas for rumination and idling (Domiciano et al., 2016). As such, these areas generally had a greater deposition of excreta compared to intergrove spaces. Before the experiment began, animals were excluded from the experimental area for one year, so that there was no residual effect of excreta previously deposited on the soil by them.

Throughout the experimental period, the plots were periodically harvested to maintain an herbage height of ~ 35 cm, and the plant cuttings were removed from the plots, simulating continuous grazing. The percentage of shade and PAR were evaluated using an AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA, USA). In SPS, 10 measurements were made in the intrarow and interrow spacing. In the area without trees, characterized by open pasture of *B. decumbens*, 10 PAR measurements were taken randomly. Measurements were made under clear skies, taking open pasture as a reference, in the rainy and dry seasons, at 09:00, 12:00 and 15:00, one meter above ground level. From these data, a 70 % reduction in PAR was calculated for SPS relative to MONO. Tree height and diameter at breast height (DBH) were measured for both tree species. *E. grandis* had an average height of 29 m and DBH of 45 cm, while *A. mangium* had a height of 14 m and DBH of

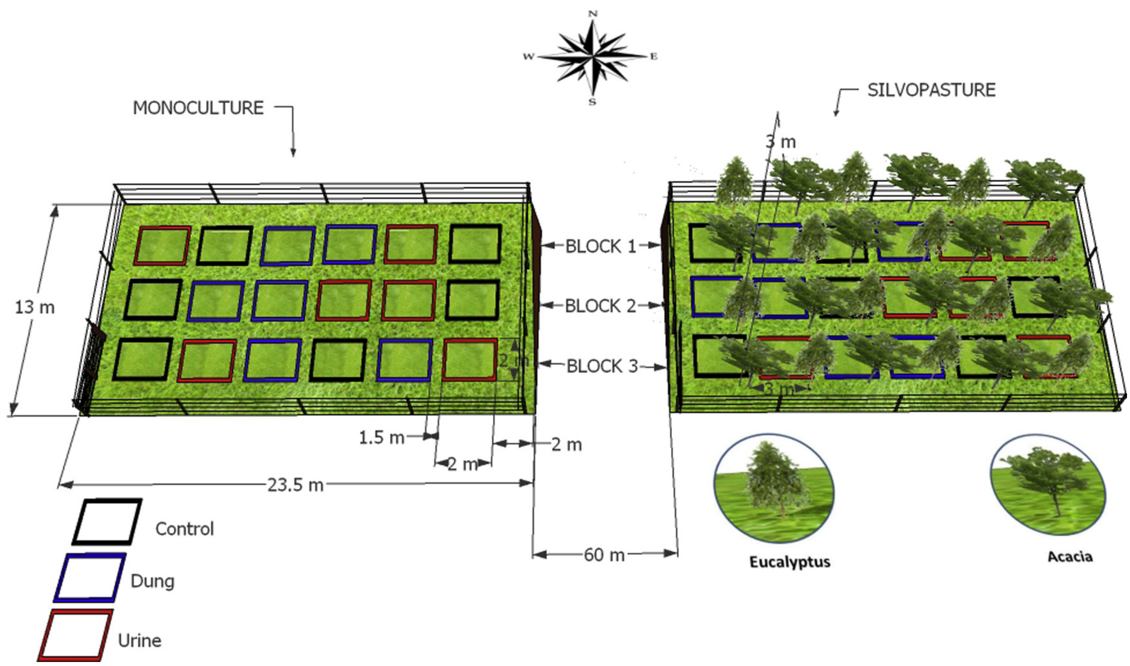

Fig. 1. Experimental schema.

32 cm.

2.2. Experimental design and excreta handling

The treatments were arranged in a 3 × 2 factorial scheme, corresponding to three excreta types (urine, dung, and control without excreta) and two pasture systems (MONO and SPS) within a complete block design, with three blocks and two replicates per block, totaling six replicates per treatment (Fig. 1). The same factorial design was used in both seasons (rainy and dry).

As our objective with these trials was to evaluate the effects of the systems as a whole (MONO and SPS) on N_2O, CH_4, and NH_3 emissions, both urine and dung from cattle grazing in each system were used since the shade level in SPS was heavy and increased the N content of the grass.

Urine and dung were collected fresh from 12 crossbred (Holstein × Zebu) cows of approximately 500 kg weight belonging to Embrapa Dairy Cattle. Six cows were allowed to graze in MONO and six in SPS for approximately 30 days (in paddocks adjacent to the fenced area) during each period of the year. The cattle received only mineral supplementation ad libitum. One day prior to the start of gas sampling, the animals were contained for collection of fresh dung and urine; the latter was collected using a probe inserted into the urethra. Immediately after collection, the dung from the six cows of each system was combined (for MONO and SPS separately), homogenized, and sampled for subsequent analysis of total N content. The same procedure was used for urine samples. Volatile solid content was analyzed through loss-on-ignition in a muffle furnace at 550 °C.

In each plot, a fresh dung patch, 1.6 kg in weight, was placed at the center of a rectangular metal frame used as the bottom of the static chamber for GHG measurement. The dung patch was deposited with the aid of a plastic ring approximately 24 cm in diameter and 5 cm in height to ensure homogeneous coverage of the area by excreta. For urine deposition, 1 L of the fresh combined sample was applied per chamber, taking care to moisten the entire area delimited by the rectangular metal frame (0.24 m^2) to simulate urination by the animal. The amounts of dung and urine applied in each plot were within the range of elimination by an adult animal in a single excretion event: 1.5–2.7 kg of dung (Haynes and Williams, 1993) and 0.8–1.7 L of urine (Whitehead, 1995).

The evaluations during the rainy season began on February 5, 2017 and ended on April 24, 2017. During dry-season evaluations, samplings began on July 29, 2017 and ended on October 26, 2017. The procedures for obtaining and depositing dung and urine were the same, although the position of the chamber within each plot was changed so that there was no overlap between the excreta applied in the rainy and dry periods.

2.3. Forage and soil litter characterization

During each trial (rainy and dry season), forage samples were collected from the plots to characterize the condition of the pasture in each system. For this, six plots were randomly selected in each block, and all forage contained within a 0.5 × 0.5 m square was removed from points representative of the average pasture condition. Samples were obtained in the same way from each of the two systems (SPS and MONO), giving a total of nine samples (3 plots × 3 blocks) from each system. The samples were dried in a forced-air oven at 55 °C for 72 h, weighed to determine dry matter (DM) yield, and then ground using a Wiley mill (1-mm sieve) and analyzed for total N using the Kjeldahl procedure (AOAC, 1990).

To characterize the existing litter in each system, six plots within each system were randomly selected, and samples of the litter within a 0.5 × 0.5 m square were collected. The samples were dried in a forced-air oven at 55 °C for 72 h, and the carbon (C) and nitrogen (N) content, as well as the C:N ratio, was determined by dry combustion (Vario EL III, Elementar Analysensysteme GmbH, Germany). The characteristics of forage and litter in each system are presented in Table 2.

2.4. Quantification of N_2O and CH_4 emissions

Manual closed static chambers, similar to that described in Alves et al. (2012), were used for GHG monitoring. In brief, chambers were of top–bottom type, the bottom being a rectangular frame made of iron, with a width of 40 cm, length of 60 cm, and a 7 cm high wall, for insertion into the soil when deployed. In the upper perimeter, a trough 2 cm wide and 2 cm high allowed a water-sealed connection with the top part. The top part had the same dimensions as the base, but its

Table 2
Characteristics of forage, dung, urine and litter in *Brachiaria* pastures under silvopasture system (SPS) or monoculture (MONO) in rainy and dry seasons.

Item	SPS rainy	SPS dry	MONO rainy	MONO dry
		Forage		
Forage mass (kg DM ha^{-1})	2217 ± 306	604 ± 62	5538 ± 459	3406 ± 283
Tiller population density (tillers m^{-2})	275 ± 33	53 ± 10	386 ± 35	276 ± 47
Nitrogen (%)	1.73 ± 0.02	1.55 ± 0.02	1.29 ± 0.05	1.27 ± 0.01
		Dung		
Nitrogen (%)	1.55 ± 0.01	1.71 ± 0.01	1.49 ± 0.01	1.52 ± 0.01
Volatile solids (%)	85.22 ± 0.21	81.46 ± 0.46	84.67 ± 0.28	79.97 ± 0.21
		Urine		
Nitrogen (%)	0.94 ± 0.00	0.37 ± 0.01	0.37 ± 0.01	0.24 ± 0.00
		Litter[a]		
Carbon (%)	37.60 ± 0.33 (SPS)		36.01 ± 0.56 (MONO)	
Nitrogen (%)	1.92 ± 0.03 (SPS)		0.79 ± 0.02 (MONO)	
C:N ratio	20.01 ± 0.20 (SPS)		45.58 ± 0.69 (MONO)	

[a] Annual average. DM (dry matter); C (carbon); N (nitrogen).

height was 24 cm when coupled to the base. It was insulated with an aluminized thermal insulation mantle to minimize temperature increase after deployment.

Chamber bases were inserted into the soil up to the level of the trough one week before the beginning of gas flux measurements, and remained in place until the end of the study to avoid interference due to soil disturbance. Chamber headspace was always sampled between 09:00 and 11:00, assuming that the GHG flux at this time represented the average of the fluxes of the day (Alves et al., 2012). The internal temperature of the chamber was also recorded using digital thermometers at the time of gas collection for correction of gas fluxes afterward. The air samples were collected at 0, 20, 40, and 60 min after chamber deployment by using 60 mL polyethylene syringes. After flushing out a 10 mL volume, a volume of 30 mL was taken from the chamber and transferred to 20 mL chromatography vials within an hour from chamber sampling. The chromatography vials were evacuated before use with the aid of an electrical vacuum pump.

In the rainy season, gas sampling started two days before excreta deposition in the plots (days "-2" and "-1"), and continued for 10 consecutive days after deposition. Subsequently, gas sampling was performed every two days for two weeks, and then weekly for a period of approximately three months. When rainfall occurred during the last period, additional sampling was carried out for two or three consecutive days. In the dry season, gas sampling also started two days before excreta deposition, but continued for five consecutive days after deposition, followed by weekly samplings for approximately three months, which coincided with the end of the dry season. After collection, N_2O and CH_4 concentrations in the gas samples were analyzed simultaneously using a gas chromatograph equipped with a flame ionization detector for CH_4 and an electron capture detector for N_2O (Autosystem, Perkin-Elmer, Waltham, MA, USA). The respective fluxes were calculated with the following equation proposed by Barneze et al. (2014):

$$f = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \frac{M}{Vm} \times \frac{273}{(T + 273)},$$

where f is the gas flux in μg m^{-2} h^{-1}; ΔC is the change in gas concentration in the chamber during the incubation period in μL L^{-1}; Δt is the incubation time in hours; V is the chamber volume in L; A is the area of soil covered by the chamber in m^2; M is the molecular weight in g mol^{-1}; Vm is the molecular volume (standard temperature and pressure [STP]) in L mol^{-1}; and T is the internal temperature of the chamber at the sampling time in °C.

The hourly fluxes were multiplied by 24 to obtain the daily fluxes. From the integration of the results for N_2O and CH_4 fluxes obtained during the evaluation periods, the fraction of N applied as excreta that was emitted as N_2O was calculated, as well as the fraction of the volatile solids (VS) present in the dung that was emitted as CH_4, in both cases after subtraction of the emissions from the control treatment (no excreta).

2.5. Soil analyses

A microplot of the same size as that used with the chamber for quantification of N_2O and CH_4 (40 cm × 60 cm) was previously delimited within each plot for soil sampling and N loss measurement by NH_3 volatilization. This area received the same amount of excreta. Soil samples were taken from the 0–10 cm depth layer using a steel probe (SONDATERRA®, S-100) and was analyzed for gravimetric moisture and mineral N content (NO_3^- and NH_4^+) according to Martins et al. (2015). Soil temperature was measured at the same depth using digital thermometers. Undisturbed cores were collected from each plot using stainless steel rings, and were oven dried to determine soil bulk density for further calculation of total soil porosity and the percentage of water-filled pore space (WFPS).

2.6. Quantification of NH_3 volatilization

A semi-open static chamber method, described in detail by Araújo et al. (2009) and Jantalia et al. (2012), was used to quantify NH_3 volatilization from urine and dung. The chamber was constructed from a transparent 2 L polyethylene terephthalate plastic bottle (soda bottle) 10 cm in diameter with the bottom removed. A 3 mm thick, 2.5 cm wide, and 25 cm long polyethylene foam strip moistened with 10 mL of 1.0 mol dm^{-3} H_2SO_4 solution + glycerin 2% (v/v) was hung vertically from the bottle top with the lower end inserted into a 60 mL plastic pot containing a volume of the acid solution that was not absorbed by the foam strip.

Ammonia volatilization was monitored for 20 days after excreta deposition during the rainy season, and for 24 days during the dry season. The foam strips were changed every two days during the first week, and then every three days until the end of the evaluations. Following replacement of foam strips, the 60-mL plastic pot containing the removed foam strip was transported to the laboratory, where the remaining solution was mixed with 40 mL of distilled water; the foam strip was immersed in this solution and put into a horizontal shaker for 20 min. Ammoniacal N was quantified by distillation and titration. Real N losses were obtained by using a correction factor under the assumption of 57 % efficiency of the semi-open chamber (Araújo et al., 2009).

2.7. Statistical analyses

Evaluations for rainy and dry seasons were carried out separately. Due to different excreta-N applied in SPS and MONO, only the data on emission factors were subjected to statistical analysis for comparing the

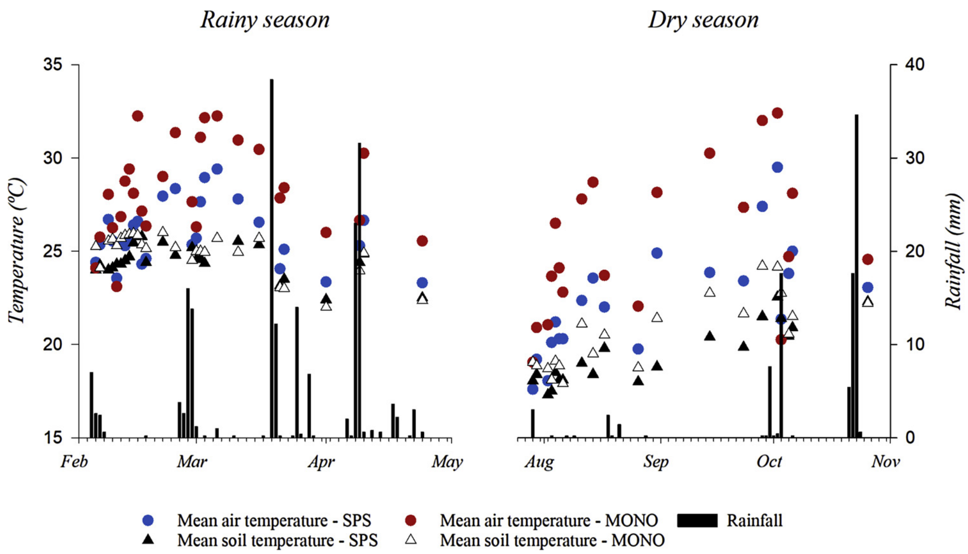

Fig. 2. Rainfall data and mean air and soil temperatures in SPS and MONO during rainy and dry seasons.

systems. All analyses were performed using PROC MIXED in SAS® (version 9.0; SAS Institute Inc., Cary, NC, USA). Due to system factor randomization constraints within each experiment, the Huynh-Feldt (HF) correction for sphericity was applied to evaluate independence between plots. In this context, the hypothesis of independence between plots was evaluated and confirmed for all variables, thus implying efficiency of the randomization method used under the conditions of this experiment. Means were compared using the *F*-test at the 5% significance level, since the control treatment was considered only for calculation of the emission factors; therefore, it was not compared with the other two treatments (dung and urine). Thus, the two factors in the study (type of excreta and type of system) each had only two levels.

3. Results

3.1. Temperature and rainfall

Air temperature was generally higher and had higher oscillations in MONO than in SPS, and temperatures were higher during the rainy season than in the dry season (Fig. 2). Soil temperature at 10 cm depth did not differ significantly between the two pasture systems during the rainy season, but it was two to four degrees higher in MONO during the dry season (Fig. 2). Total cumulative rainfall was 141.8 mm during the rainy season and 92.4 mm during the dry season. Overall, 63 % of the rainfall during the dry season occurred in late October.

3.2. Carbon and nitrogen content of forage, litter, and cattle excreta

The available forage mass in MONO and SPS was 5.5 and 2.2 Mg ha^{-1} on a dry mass (DM) basis, respectively, in the rainy season, while it was 3.4 and 0.6 Mg DM ha^{-1}, respectively, in the dry season (Table 2). As a function of greater forage availability, tiller density was also greater in MONO, irrespective of season. On the other hand, N content in forage mass was 22–34 % higher in SPS than in MONO.

Plant litter in MONO had a N content of 0.79 % that was almost 61 % of that in forage mass (1.3 %). On the other hand, in SPS, the N content of litter was 1.92 %, while that of forage mass was 1.55–1.73 %, suggesting that a significant proportion of plant litter originated from the legume trees in this system. The C content of litter was approximately 36–37 % in both systems. As a consequence, the C:N ratio of soil litter in SPS was nearly 20 against almost 46 in MONO (Table 2).

The excreta collected from the cattle grazing in SPS were richer in N compared to the excreta from animals in MONO (Table 2). In the rainy season, urine from animals in SPS had 2.5 times more N than urine from animals grazing in MONO. This difference was small in the dry season, but the N content in urine from animals in SPS was still 54 % higher than that from animals in MONO.

3.3. Soil moisture and mineral N content

The possible effects on WFPS of urine and dung deposition on soil were not demonstrated by our measurements. Soil WFPS was 40–50 % (mean 44 %) in SPS and 40–60 % (mean 47 %) in MONO during the rainy season (Fig. 3a and b). In the dry season, soil WFPS remained 30–40 % in SPS (mean 36 %) and MONO (mean 39 %) throughout the period (Fig. 3a and b). Soil moistening coincided with rain events in both seasons. In both systems, there was no great difference between plots treated with dung or urine and the control plots (Fig. 3a and b).

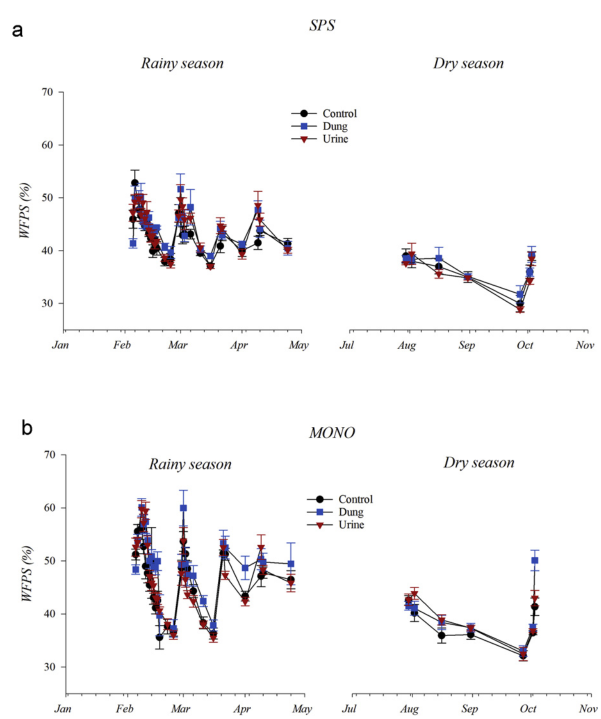

Fig. 3. WFPS in the 0-10 cm layer of soil in SPS and MONO in the rainy and dry seasons. The bars represent the standard error of the means.

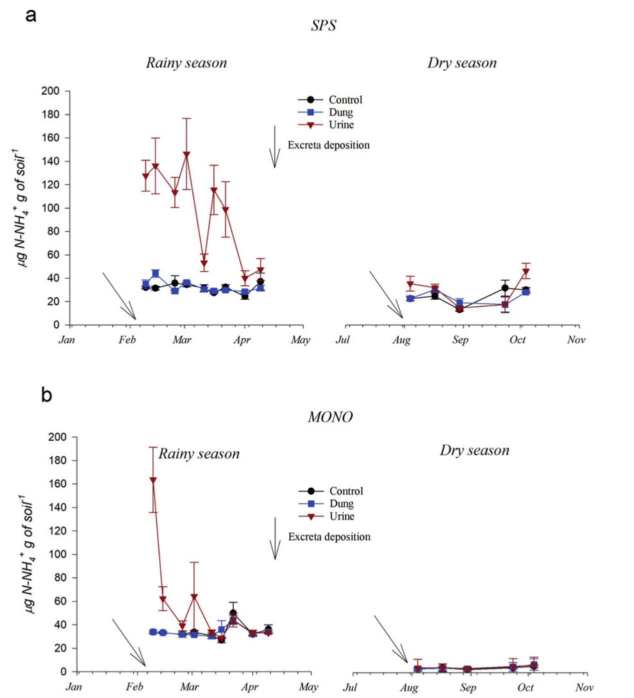

Fig. 4. NH_4^+ contents in the 0-10 cm soil layer in SPS and MONO in the rainy and dry seasons. The bars represent the standard error of the means.

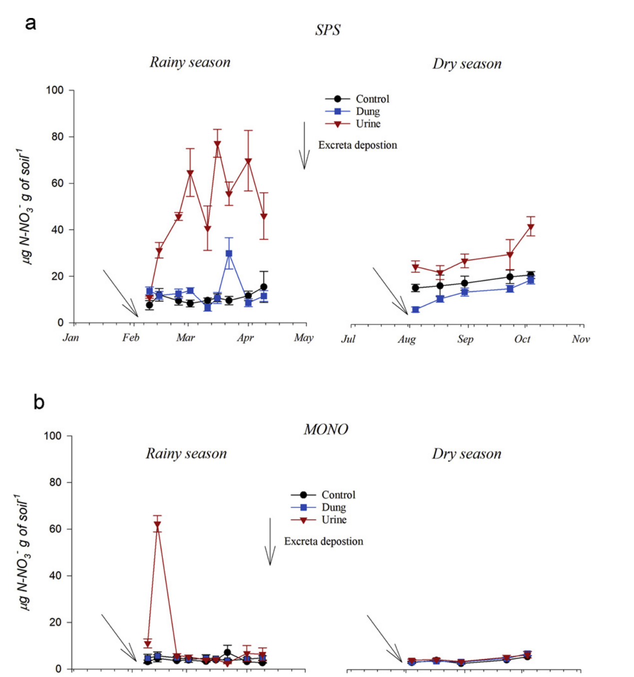

Fig. 5. NO_3^- contents in the 0-10 cm soil layer in SPS and MONO in the rainy and dry seasons. The bars represent the standard error of the means.

During the rainy season, urine application significantly increased mineral N levels (NH_4^+ and NO_3^-) in the soil relative to the control plots under both systems, whereas application of dung had a small effect (Figs. 4a, b, Fig. 5a, and b). In SPS, mineral N content in the plots that received urine remained higher than in the other plots throughout the evaluation period, whereas an increase was observed only in the first week following application in MONO, with the plots remaining at similar levels to the control during the rest of the evaluation period. During the dry season, mineral N concentration in the soil was markedly lower than in the rainy season, but it was always higher in SPS (Figs. 4a, 4b, 5a, and 5b).

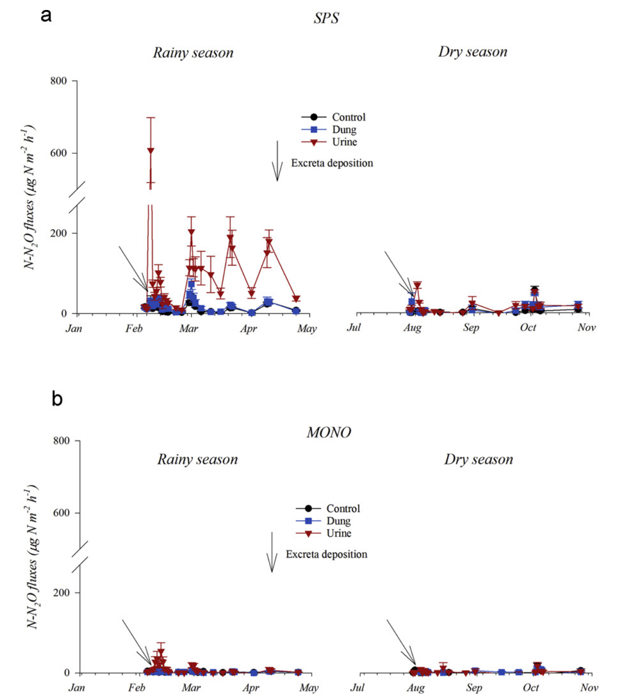

Fig. 6. Mean daily fluxes of N_2O in SPS and MONO in the rainy and dry seasons. The bars represent the standard error of the means.

3.4. Nitrous oxide emissions

During the rainy season, N_2O fluxes in SPS were rather higher than the fluxes in the MONO system (Fig. 6a and b). Although of much lower magnitude, SPS continued to exhibit higher N_2O emissions than MONO in the dry season. The type of excreta also induced N_2O fluxes differently, with a peak of 608 µg N m^{-2} h^{-1} where urine was applied, almost five times the highest peak induced by dung in the SPS area during the rainy season (Fig. 6a). A peak about 10 times lower, of approximately 54 µg N m^{-2} h^{-1}, from urine was registered in MONO in the rainy season, but it was at least three times that from dung (Fig. 6b). In both systems, there was no difference between plots treated with dung and the control plots (Fig. 6a and b).

In SPS, in the rainy season especially, N_2O fluxes from the urine-applied area peaked soon after excreta application and oscillated strongly during the monitoring period, indicating responses to external stimuli (Fig. 6a). The N_2O fluxes increased after rainfall events, and reductions in fluxes were associated with drier days. Gas flux oscillations coincided with fluctuations in air temperature and rainfall (Fig. 2), as well as with variations in soil WFPS (Fig. 3a). In MONO, emission peaked only on the fifth day after excreta application, but unlike in SPS, subsequent rainfall events did not result in a significant increase in N_2O fluxes (Fig. 6b).

In the case of cumulative N_2O emissions from excreta-treated areas during the measurement periods, while subtracting the cumulative N_2O emission from control plots, the fraction of N lost as N_2O was estimated by the ratio of net N_2O emissions and the respective amount of N applied as excreta. Significant effects of the pasture system ($p < 0.001$), type of excreta ($p < 0.001$), and the interaction between these factors ($p < 0.05$) were observed (Table 3). During the rainy season, the percentage of N from urine lost as N_2O was higher ($p < 0.05$) in SPS (0.39 %) than in MONO (0.04 %). However, the pasture system did not significantly influence the percentage of N lost as N_2O from dung-treated areas during the rainy season ($p > 0.05$; Table 3). During the

Table 3
N content applied as urine or dung per area unit and fraction of N emitted as N_2O.

Treatment	N applied ($g\ m^{-2}$) SPS	MONO	Fraction of N emitted as N_2O (%) SPS	MONO	SEM[a]
			Rainy		
Dung	83.72	66.50	0.06 Ba	0.00 Aa	0.047
Urine	40.34	15.74	0.39 Aa	0.04 Ab	
			Dry		
Dung	80.72	76.77	0.04 Aa	0.03 Aa	0.028
Urine	15.99	10.23	0.10 Aa	0.06 Aa	

Means on the same line followed by different lowercase letters differ from each other ($P < 0.05$) by the F test.
Means in the same column followed by different capital letters differ from each other ($P < 0.05$) by the F test.
[a] Standard error of means.

Table 4
N content applied as urine or dung per area unit and fraction of N emitted as NH_3.

Treatment	N applied ($g\ m^{-2}$) SPS	MONO	Fraction of N emitted as NH_3 (%) SPS	MONO	SEM[a]
			Rainy		
Dung	83.72	66.50	1.23 Ba	1.77 Ba	0.604
Urine	40.34	15.74	4.28 Ab	8.25 Aa	
			Dry		
Dung	80.72	76.77	5.80 Aa	3.63 Ba	1.984
Urine	15.99	10.23	1.73 Ab	17.10 Aa	

Means on the same line followed by different lowercase letters differ from each other ($P < 0.05$) by the F test.
Means in the same column followed by different capital letters differ from each other ($P < 0.05$) by the F test.
[a] Standard error of means.

dry season, no significant difference ($p > 0.05$) was observed between any of the treatments (Table 3).

3.5. Ammonia volatilization

During the rainy season, the largest amounts of NH_3-N loss by volatilization were observed with urine deposition in both systems, reaching 14 mg N chamber^{-1} in SPS and 11 mg N chamber^{-1} in MONO, which was equivalent to 1.8 g N m^{-2} in SPS and 1.4 g N m^{-2} in MONO. Cumulative NH_3-N losses during the rainy season for dung amounted to 8.6 mg N chamber^{-1} (equivalent to 1.0 g N m^{-2}) and 9.8 mg N chamber^{-1} (equivalent to 1.2 g N m^{-2}) in SPS and MONO, respectively (Fig. 7). Losses by ammonia volatilization in both urine and dung patches were more severe during the dry season than during the rainy season. Total cumulative NH_3-N losses in urine patches were higher in MONO, totaling approximately 16 mg N chamber^{-1} or 2 g N m^{-2}, compared to only 3 mg N chamber^{-1} or 0.4 g N m^{-2} in SPS over 24 days (Fig. 7). Ammonia losses in the plots that received dung were higher in SPS, reaching 39 mg N chamber^{-1} or 4.9 g m^{-2} over 24 days of monitoring, while the cumulative N loss in MONO was approximately 25 mg N chamber^{-1} or 3.1 g N m^{-2} (Fig. 7). While NH_3 losses occurred in the first days after urine application, losses from dung started later and took longer, which was more clearly observed in SPS during the rainy season.

Differences between systems and excreta type were found in the percentage of N lost as NH_3. In the rainy season, the system ($p < 0.001$), excreta ($p < 0.0001$), and the interaction between the two ($p < 0.05$) affected the fraction of N lost as NH_3. The fraction of urine-N lost as NH_3 was significantly higher compared to the dung-N lost as NH_3, except during the dry season in SPS (Table 4). Differences between systems were only observed for urine, which had a higher percentage of N lost in MONO than in SPS, irrespective of the season (Table 4).

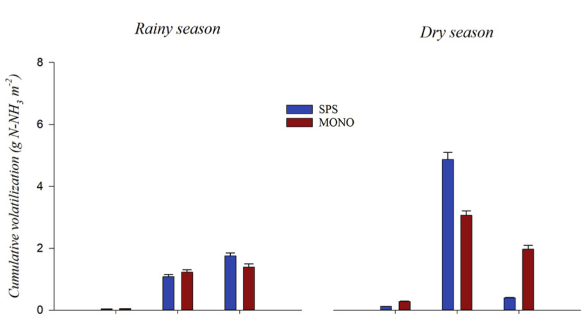

Fig. 7. Cumulative volatilization of NH_3 in SPS and MONO systems during rainy and dry season. The bars represent the standard error of the means.

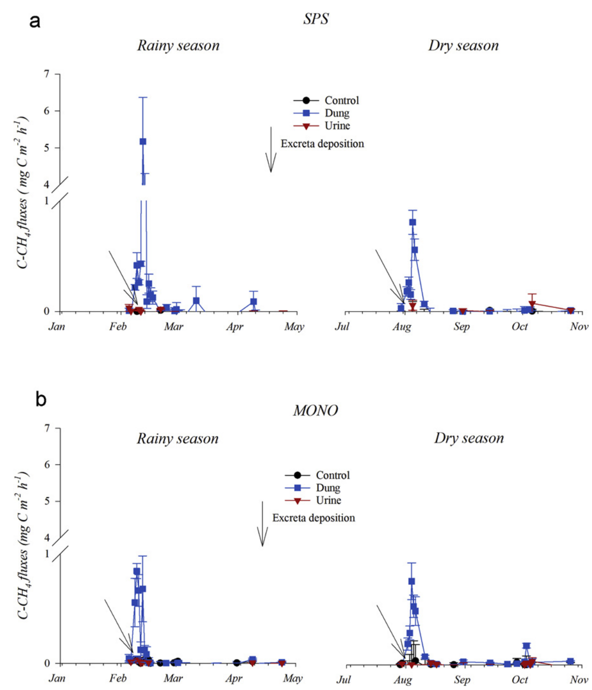

Fig. 8. Mean daily fluxes of CH_4 in SPS and MONO in the rainy and dry seasons. The bars represent the standard error of the means.

3.6. Methane emissions

CH_4 fluxes from dung-treated areas during the rainy season were higher in SPS than in MONO (Fig. 8a and b). Peak CH_4 emissions occurred in both systems soon after excreta application, although at different magnitudes. In SPS, peak CH_4 emissions reached approximately 5 mg m^{-2} h^{-1}, whereas the recorded peak was only 0.8 mg m^{-2} h^{-1} in MONO (Fig. 8a and b). In both systems and during both seasons, significant CH_4 flux increases induced by dung were observed during the first six days after deposition on the soil, with a subsequent lowering (similar to fluxes in the control group). Urine deposition did not induce any significant CH_4 flux increases across both systems and seasons.

In the case of CH_4 EF, a significant difference ($p < 0.05$) was observed between systems during the rainy season in the fraction of volatile solids in dung emitted as CH_4; it was significantly higher in SPS than in MONO (Table 5), whereas no difference ($p > 0.05$) was observed between the systems during the dry season (Table 5).

Table 5
Total volatile solids (VS) applied as dung per area unit and fraction of volatile solids emitted in CH_4 form.

	VS applied ($g\ m^{-2}$)		Fraction of VS emitted as CH_4 (%)		SEM[a]
Period	SPS	MONO	SPS	MONO	
Rainy	4612.73	3770.66	0.03 a	0.01 b	0.005
Dry	3837.58	4030.37	0.01 a	0.02 a	0.003

Means on the same line followed by different lowercase letters differ from each other ($P < 0.05$) by the F test.

[a] Standard error of means.

4. Discussion

4.1. N_2O emissions

The magnitude of obtained N_2O fluxes in both treatments is in line with the findings of several studies conducted across different soil types in other regions of Brazil, which also observed higher fluxes during the summer than in the winter, and from urine rather than dung deposition (Lessa et al., 2014; Sordi et al., 2014; Cardoso et al., 2016a). In the SPS system, denitrification may have been favored because N_2O peaks occurred after rainfall events that increased soil WFPS (Figs. 2 and 3a). Although the increase in WFPS after rainfall events was higher in MONO (Fig. 3b), the availability of mineral N in this system was lower than in SPS, which probably limited N_2O production more than in SPS. The presence of trees in SPS can explain the differences in WFPS, as bulk density of both areas was similar. In general, a small fraction of rainfall is intercepted by trees and runs along branches and trunks, making throughfall lower than in open-field incident precipitation (Knulst, 2004). Low N2O fluxes associated with excreta deposition in both systems occurred after a long period without rain, and even the urine volume was not enough to stimulate nitrification. This confirms that soil moisture is a main driver of N2O production (Smith et al., 2003; Cardoso et al., 2016), as also seen by the absence of significant N2O fluxes in both SPS and MONO during the dry season. After the return of rainfall in October, there was a small increase in soil mineral N concentration, mainly in SPS (Figs. 4a and 5a), suggesting that soil microbial activity was broadly limited by low soil moisture during the dry season. The difference in N_2O emissions during the rainy season between SPS and MONO can be attributed to the higher N content in urine from animals in SPS (de Klein et al., 2014) and due to the maintenance of favorable soil conditions (e.g., soil moisture, microbial activity, etc.) for a longer period in SPS systems.

Lima et al. (2019) evaluated the forage nutritive value and performance of dairy heifers grazing *B. decumbens* in the same experimental area of this study (SPS and MONO) for two years and observed crude protein content 25 % and 33 % higher in SPS relative to MONO during the first and second experimental year, respectively. While shaded plants may exhibit increased N concentration in leaves, the low C:N ratio in litter from legume trees seems also to be a suitable explanation for the high N content in *B. decumbens* aerial tissue in SPS, irrespective of season. The high C:N ratio of the litter in MONO (Table 2) may have resulted in higher immobilization rates and lower N mineralization when compared to the low C:N ratio of the litter deposited in SPS. Xavier et al. (2011) compared litter dynamics in the same areas of the present study and verified a larger amount of N in legume and eucalyptus litter in SPS, even though its decomposition rate was not different from that of MONO litter, which indicates a greater release of N to the soil in SPS. In addition, pasture biomass in MONO was clearly larger (Table 2), suggesting that plant competition for soil mineral N resulted in a limited supply for nitrification and denitrification (Verhagen et al., 1994; Mikola et al., 2009), resulting in lower N_2O emission.

Differences between excreta type were also observed by Lessa et al. (2014), who found EFs of 1.9 % and 0.14 % for urine and dung, respectively, during the summer in the Brazilian Savanna (Cerrado), values that decreased almost to zero during the dry season. Although relatively lower in magnitude, in Sordi et al.'s (2014) study, emissions from urine (mean EF of 0.26 %) were greater than those from dung (mean EF of 0.15 %) in the summer period in southern Brazil. Cardoso et al. (2019) also found differences between excreta type: EF of 0.73 % for urine and 0.41 % for dung. This difference between excreta in the percentage of N lost as N_2O usually found in the literature can be explained by the N composition of urine and dung. At least 70 % of the N in urine is in the form of urea (Haynes and Williams, 1993), which is rapidly hydrolyzed into NH_4^+ on contact with soil urease. On the other hand, the N present in dung is part of more complex organic forms, and is not readily available for hydrolysis (Haynes and Williams, 1993). Therefore, the release of mineral N from dung to the soil is slower than from urine, possibly by immobilization intensification stimulated by the relatively high C:N ratio of dung (Senbayram et al., 2012). In this study, lower NH_4^+ concentrations were observed in areas affected by dung than in areas affected by urine.

Recently, the IPCC published the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019). In this refinement, studies of 30 days or more in duration were considered to calculate N_2O emissions factors. In our case, we conducted one trial of 78 days in the rainy season and another of 89 days in the dry season. Therefore, to put our study into the context of GHG inventory studies, we calculated average EF under the reasonable assumption that in the studied area half the year corresponded to the rainy season and the other half to the dry season (Fig. 1). The estimated mean annual fraction of N from excreta lost as N_2O would be 0.25 % for urine and 0.05 % for dung in SPS, while it would be 0.05 % for urine and 0.01 % for dung in MONO. Considering urine excretion close to that estimated by Da Silva et al. (2001) and Barneze et al. (2014) of 10 liters per animal per day and fecal excretion close to that estimated by Orr et al. (2012) and Mazzeto et al. (2014) of 10 kg per animal per day, emissions of approximately 0.25 g N-N_2O per animal per day in SPS and of 0.03 g N-N_2O per animal per day in MONO were obtained, assuming average N content in urine and dung in each of the systems (Table 2).

This contribution of the N-N_2O emissions per animal estimated for each system would certainly be much higher if we considered an EF of 0.4 % for excreta as suggested by the IPCC (2019), without distinguishing dung and urine (approximately 0.92 g N-N_2O $animal^{-1}$ day^{-1} in SPS and 0.74 g N-N_2O $animal^{-1}$ day^{-1} in MONO), which demonstrates the need for local assessments to determine emissions with greater precision. Despite the higher emission per animal estimated for SPS than for MONO, the higher N content in the former may constitute a nutritional benefit for the animals and compensate for reduced forage mass (Lima et al., 2019). In addition, SPS with moderate shade has been proven to allow greater animal productivity than monoculture (Paciullo et al., 2011), which would lower the intensity of GHG emission (Cardoso et al., 2016). However, under on-farm conditions, tree management (pruning and thinning) should be planned to provide moderate levels of shade and sustain pasture and animal productivity over time.

The average EF of N_2O found in our study in both systems may have been underestimated when compared to other studies carried out in Brazil due to the greater slope of the experimental area. Gu et al. (2011) and Luo et al. (2013) demonstrated that topography can affect N_2O emissions, with higher emissions in low-slope soils due to greater soil fertility, soil aeration and microbial activity (e.g., nitrification and denitrification) in these areas compared to hilly areas. However, our main objective was to assess the effect of different grazing systems on emissions and to relate this EF to the default suggested by IPCC. In addition, animal production on hilly pastures is prevalent worldwide, especially in the region of the present study. Therefore, as the slope of the two systems was the same and the IPCC guidelines do not separate areas by slope, our comparison is fair and relevant in an attempt to estimate local emissions more accurately. Future studies are needed to investigate the effect of slope on N_2O emissions in comparisons of MONO and SPS.

4.2. Ammonia volatilization

Volatilized NH_3 is one of the sources of indirect emission of N_2O (IPCC, 2006). The percentage of N lost by volatilization of NH_3 obtained in this study agrees with the range of results reported in the literature. Saarijärvi et al., 2006, in a study conducted in Finland, found losses by NH_3 volatilization of 18 % and 1.5 % for N applied in the form of urine and dung, respectively, while Lessa et al. (2014) in Brazil, under conditions similar to those of the present study, found N losses by NH_3 volatilization of 23.6 % and 2.5 % in the rainy season and 20.8 % and 4.6 % in the dry season for urine and dung, respectively. Cardoso et al. (2019), also studying a tropical grassland, measured NH_3 volatilization of 6.3 % and 7.2 % in the rainy season and 14.2 % and 6.0 % in the dry season for urine and dung, respectively.

The lower N volatilization in the MONO treatment can be attributed to the low levels of free-NH_4^+ in dung owing to the greater recalcitrance of organic N, as discussed for N_2O emissions (see also Lessa et al., 2014). In an experiment conducted in New Zealand, Laubach et al. (2013) also found that 88 % of the N losses by volatilization occurred in urine and 12 % in dung, corroborating the results of the present study, although the losses in our study were smaller (Table 4). Ammonia volatilization is a pH-dependent process, and after dung deposition, there is a slow increase in pH in the liquid phase that is followed by a concomitant increase in NH_3 volatilization (Nichols et al., 2018; Cardoso et al., 2019). This process is impaired by dung dryness with the formation of a crust that limits gas diffusion (Petersen et al., 1998; Mulvaney et al., 2008). In the present study, the temperature was high throughout the year and there was no precipitation immediately after excreta deposition in either of the two seasons (Fig. 2), and, consequently, rapid crust formation on the deposited dung was observed.

The seasonal difference in NH_3 volatilization from both dung and urine in SPS and from urine in MONO, with higher volatilization in the dry period, can be explained by lower air humidity and higher wind speed during the dry season, which favor the diffusion of the gas into the atmosphere. Some climatic factors that affect the transfer of NH_3 gas from the soil solution to the atmosphere are temperature, air humidity, and wind speed, with higher losses by volatilization under high temperature conditions, low air humidity, and higher wind speed (Terman, 1980; Saggar et al., 2004). Given that soil properties differed little between SPS and MONO (Table 1), the significant difference in NH_3-N losses between the two systems in the area treated with urine in both seasons, with greater NH_3 volatilization in MONO, can be explained by differences in the microclimate. In SPS, the presence of trees may have functioned as a windbreak, thereby hampering NH_3 loss at the soil–atmosphere interface.

The weighted average fraction of N from excreta lost by NH_3 volatilization ($Frac_{GASM}$) was 3% for urine and 3.5 % for dung in SPS, and 12.7 % for urine and 2.7 % for dung in MONO. These emissions are lower than the default value suggested by the IPCC in the revised guidelines, which considered that 20 % of N from excreta is lost by NH_3 volatilization without distinguishing dung and urine.

4.3. CH_4 emissions

The CH_4 emission pattern following excreta deposition in the present study (Fig. 8a and b) was similar to that observed by Cardoso et al. (2018) in tropical pastures; they recorded 90 % of the emissions in the first four days after dung application, with reduction to levels close to the control treatment from the sixth day onward. Several other studies have also observed a significant contribution of CH_4 fluxes to cumulative CH_4 emissions in the first few days following excreta deposition (Jarvis et al., 1995; Saggar et al., 2004; Mazzeto et al., 2014; Mori and Hojito, 2015). This behavior is related to dung remaining wet in the first few days following deposition on the soil, ensuring adequate anaerobic conditions for methanogenesis. According to Holter (1997), Mazzeto et al. (2014), and Mori and Hojito (2015), after dung dries naturally, any new moistening caused by rainfall does not result in a stimulation of CH_4 fluxes, which is verified by the present study (Figs. 2, 8a, and b).

The differences in the fraction of total volatile solids emitted as CH_4 observed between the rainy and dry seasons in SPS may be related to air temperature and humidity differences between the two periods. CH_4 production occurs in a strictly anaerobic environment, and it has a positive correlation with soil moisture content (Gao et al., 2014). In addition, increasing temperature raises methanogenesis rates, provided that other parameters are kept constant (Williams, 1993; Saggar et al., 2004), owing to stimulation of respiration rates and the consequent O_2 depletion (Butterbach-Bahl et al., 2013). In MONO, CH_4 production was low after dung deposition, but there were no differences between seasons. Moreover, Mazzeto et al. (2014), Mori and Hojito (2015), and Cardoso et al. (2016, 2019) also observed higher CH_4 emissions in the hot and rainy season, and associated this response with the combination of elevated temperature and precipitation.

Although the nutritional management of the animals was the same in both systems (extensive management), the higher N content in SPS forage (Table 2) was accompanied by a higher N content in dung. According to Jarvis et al. (1995), there is an inverse relationship between CH_4 emission and the C:N ratio of dung, which was also observed by Pelster et al. (2016), confirming that dung N content influences the nature of organic fractions excreted by animals, especially the volatile solids, and results in higher CH_4 emissions. This explains the higher CH_4 emission from dung in SPS in the rainy season compared to SPS during the dry season and MONO during both seasons. In addition, dung deposited in SPS remained visually wetter for a longer period, whereas higher temperatures in MONO appeared to dry the dung more quickly and form a crust, which limited the emission of CH_4, as reported by Yamulki et al. (1999).

Using the average content of volatile solids in dung for each system and a fecal yield of 10 kg of fresh feces per animal per day (Orr et al., 2012; Mazzeto et al., 2014) in conditions similar to those of the present study, we could arrive at an average annual EF of 0.09 kg CH_4 $head^{-1}$ $year^{-1}$ in SPS and 0.06 kg CH_4 $head^{-1}$ $year^{-1}$ in MONO, close to the EF values of 0.1 and 0.06 kg CH_4 $head^{-1}$ $year^{-1}$ observed in a tropical climate by Mazzeto et al. (2014) during summer and winter, respectively. Our estimate was well below the EF of 1 kg of CH_4 $head^{-1}$ $year^{-1}$ estimated by the IPCC (Tier 1) and, lower than that found by Cardoso et al. (2019) of 0.79 kg $head^{-1}$ $year^{-1}$ and 0.18 kg $head^{-1}$ $year^{-1}$ in rainy and dry seasons, respectively, in the northeast of São Paulo, Brazil. On the other hand, Cardoso et al. (2018) calculated an EF of 0.95 kg of CH_4 $head^{-1}$ $year^{-1}$ in a study conducted in the state of Rio de Janeiro; however, a daily excretion rate of 24 kg of dung per animal was assumed in these calculations. If we consider this same daily excretion rate, the estimated EF would be 0.21 kg of CH_4 $head^{-1}$ $year^{-1}$ in SPS and 0.15 kg of CH_4 $head^{-1}$ $year^{-1}$ in MONO, which demonstrates the wide variability in emission factors found in different regions and under different conditions, as well as the need to generate factors that accurately represent local emissions.

5. Conclusions

Our study shows that N_2O and CH_4 emissions are higher in a long-term SPS than in a MONO system and that they are dependent on season. The differences are larger during the rainy season. This study also confirms previous findings that urine is the main source of N_2O losses from bovine excreta.

Regardless of excreta type and season, the measured fraction of N emitted as N_2O was well below 0.4 %, which is the IPCC (2019) emission factor. The same applies to our measured NH_3 volatilization losses and CH_4 emissions from dung when compared to the respective

EFs from the IPCC. Although IPCC guidelines included studies with a minimal duration of 30 days and a long campaign of GHG measurement, other silvopasture spatial arrangements (e.g., tree and grass species and shade levels) and soil types are required to confirm our findings and measure the key driving variables in SPS.

SPS appears to be an alternative for mitigating NH_3 losses from animal excretion as the microenvironmental changes in SPS reduced N losses through volatilization compared to MONO.

Declaration of Competing Interest

The authors declare no conflicts of interest.

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Changes in Soil Carbon Stocks under Integrated Crop-Livestock-Forest System in the Brazilian Amazon Region

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Abstract

Several studies indicate that the use of integrated production systems, such as integrated crop-livestock-forest systems (ICLF), improves the quality of the soil and consequently the sequestration of organic carbon in the soil. In this way, this work aims to evaluate the carbon stocks in soil under different management systems in the Cerrado/Amazonia transition zone, namely: ICLF, no-tillage, pasture and eucalyptus plantation. For this, two soil samplings were done in 2011 and 2014, in the 0 - 5, 5 - 10 and 10 - 30 cm layers. Soil carbon and nitrogen stocks were analyzed. ICLF system was the treatment that obtained the highest percentage of carbon gain (7.8%) after three years of establishment which represents to an increase of 5.5 $Mg \cdot ha^{-1}$. Management systems, such as ICLF, with minimal soil disturbance combined with crop rotations that contribute to the quantity and quality of residues input, increase soil organic matter content. Carbon stock data show the potential of ICLF systems to increase soil carbon stocks.

Keywords

Agriculture, Soil Carbon, ICLF, Soil Management

1. Introduction

Until the end of the last century, agriculture development was based on the expansion of new areas for cultivation, leading to the deforestation of large areas of native forests and natural ecosystems [1], resulting in losses of environmental services. According to [2], approximately 55 to 90 Pg of soil C have been lost from managed areas since the advent of agriculture, being one of the main causes of degradation and consequent decline of soil fertility.

As described by [3] and [4], while ensuring food security, there is an urgent need to reduce the impact of food production on the climate [5] and to improve the resilience of food production to future environmental changes [6], [7]. According to the projections of the Intergovernmental Panel on Climate Change (IPCC), the agricultural sector will be greatly affected by global climate change with impacts on its productivity, management and spatial distribution of crops. Thus, it is necessary to change the paradigm of agriculture with the use of management practices that favor the positive balance of physical and chemical attributes of the soil, such as increasing of C, N, water retention, reduction of soil loss by erosion and leaching.

During UNFCCC COP 15 (15^{th} Conference of the Parties under United Nations Framework Convention on Climate Change) in Copenhagen, Brazil undertakes a voluntary national commitment to reduce GHG emissions. This commitment was to reduce by 36.1% and 38.9% the 2020 projected emissions. With this, Brazil will mitigate between 975 million and 1 billion tons of carbon dioxide by 2020. For The fulfillment of the commitment, the Brazilian government created several mitigation and adaptation plans for different sectors of the economy, among them are the Low Carbon Agriculture Plan.

The GHG emission reduction potential of this plan is approximately 150 million Mg CO_2e, and does not consider the potential for removal from the forest plan. This plan corresponds to seven programs, six of which are related to mitigation technologies, and a last program with actions to adapt to climate change: Recovery of Degraded Pastures; Integrated Crop-Livestock-Forest System (ICLF) and Agroforestry Systems (AFs); No-Tillage System (NT); Biological Nitrogen Fixation (BNF); Planted Forests; Animal Waste Treatment; and Climate Change Adaptation.

In addition to this, Brazil has made a new commitment for the NDC (Nationally Determined Contributions) under Paris Agreement (UNFCCC COP21) to implement more 15 million hectares for recovery of degraded pastures and 5 million hectares of ICLF systems by 2030, confirming the potential of these technologies to mitigate greenhouse gases emissions and develop a low carbon agriculture in Brazil.

In agricultural soils, the carbon stocks are affected by changes in land use systems or management practices. Thus, the adoption of more sustainable management systems, such as ICLF, emerges as an alternative to conventional farming systems, with great potential to promote improvements in soil quality, especially with regard to the increase carbon stocks in the short- and long-term [8] [9] [10] [11] [12]. Tee-based systems are expected to have better soil C sequestration potential than most row crop agricultural systems [13]. At the same time, appropriate pasture management may affect soil C balance under ICLF systems and contribute to increase soil carbon stocks, because of higher biomass production associated with deep root systems while increasing physical protection of soil organic matter (SOM) against mineralization.

Soil organic matter (MOS) plays an important role in maintaining agricultural productivity. The accumulation of MOS promotes improvements in the physical, biological and chemical soil properties, allowing an increase in productivity and reduction of expenses with irrigation, fertilizers, soil conditioners and other agricultural inputs. Understanding how MOS behaves in different types of management is essential for the direction of public policies aimed at the dissemination of agricultural practices that increase the stocks of soil organic C and reduce GHG emissions.

2. Material and Methods

The sampling areas were located on experimental field at the Embrapa Agrosilvopastoral Research Center (11˚51'S, 55˚35'W; 384 m asl) in Sinop, State of Mato Grosso, Brazil. The mean annual temperature is 25˚C and mean annual rainfall is 2.550 mm [14]. The soil of the experimental site is classified as a Red Yellow Latosol (Oxisol) [15], a Udox [16]. The soil is a well-drained clay (32% sand, 56% clay), with non-hydromorphic characteristics. The top 0-20 cm layer has the following properties: pH (H_2O) = 5.6; CEC = 7.5 $cmol_c \cdot kg^{-1}$; Ca^{2+} = 2.5 $cmol_c \cdot kg^{-1}$; Mg^{2+} = 0.81 $cmol_c \cdot kg^{-1}$; K^+ = 0.19 $cmol_c \cdot kg^{-1}$; P = 14.3 $mg \cdot kg^{-1}$.

The experimental area was cleared of its native vegetation in 1984 for cultivation of cassava (*Manihot esculenta* Crantz) [17]. Any additional deforestation was stopped during the 2000s. [18] reported that rice (*Oryza sativa* L.) was cultivated on this land during the early 1990s, followed by soybean [*Glycine max* (L.) Merril]. Between 2002 and 2007, soybeans and maize (*Zea mays* L.) were incorporated into the conventional system.

During the 2007/2008 and 2008/2009 crop seasons, subsequently, the soybean and cotton (*Gossypium hirsutum* L.) successions were followed. During the 2009/2010 and 2010/2011 crop seasons the area was left fallow. In November 2011, subsoiling (chisel plowing to 40 cm depth) was done to alleviate compaction.

The experiment was then established in 2011 and comprised the following treatments: 1) Eucalyptus plantation (*Eucalyptus urograndis*, clone H13); 2) No-tillage system with soybean "BRSGO 8560RR" followed by corn (*Z. mays*) intercropped with *Urochloa brizanta;* 3) Pasture of *U. brizanta* "Marandu"; and 4) ICLF–integrated crop-livestock-forest system, comprising of three rows of eucalyptus (*E. urograndis)*, soybean followed by corn (*Z. mays*) intercropped with *U. brizanta* cultivated between tree rows. An area under Native Forest was used as a reference.

Soil samples were taken from 0 - 5, 5 - 10, 10 - 30 cm layers were obtained in 2011 and 2014 for determination of total C and N content. Each replicate was obtained of four subsamples bulked together. Samples were air dried, sieved through a 2-mm sieve, then further ground by a mill to pass through a 0.106 mm sieve and analyzed for total N and C concentrations by dry combustion (Vario Macro, Elementar Analysensysteme, Hanau, Alemanha) [19].

Soil cores (100 cm^3) were also collected from 0 - 5, 5 - 10 and 10 - 20 cm layers to evaluate soil bulk density (*BD*). The C and N stocks for each depth, were determined according to [20]:

$$Y_{\text{stock}}\left(\text{Mg}\cdot\text{ha}^{-1}\right) = X \times BD \times th \times (1 - S) \times 10^{-1} \quad (1)$$

where X is the C or N concentrations (g kg^{-1}); BD is the bulk density ($Mg\cdot m^{-3}$), th is the thickness of the soil layer (cm), and S is the stone content.

The amounts of carbon and nitrogen stocks were corrected by the equivalent mass method [21]:

$$Cs/Ns = \sum_{i=1}^{n-1} C/N_{Ti} + \left[M_{Tn} - \left(\sum_{i=1}^{n} M_{Ti} - \sum_{i=1}^{n} M_{Si} \right) \right] C/N_{Tn} \quad (2)$$

where Cs/Ns correspond to the stock of carbon or nitrogen ($Mg\cdot ha^{-1}$) in the soil to a depth equivalent to the reference. $\sum_{i=1}^{n-1} C/N_{Ti}$ the sum of the total content of carbon present in the first layer to the penultimate layer ($n - 1$) evaluated treatment. M_{Tn} the corresponding soil mass last layer of the estimated treatment. $\sum_{i=1}^{n} M_{Ti}$ the sum soil mass of the first to the last layer of the evaluated treatment. $\sum_{i=1}^{n} M_{Si}$ the sum of the soil mass first to the last layer of the reference area and C/N_{Tn} the C or N concentrations ($Mg\cdot Mg^{-1}$) in the last layer of the evaluated treatment.

Comparison of means was done by using standard errors values and the differences were attributed to the management systems, since evaluated treatments and Native Forest area presented similar soil type and topography.

3. Results and Discussion

Total carbon concentrations varied from 17.2 to 38.4 $g\cdot kg^{-1}$ (**Figure 1**). From 2011 to the end of 2014, changes in the contents of C and N were observed only in the uppermost soil layer (0 - 5 cm). However, the observed carbon values did not differ from 2011 and 2014 among the evaluated treatments.

After three years of cultivation, ICLF presented the highest increase of carbon concentration (15%) in the 0 - 5 cm layer, followed by Eucalyptus (13%), Pasture (9%) and No-tillage (8%). Except for Eucalyptus, management systems also contribute to increase total nitrogen, in the 0 - 5 cm layer. However, the increase in total nitrogen in all investigated soil layers was only observed for ICLF. The increase in total carbon concentration is probably related to the higher inputs of vegetal residues in the surface layer. Especially in the ICLF system, higher residues input were probably due to the combination of tree, pasture and crop in the same area. This higher availability of total carbon and nutrients, mainly in the

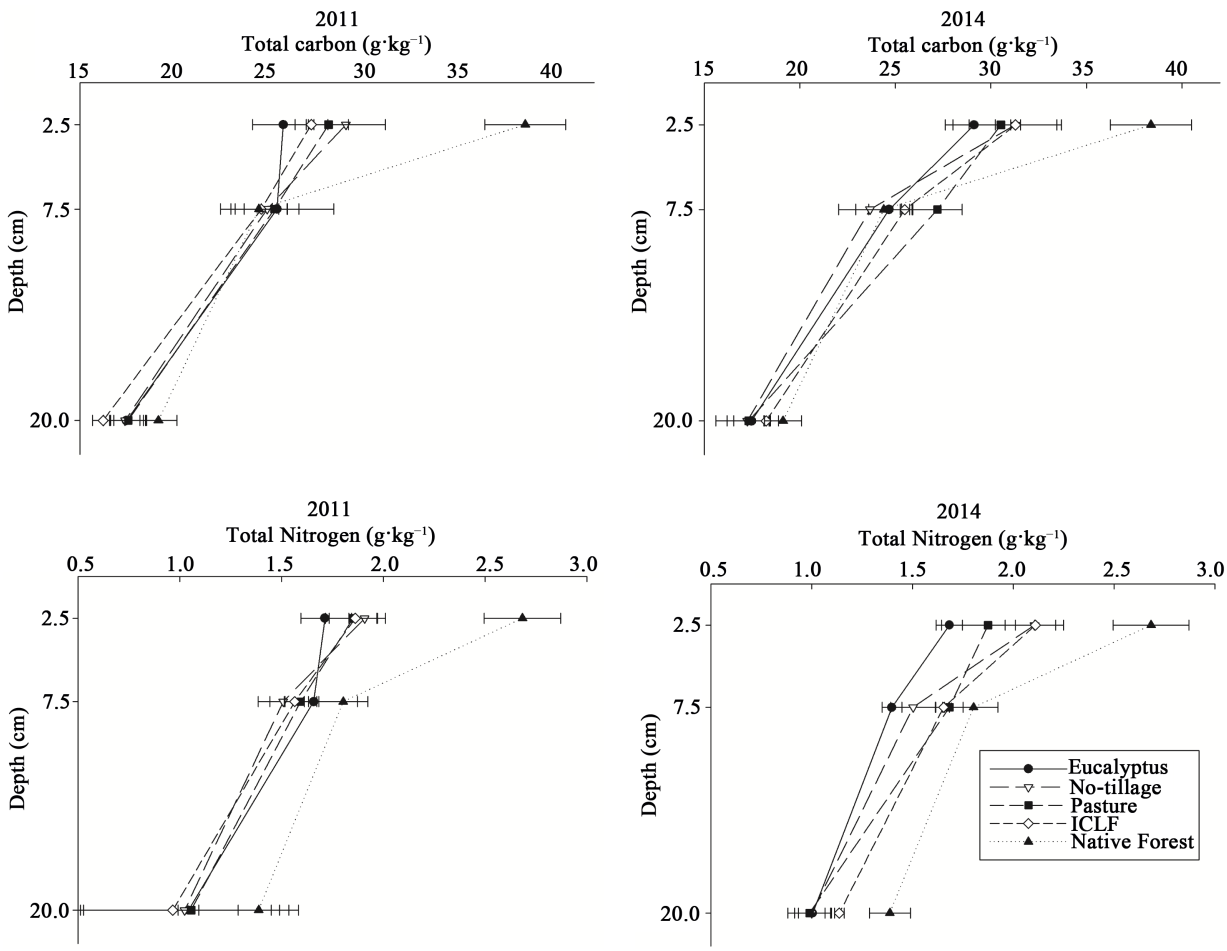

Figure 1. Total C and N concentrations in the 0 - 5, 5 - 10 and 10 - 30 cm layers in soils under Eucalyptus plantation; No-tillage; Pasture; ICLF–integrated crop-livestock-forest system and Native Forest. Horizontal bars represent the standard error (n = 4).

soil surface layer (0 - 5 cm) could contribute to higher amounts of microbial biomass and activity promoted by ICLF system.

ICLF and Pasture showed the highest total C stock in the 0 - 30 cm layer. Nitrogen stocks followed the same trend of carbon, however only ICLF presented the highest nitrogen stock (**Figure 2**). Soil carbon stocks values observed in 2014 for Pasture (71 Mg·ha^{-1}) and ICLF (70 Mg·ha^{-1}) were similar to that found in the Native Forest (75 Mg·ha^{-1}).

Three years of ICLF promoted changes in soil C and N stocks (**Table 1**). Despite the similar values of carbon stocks in soil under Pasture and ICLF treatments, after three years, ICLF contribute to increase total carbon stock by 5.5 Mg·ha^{-1} in the 0 - 30 cm layer. This result indicates that ICLF could be promising to improve soil carbon sequestration and nutrient cycling.

According to [22], significant increase in soil C stocks is only possible under a management system that reduces degradation of soil organic matter as well as contributes to increase N in the soil-plant system. In the ICLF system, pasture contributes to great amounts of high C/N ratio residues, providing an increase in

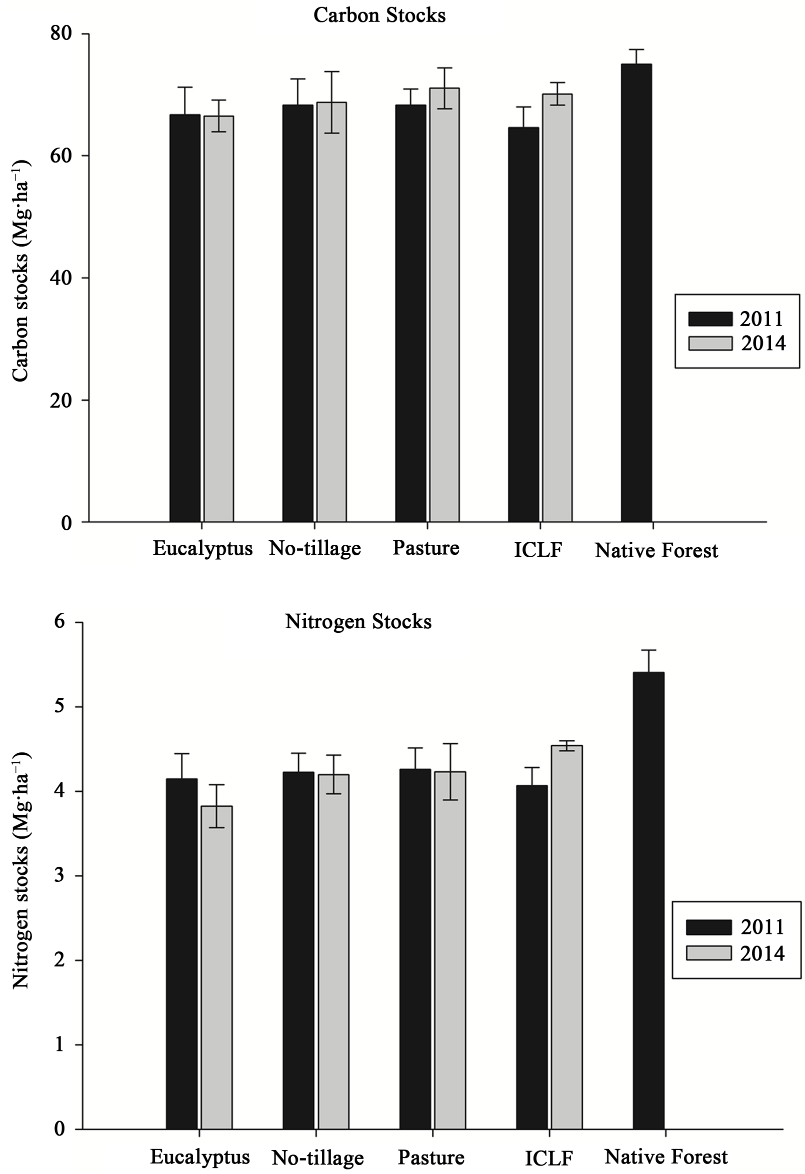

Figure 2. Total C and N stocks in the top 0 - 30 cm layers in soils under Eucalyptus plantation; No-tillage; Pasture; ICLF–integrated crop-livestock-forest system and Native Forest. Vertical bars represent the standard error (n = 4).

Table 1. Gains and losses in soil C and N stocks of different management systems after three years establishment.

Soil layer (cm)	Gains and losses in soil carbon (%)			
	Eucalyptus	No-tillage	Pasture	ICLF
0 - 30	−0.3	+0.6	+3.9	+7.8
	Gains and losses in soil nitrogen (%)			
	Eucalyptus	No-tillage	Pasture	ICLF
0 - 30	−8.3	−0.7	−0.6	+10.4

(−) Losses; (+) Gains.

the persistence of soil cover. However, high C/N ratio residues could reduce N availability for crops [11], [23], [24].

On the other hand, leguminous crops in the rotation system, such as soybeans, can provide a significant source of N for the subsequent crops [25]. [10] attributed the increase of total carbon in soil under crop-livestock integration systems to the combination of maize with brachiaria. According to the authors, higher deposition of plant residues combined with slower degradation rate of the residues could contribute to increase soil organic matter. On this context, brachiaria call attention, because of the well-developed root system, distributed along the soil profile.

Additionally, the tree component (eucalyptus) in the ICLF system is also an important carbon sink, because of its high potential to accumulate large amounts of carbon in the woody biomass and to provide more recalcitrant residues [26]. [27] observed that ICLF promoted higher carbon stocks when compared to an integrated crop-livestock system, no-tillage and native vegetation, not only in the surface layer, but also in deep soil layers (1 m). The higher carbon stocks observed for ICLF was attributed to the deposition of the crop residues on the soil surface, but also the greater amounts of residues provided by pasture and trees in deeper soil layers.

According to [28], the highest concentration of C in the soils under ICLF systems is likely due to the combination of pasture and forest on the same area, since both ICLF components have high capacity to accumulate carbon in deeper soil layers through accretion and deposition of organic material resistant to degradation.

Combined with minimal soil disturbances that favor carbon protection [8], [29], all these mentioned benefits provide by ICLF systems could contribute to the increase of soil carbon stocks. [30] and [31] suggested that the use of legumes, combined with a greater diversity of species in succession or crop rotation, such as the ICLF, significantly increase C and N retention in the soil, with important implications for the balance of both elements on a regional and global scale and for sustainable production and environmental quality.

In addition, ICLF systems are the target of public policies to promote a more sustainable and resilient agriculture to climate change in Brazil. The data of this work show that ICLF promotes improvements in the chemical, physical and biological soil conditions, besides promoting increases of the CO_2 removal from the atmosphere, through tree growth and soil carbon accumulation.

4. Conclusion

After three years establishment, the integrated crop-livestock-forest system showed the highest potential of soil carbon sequestration with values similar of those found under Native Forest. Thus, we consider that ICLF could be an important tool to help Brazil meet its voluntary greenhouse gas emission targets in COP15, especially in agriculture sector.

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Evaluation of a long-established silvopastoral *Brachiaria decumbens* system: plant characteristics and feeding value for cattle

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Abstract. One of the main challenges of using a silvopastoral system (SPS) is maintaining pasture and animal productivity over time. Our objective was to compare the productive characteristics and nutritive value of signal grass (*Brachiaria decumbens* cv. Basilisk) and the liveweight gain of dairy heifers in a SPS and open pasture (OP, signal grass under full sunlight) during the rainy seasons of four experiments between 2003 and 2016, which characterised systems from their 6th to 19th years after establishment in south-eastern Brazil when analysed together. The experimental design was a randomised complete block in a 2 × 4 factorial scheme (two production systems (SPS and OP) and four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016)). From the 7th year onwards, the progressive reduction of photosynthetically active radiation negatively impacted the productive characteristics of the SPS pasture. Total forage mass was reduced by 19% in SPS compared with the OP in 2004–2007, 38% in 2011–2014 and 31% in 2014–2016. Crude protein content was 23% and 30% higher in the SPS than in the OP in 2011–2014 and 2014–2016, respectively. However, during the study period (until the 19th year), the liveweight gain of heifers was similar between systems since the higher crude protein content available in SPS contributed to improved forage nutritional value. From the 17th to the 19th year, weight gain per area was lower in the SPS compared with the OP (169 vs 199 kg ha^{-1}), although the difference between systems was small. Signal grass presents a high degree of phenotypic plasticity in response to changes in shade levels, which gives this species a high potential for use in SPS.

Additional keywords: dry matter production, integrated land management, nutritive value of pasture, shading, sward structure, tropical pastures.

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Introduction

Globally, much has been discussed regarding the impacts of agriculture on climate change. One production strategy for the sustainable intensification of land use with the potential of mitigating or compensating for environmental impacts is the integration of livestock and forestry activities (trees, pastures, and animals) in the same area within a silvopastoral system (SPS) (Nahed-Toral *et al*. 2013; de Moura Oliveira *et al*. 2018). The potential benefits of SPS include increased soil fertility, soil organic carbon and soil carbon stock (Murgueitio *et al*. 2011; Cárdenas *et al*. 2019; Aryal *et al*. 2019); decreased greenhouse gas emissions (Torres *et al*. 2017); increased crude protein (CP) and decreased fibre content in forage (Neel and Belesky 2017; Lima *et al*. 2019); greater animal welfare and thermal comfort (de Oliveira *et al*. 2018; Améndola *et al*. 2019; Pezzopane *et al*. 2019); and increased income diversification for farms (Broom *et al*. 2013).

However, in systems incorporating trees (e.g. SPS), management can represent a greater challenge due to the various interactions that occur among their components. In fact, one of the limitations of SPS related to the advancement of tree age (i.e. greater height and tree crown diameter), which causes a reduction in photosynthetic photon flux density and in the red to far-red (R : FR) ratio of photosynthetically active radiation (PAR) that reaches the understory. In general, changes in forage plant physiology and morphology compensate for low light quantity and quality by optimising for light interception (Cavagnaro and Trione 2007; do Nascimento *et al*. 2019), thus affecting forage production, its nutritive value, and the response of animals (Geremia *et al*. 2018; Santos *et al*. 2018).

For example, certain studies with C_4 tropical grasses have suggested that sward cultivated under lower sunlight incidence develop adaptations such as increased specific leaf area and shoot/root ratios as well as decreased tiller population density, forage bulk density, and morphological components of forage mass (Paciullo *et al*. 2010; Santos *et al*. 2016, 2018; Lima *et al*. 2019). These predominant changes may decrease the daily nutrient intake and, consequently, animal production (Geremia *et al*. 2018; da Silveira Pontes *et al*. 2018; Santos *et al*. 2018). Moreover, shade increases chlorophyll content (Martuscello *et al*. 2009) and CP content (Santos *et al*. 2016; Paciullo *et al*. 2017), whereas neutral detergent fibre (NDF) and *in vitro* dry matter digestibility (IVDMD) content have not shown a definite pattern of response to shading in SPS (Gobbi *et al*. 2009; Soares *et al*. 2009).

In this context, the intensity of the plant response depends on the ability of forage species to adapt to more intense light restriction. Signal grass (*Brachiaria decumbens* cv. Basilisk, syn. *Urochloa decumbens* Stapf R.D. Webster) is one of the most important tropical perennial grasses. Notably, it utilises the C_4 photosynthetic pathway, which is widely used in production systems of the Brazilian tropics and has been reported as being tolerant to moderate shading (Paciullo *et al*. 2007; Guenni *et al*. 2008). Additionally, it presents good productivity and nutritive value and represents a forage species that adapts to soils with low-input usage, as indicated by its use in the recovery of degraded areas.

In the present study, we investigated the hypothesis that the long-term increase of forage CP content under an SPS positively influences the individual performance of dairy heifers, and that increased shading limits forage production, thereby reducing stocking rate (SR) and animal production per area. Our objective was to compare the productive characteristics and nutritive value of signal grass (*B. decumbens* cv. Basilisk) as well as the liveweight gain of dairy heifers in a SPS and open pasture (OP, signal grass under full sunlight) system from 2003 to 2016, which characterised the systems from their 6th to 19th years after establishment in south-eastern Brazil.

Materials and methods

Study area

The study was conducted at Embrapa Dairy Cattle experimental station, located in the municipality of Coronel Pacheco, Minas Gerais state, Brazil (21°33′S, 43°15′W; 410 m above sea level; Fig. 1) during the rainy seasons (December to May each year) of four experiments: 2003–2004, 2004–2007, 2011–2014, and

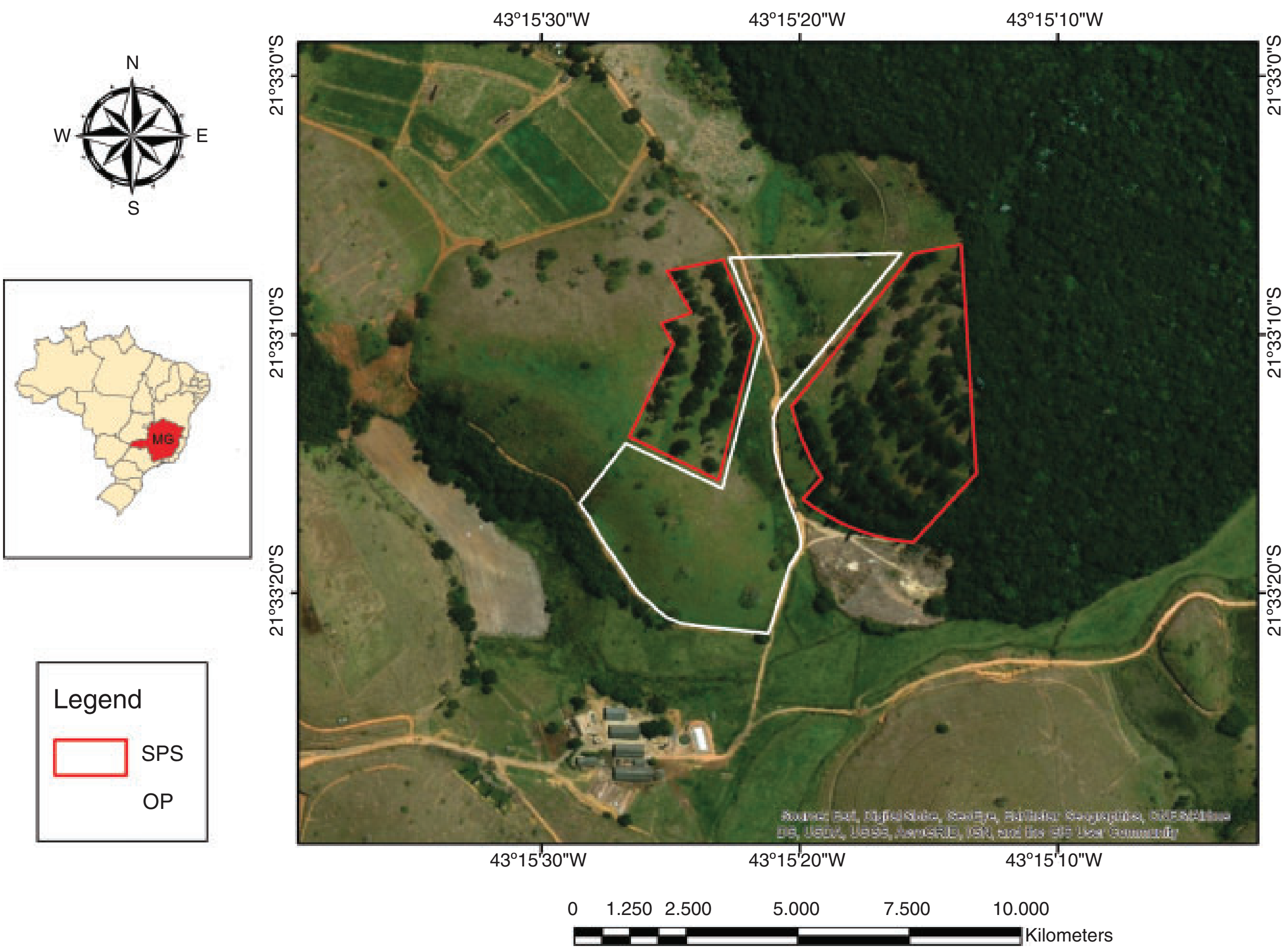

Fig. 1. Location map of the study area for the silvopastoral system (SPS) and open pasture (OP) at Embrapa Dairy Cattle, Minas Gerais (MG), Brazil.

2014–2016. According to the Köppen classification, the climate of the region is Cwa type (humid subtropical), with dry winters and rainy summers. Weather data for the four experiments were recorded at the Embrapa Dairy Cattle weather station located 500 m from the study site (Fig. 2). The experimental area was on a west-facing hillside with a slope of 30–40%. The soil is classified as dystrophic Red–Yellow Latosol with a medium clay texture and undulating relief (Embrapa 2013). Soil samples were collected at depths of 0–20 cm using a probe type for chemical characterisation (for details on soil, see Supplementary Material table S1 available at the journal's website). For the SPS, samples were collected from two positions: near a tree (0.5 m from the tree trunk) and far from trees (15 m from the tree trunk), providing a total of 20 samples for each replicate (paddock). For the OP, no sampling by position was performed, thus providing a total of 20 randomly collected samples for this system. After sampling, the soils were transported to a laboratory in plastic bags, air-dried, crushed, and then passed through 2-mm sieves, thereby obtaining air-dried fine earth for subsequent analysis.

The experimental area was established in November 1997. To establish the experiment, the area was tilled along the contour using a horse-drawn mouldboard plough. The forage component was composed of signal grass planted in an OP (full sunlight) and in an SPS. The SPS encompassed a pasture area 30 m wide, alternating with 10 m wide groves with the trees species *Eucalyptus grandis* and the tree legumes *Acacia mangium*, *Acacia angustissima*, *Mimosa artemisiana* and *Leucaena leucocephala*, which were planted perpendicular to the incline of the slope in a north–south direction to prevent soils from surface erosion. Trees were arranged in groves comprising four parallel rows with an intra-row spacing of 3.0 m and an inter-row spacing of 3.0 m, totalling 342 trees ha^{-1}. The tree species were planted alternately (mixed) in each of the four rows. The *L. leucocephala*, *A. angustissima* and *M. artemisiana* did not survive the term years (probably due to the acidic soil conditions, even after liming). A schematic representation of the experimental site and tree species present in the SPS is provided in Fig. 3. Tree legumes were used for the purpose of providing shade and biomass rich in nitrogen (N) and other nutrients, whereas the *Eucalyptus* were planted for the purpose of producing shade and wood. During the first year, the area remained without animals to allow pasture establishment and initial tree growth.

Prior to planting the trees, and according to the soil analysis, 1000 kg ha^{-1} of dolomitic limestone, 600 kg ha^{-1} of natural rock phosphate (200 kg ha^{-1} of P_2O_5), 250 kg ha^{-1} of single superphosphate (45 kg ha^{-1} of P_2O_5), 100 kg ha^{-1} of potassium chloride (60 kg ha^{-1} of K_2O), and 30 kg ha^{-1} of micronutrients FTE BR-16 (35, 15, 35, and 0.4 g kg^{-1} of Zn, B, Cu and Mo, respectively), were applied in the area where grass was planted. The planting hole for each legume tree seedling was fertilised with 50 g of dolomitic limestone, 80 g of natural rock phosphate, 100 g of P (P_2O_5), 25 g of K (KCL), and 10 g of FTE BR-16 and, for *E. grandis*, 75 g of N as ($(NH_4)_2SO_4$), 225 g of P (P_2O_5), and 15 g of K (KCL) was applied.

For the establishment of the OP, the protocol of soil preparation and application of correctives and fertilisers was similar to that adopted in the SPS since the areas were contiguous and presented the same slope and type of soil. Since planting, the pasture areas had not received any additional fertiliser or corrective applications until 2010. Between 2011 and 2014, the pastures received 64 kg N ha^{-1} urea, 16 kg P ha^{-1} (P_2O_5), and 64 kg K ha^{-1} (K_2O) annually, divided into two applications during the summer. From 2014 to 2016, there were no fertiliser applications. Weeds and leaf-cutting ants were controlled during the entire experiment duration in both systems. Leaf-cutting ants were controlled by the application of granulated baits (sulfluramid 0.3% active ingredient) at a dosage of 10 g per square meter of ant hill. Weeds were controlled by the herbicide application 2,4-dichlorophenoxyacetic acid at 1.0 L ha^{-1} (670 g active ingredient ha^{-1}). The application of the herbicide was done with a manual costal sprayer, with capacity for 20 L.

In 2003–2004 and 2004–2007, the experimental area consisted of 16 ha (8 ha for each system) with 32 paddocks of 0.5 ha each. For the experiments in 2011–2014 and 2014–2016, a total area of 8.4 ha (4.2 ha for each system) was used, with six paddocks of 1.4 ha each.

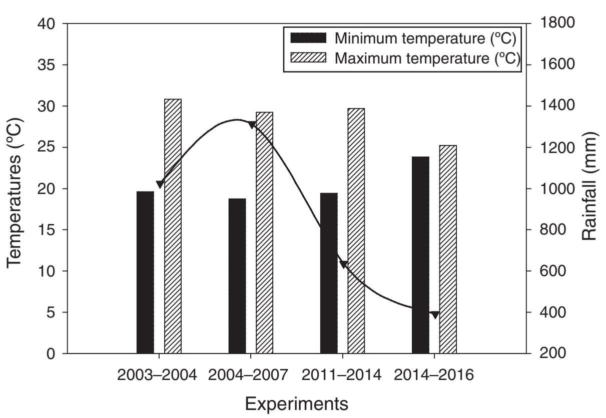

Fig. 2. Average temperatures and rainfall during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016).

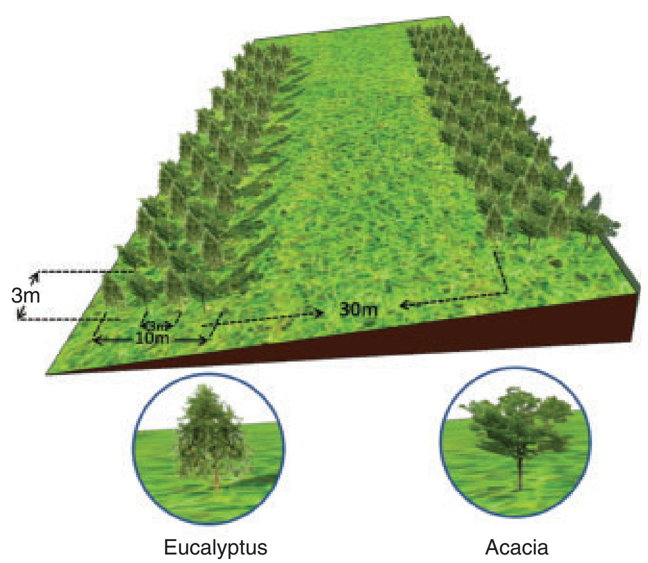

Fig. 3. Schematic representation of the distribution of trees in the silvopastoral system (SPS).

Experimental design and treatments

All experiments were performed under a randomised complete block design (due to the heterogeneity of the experimental area) in a 2 × 4 factorial scheme (two production systems – SPS [i.e. shaded] and OP [i.e. full sunlight]; four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016)). Two replicates (paddocks) were used for the experiment between 2003–2004, and three replicates were used in the experiments between 2004–2007, 2011–2014, and 2014–2016.

Tree measurements and shade percentage

Tree height, diameter at breast height (DBH), and shade percentage were measured during experiments (Table 1). Height measurements were estimated using the optical height meter (clinometer) and DBH was measured using a dendrometric tape where the circumference was measured at 1.30 m above the ground. Shade was measured using a LI-190SA ceptometer connected to a LI-COR portable model radiometer (model LI-189) in 2003–2004, and an AccuPAR LP-80 ceptometer (Decagon Devices) in 2004–2007, 2011–2014, and 2014–2016, by which the PAR that arrived in the understory was non-destructively evaluated. Percentage shade measurements were taken under clear skies during the rainy season at 09:00, 12:00 and 15:00 hours at 1 m above ground level nearby the trees (between 1 and 2 m from the tree trunk) in the middle of the tree grove (between the second and third tree rows).

Animals and grazing management

All animal care and handling procedures followed regulations and were approved by the Ethics Committee of the Embrapa Dairy Cattle. Between 1998 and 2000, the pastures remained free of animals in order to guarantee the initial growth of the trees. In 2001 and 2002, the pasture was grazed for non-lactating crossbred (Holstein × Gyr) cows, according to the Aroeira *et al*. (2005). During the four experiments, paddocks were grazed by crossbred (Holstein × Gyr) dairy heifers that were an average age of 12 months of age and with a bodyweight (BW) of 200 ± 50 kg. All animals had unrestricted (*ad libitum*) access to shade in the SPS, with water and mineral supplements being provided in both the SPS and OP.

For the experiments in 2003–2004 and 2004–2007, pastures were managed under rotational stocking with a defoliation interval of 35 days and 7 days of paddock occupation being established, which, at the time of the interruption of regrowth, coincided with pre- and post-grazing canopy heights of 40 and 20 cm respectively. In 2011–2014 and 2014–2016, pastures were continuously stocked by using a variable stocking rate to maintain a canopy height at around 30–35 cm. Each paddock received 'testers animals' (animals that remained throughout the experimental period). According to the need for an adjustment of the SR, additional 'grazers animals' were added to, or subtracted from, each paddock to maintain the desired heights according to put-and-take method (Mott and Lucas 1952).

Pasture measurements

Canopy height was measured weekly using a ruler graduated in centimetres. A total of 50 points were measured in each paddock (replicates) in 2003–2004 and 2004–2007, and 140 points were measured in 2011–2014 and 2014–2016. In the OP, these measurements were taken at random in each paddock. In the SPS, due to the influence of shade on the structural characteristics of the sward, 30% of the measurements were made within the tree groves (10 m), while the remainder were taken in the area situated between two groves (30 m) while avoiding areas around gates, watering points, and resting sites.

Forage mass was estimated by direct (destructive) sampling every 14 days in 2003–2004 (20 samples from each paddock), 35 days in 2004–2007 (20 samples from each paddock), 21 days in 2011–2014 (10 samples from each paddock), and 28 days in 2014–2016 (12 samples from each paddock). For forage mass estimation, samples were cut at 5 cm from ground level at sites representative of the mean canopy height using a 0.25 m^2 (0.5 m × 0.5 m) metal frame and a manual cutter. The samples were weighed and separated into two subsamples. One subsample (300 g) set was placed in paper bags and dried in a forced-air oven at 55°C for 72 h to estimate the dry matter (DM) content of the total sample. The other subsample (200 g) was manually separated into green and dead fractions. In the green fraction, the number of tillers was counted to estimate the tiller population density. Then, the green fraction was separated into leaves and stems to determine the morphological composition by separation

Table 1. Tree characteristics and shade in the silvopastoral system (SPS) during four experiments
DBH, diameter at breast height (= 1.3 m); n.m., not measured

Variable	Experiments			
	2003–2004[A]	2004–2007[B]	2011–2014[C]	2014–2016[D]
Years after establishment	6–7	7–10	14–17	17–19
Tree height (m) (*Eucalyptus grandis*)	n.m.	22	n.m.	29
DBH (cm) (*Eucalyptus grandis*)	n.m.	26	n.m.	45
Tree height (m) (*Acacia mangium*)	n.m.	14	n.m.	14
DBH (cm) (*Acacia mangium*)	n.m.	20	n.m.	32
Trees ha^{-1}	170	105	n.m.	81
Shade (%)	23	29	46	51

[A]Paciullo *et al*. (2009).
[B]Paciullo *et al*. (2011).
[C]Fernandes (2016).
[D]Lima *et al*. (2019).

of the following components of the plants: green leaf blades, considered to be those blades with less than 50% senescent tissue plus leaf blades in expansion; stem and sheath of the tiller that either had or did not have an inflorescence; and dead material, necrotic leaf tissue that adhered to the tiller and completely necrotic material that did not adhere to the tiller. The plant components were then placed in paper bags and dried in a forced-air oven at 55°C for 72 h, to determine their DM.

Based on this information, the total forage, leaf blade, stem, and dead material forage masses were estimated. The green forage mass consisted of the sum of the leaf and stem masses, while the total forage mass represented the sum of green forage mass and dead material. The total and green forage bulk densities were calculated from the total and green and forage mass divided by the mean height of the pasture.

Forage samples were cut using a hand-plucking technique proposed by Sollenberger and Cherney (1995), in which forage is collected manually after observing the grazing habits of the animals. At the end of the resting period (forage grass with 35 days of regrowth) from 2003–2004 and 2004–2007 and every 28 days from 2010 to 2016, the samples were cut at 15 sites within paddocks at points with average canopy height. The samples from each point were pooled and constituted a single sample per paddock. This was assessed in order to detect differences in the quality of the forage that animals were consuming. These samples were placed in paper bags and dried in a forced-air oven at 55°C for 72 h. After drying, ~300 g of sample was ground using a Wiley mill, then passed through a 1-mm sieve and sent for analysis of the nutritive value at the Animal Nutrition Laboratory of Embrapa Dairy Cattle. Forage samples were analysed for their DM content at 105°C. The CP, NDF and IVDMD contents were also analysed. N content was determined according to the Kjeldahl method (AOAC 1990). CP content was calculated as the total N content × 6.25. NDF was analysed according to the methodology proposed by Van Soest *et al*. (1991), whereas the IVDMD analysis was performed according to the technique described by Tilley and Terry (1963).

Weight gain of heifers

The animals were weighed every 35 days in 2003–2004 and 2004–2007 and every 28 days in 2011–2014 and 2014–2016, after fasting from solids and liquids for 12 h. The SR (based on an adult animal with 450 kg BW) was calculated based on the weights of the 'testers animals' plus the weights of the 'grazers animals' during the period that they remained in the paddock and the total area of each treatment. The average daily gain (ADG) of all animals (testers and grazers) was obtained by the difference between weights (final and initial weights) divided by the weighing interval. The gain per area (GPA) was obtained by multiplying the average daily gain of the animals (testers and grazers) by the SR per paddock and by the number of days that remained in the grazing period.

Statistical analysis

All statistical procedures were performed using the PROC MIXED of SAS software (SAS Institute). The experiments, systems and its respective interactions were assumed as fixed effects. In order to account for variation among experiments, the random effect of blocks within experiments was included as random subject in the mixed model. For all analyses, the used significance level was 0.05.

Results

Shading percentage

The decrease in PAR in the SPS compared with the OP was 23% in 2003–2004, 29% in 2004–2007, 46% in 2011–2014 and 51% in 2014–2016 (Table 1).

Sward structural characteristics, forage mass, forage bulk density and morphological composition

There was no effect between systems for the canopy height variable ($P > 0.05$; Fig. 4*a*). Tiller population density only varied with system in the 2011–2014 experiment, when lower tiller density was observed in the SPS relative to the OP (634 vs 760 tillers m^{-2}) ($P < 0.05$; Fig. 4*b*). Lower total and green forage mass as well as lower total and green forage bulk density were observed in the SPS compared with the OP from 2004 to 2016 ($P < 0.05$; Fig. 4*c–f*). Total forage mass was reduced by 19% in SPS compared with the OP in 2004–2007, 38% in 2011–2014 and 31% in 2014–2016 whereas total forage bulk density was decreased by 18% in SPS compared with the OP in 2004–2007, 34% in 2011–2014 and 30% in 2014–2016 respectively.

A significant difference between systems was observed for the variables leaf blade mass, stem, and dead material ($P < 0.05$; Fig. 5). A reduction in leaf blade mass was observed in the SPS compared with the OP in 2004–2007 (918 vs 1152 kg ha^{-1} respectively), 2011–2014 (713 vs 1047 kg ha^{-1} respectively) and 2014–2016 (716 vs 947 kg ha^{-1} respectively) (Fig. 5*a*). The stem mass was higher in the OP than in the SPS in 2011–2014 (1688 vs 1088 kg ha^{-1} respectively) and 2014–2016 (1331 vs 998 kg ha^{-1} respectively) ($P < 0.05$; Fig. 5*b*). Similar behaviour was observed for dead material mass, with higher values in the OP than in the SPS in 2011–2014 (739 vs 379 kg ha^{-1} respectively), and 2014–2016 (862 vs 494 kg ha^{-1} respectively) ($P < 0.05$; Fig. 5*c*).

Nutritive value

For CP content, there were significant differences between systems during the experiments ($P < 0.05$; Fig. 6*a*). CP content was 23 and 30% higher in the SPS than in the OP in 2011–2014 (139 vs 113 g kg^{-1} respectively) and 2014–2016 (118 vs 91 g kg^{-1} respectively), whereas no significant difference was observed between systems in 2003–2004 and 2004–2007. NDF content did not vary with system in any experiment ($P > 0.05$; Fig. 6*b*). IVDMD was only affected by system in 2011–2014 ($P < 0.05$; Fig. 6*c*). The IVDMD value for the OP was higher than that observed for the SPS (637 vs 597 g kg^{-1} respectively).

Weight gain of heifers

Due to N fertilisation in 2011–2014 and the greater availability of forage mass in the OP, SR (heifer ha^{-1}) was significantly higher in the OP than in the SPS (2.5 vs 2.3 respectively); however, there

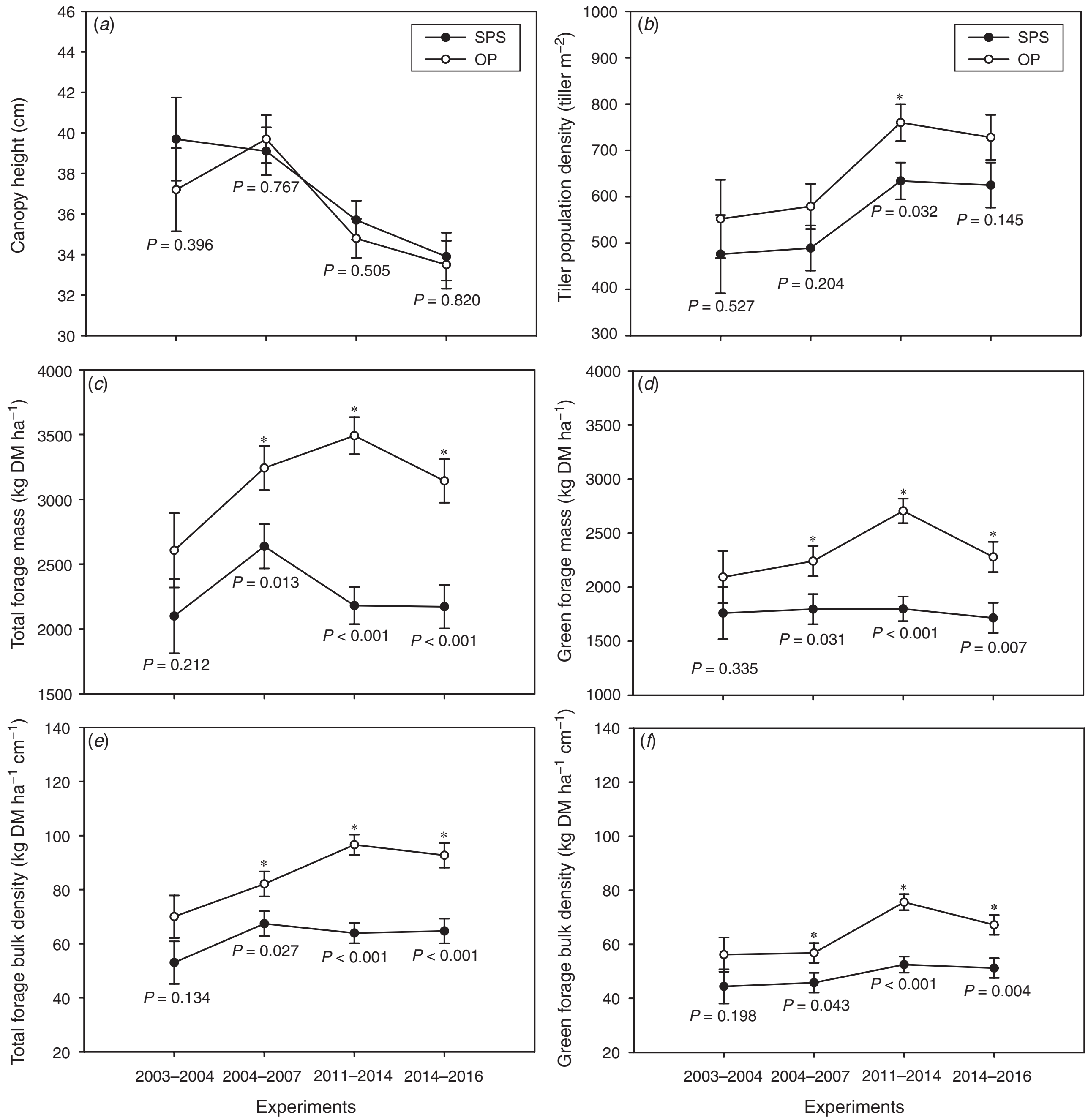

Fig. 4. Structural characteristics and forage production of signal grass in the silvopastoral system (SPS) and open pasture (OP) during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016). Means and standard errors (indicated with error bars) followed by asterisks (*) in the SPS and OP within each experiment were significantly different based on an *F*-test at the 5% probability level ($P < 0.05$).

was no difference between systems in the other experiments ($P < 0.05$; Fig. 7*a*). For SR (animal unit/ha – AU ha^{-1}), no significant effect was observed ($P > 0.05$; Fig. 7*b*). Moreover, no significant differences were observed between systems for ADG during the experimental period ($P > 0.05$; Fig. 7*c*). GPA was only influenced by system in 2014–2016, when weight gain in the OP was higher than in the SPS (199 vs 169 kg ha^{-1} respectively) ($P < 0.05$; Fig. 7*d*).

Discussion

Sward structural characteristics, forage mass, forage bulk density, and morphological composition

The significant difference in tiller density between systems in 2011–2014 may be associated with the N fertilisation performed during this period, which had a greater positive effect on the OP than on the SPS, favouring a greater disparity between values

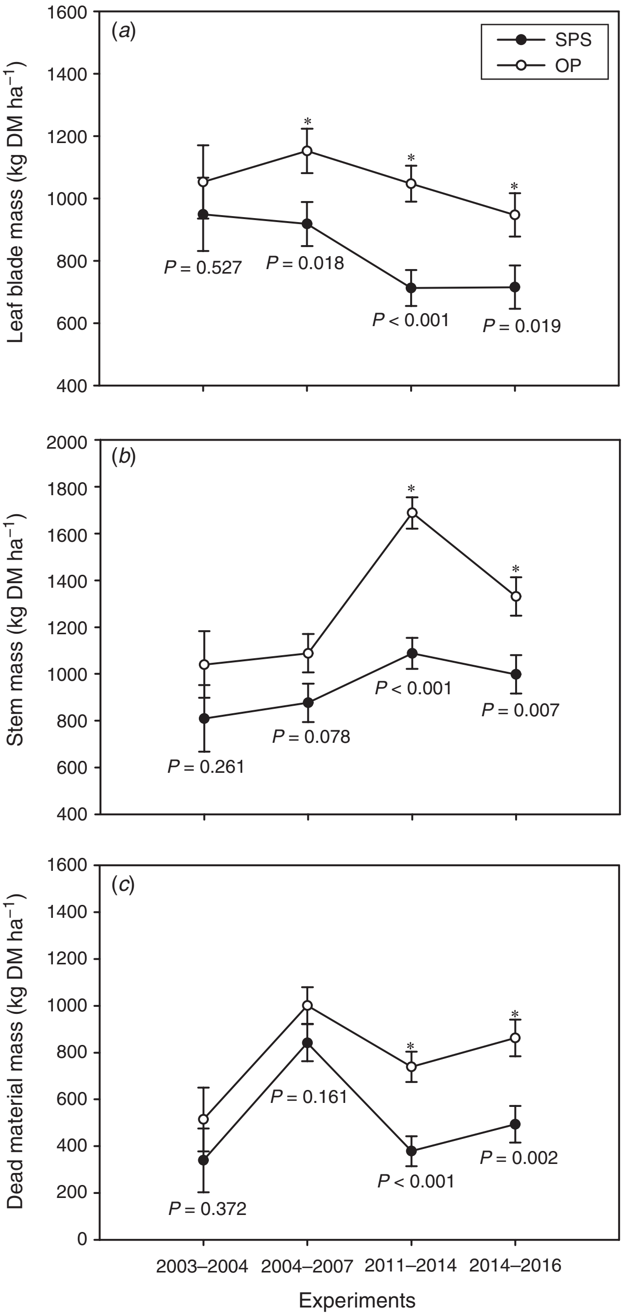

Fig. 5. Morphological composition of signal grass in the silvopastoral system (SPS) and open pasture (OP) during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016). Means and standard errors (indicated with error bars) followed by asterisks (*) in the SPS and OP within each experiment were significantly different based on an *F*-test at the 5% probability level ($P < 0.05$).

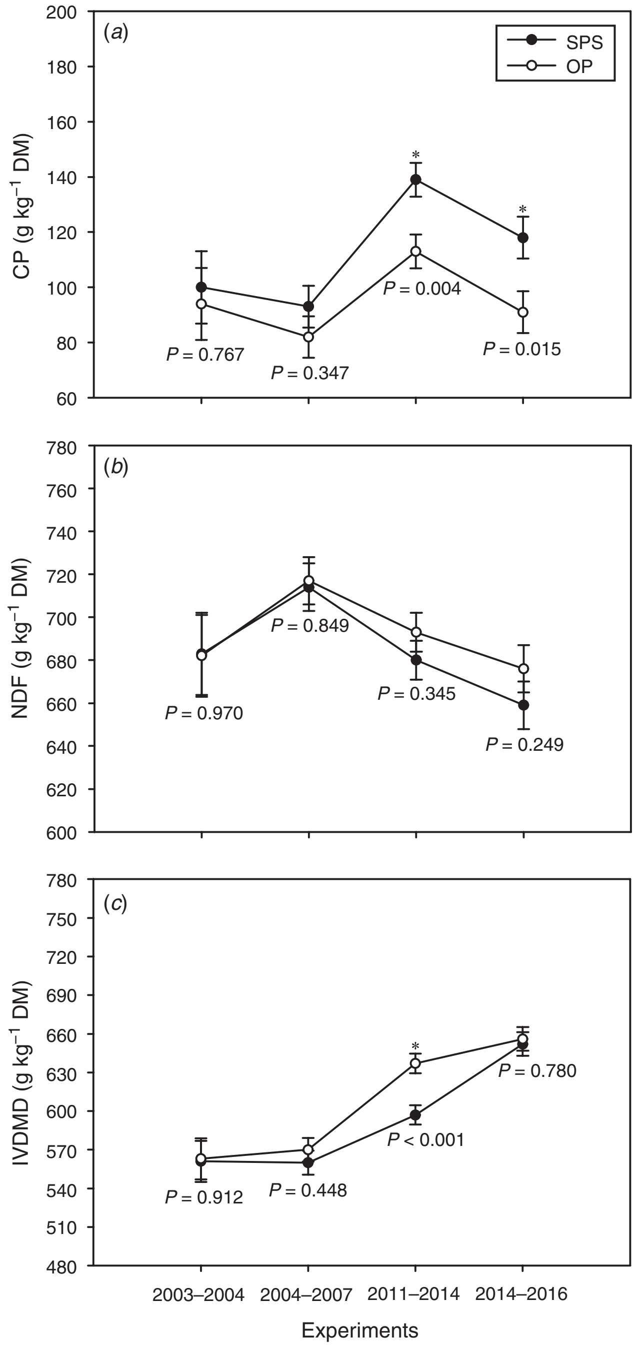

Fig. 6. Crude protein (CP), neutral detergent fibre (NDF), and *in vitro* dry matter digestibility (IVDMD) content of signal grass in the silvopastoral system (SPS) and open pasture (OP) during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016). Means and standard errors (indicated with error bars) followed by asterisks (*) in the SPS and OP within each experiment were significantly different based on an *F*-test at the 5% probability level ($P < 0.05$).

(Fig. 4*b*). Lopes *et al*. (2017) found that fertilisation is more effective in increasing tillering under full sun conditions than under shade. N fertilisation increases the rate of leaf appearance and the number of basal buds that can produce new tillers, resulting in increased tiller density (De Bona and Monteiro 2010). Even with higher N availability in soil under the SPS, there was less response to N fertilisation due to the low carbon supply for plants via photosynthesis, which limits tillering. Faria *et al*. (2018) evaluated the productive and qualitative response of *B. decumbens* and *Brachiaria ruziziensis* to three levels of shade (0, 36 and 54%) and four N fertilisation doses (0, 50, 100 and

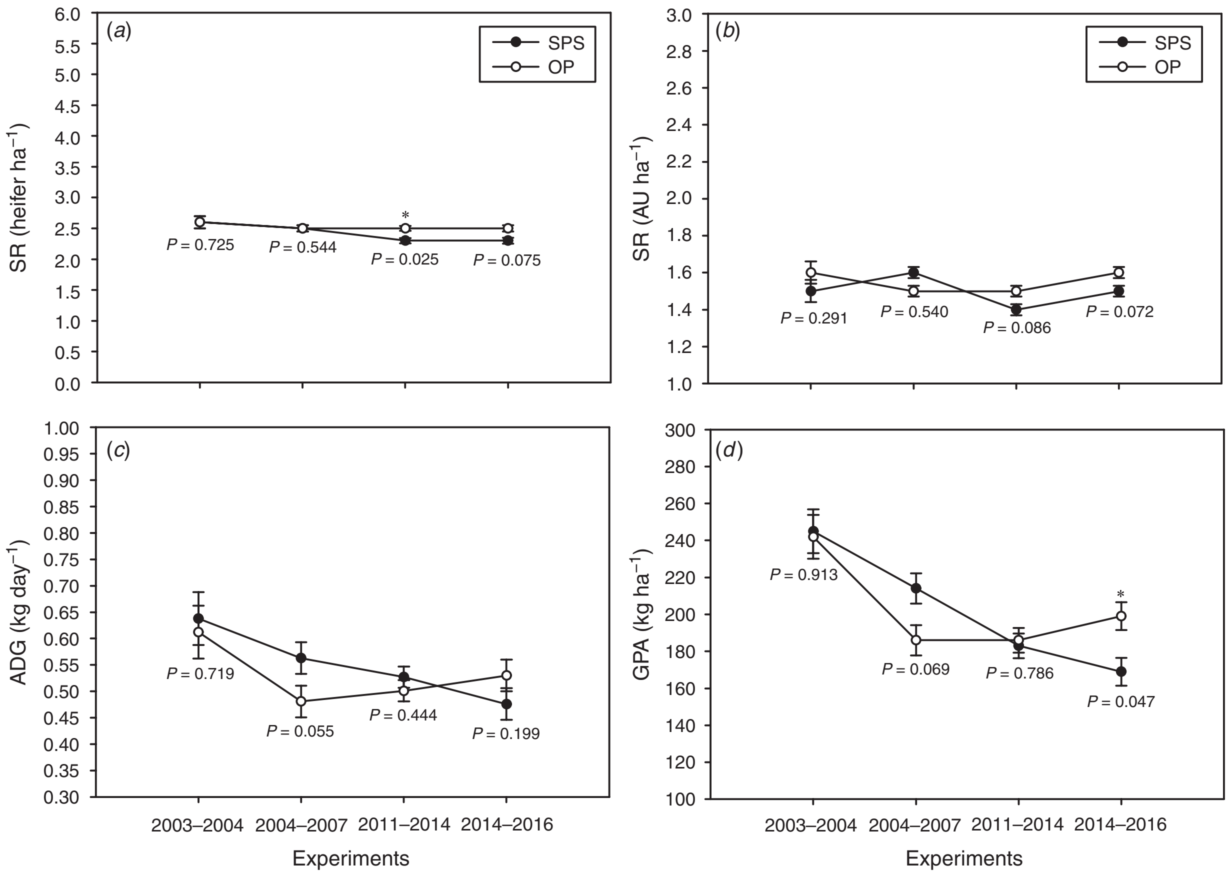

Fig. 7. Stocking rate (SR), average daily gain (ADG), and average gain per area (GPA) of dairy heifers (Holstein × Gyr) grazing on signal grass in the silvopastoral system (SPS) and open pasture (OP) during the rainy seasons of the four experiments (2003–2004, 2004–2007, 2011–2014 and 2014–2016). Means and standard errors (indicated with error bars) followed by asterisks (*) in the SPS and OP within each experiment were significantly different based on an *F*-test at the 5% probability level ($P < 0.05$).

150 mg dm^{-3} soil), and observed a reduction in tillering for both species with increased shade and N levels, whereas highlighting that forage under shade requires lower levels of N, unlike the response of forage grown in full sun. However, this result indicates the ability of signal grass to adapt and maintain tillering, even under conditions of increasingly intense light restriction. However, it was observed that the change in rotational grazing method for continuous stocking during the experiments during 2011–2014 and 2014–2016 provided an increase in tiller density across both systems.

The similarity in total and green forage mass between the SPS and the OP in 2003–2004 is related to the tolerance of signal grass to moderate shade (i.e. 23%) imposed by the tree component (Paciullo *et al*. 2007; Guenni *et al*. 2008; Fig. 4*c, d*). In the subsequent years, there was a progressive increase in shade levels in the SPS, which resulted in a reduced total and green forage mass in relation to the OP. Reduction in the productive capacity of pastures in SPS has mainly been related to lower light quantity (i.e. photon flux density) and quality (e.g. changes in the red to far-red (R : FR) ratio) of the light spectrum arriving at the understory with advancing tree age (Wilson and Ludlow 1991; Dodd *et al*. 2005; Beaudet *et al*. 2011). A decrease in the forage mass with increased shade level in SPS has been observed by other authors (Gómez *et al*. 2013; Bosi *et al*. 2014; de Oliveira *et al*. 2014; Santos *et al*. 2018). In 2011–2014 and 2014–2016, the average height/DBH of *E. grandis* and *A. mangium* trees were 21.7 m/25.5 cm and 14 m/20 cm, respectively, for 2011–2014 and 29 m/45 cm and 14.2 m/32 cm, respectively, for 2014–2016. The increased dendrometric characteristics associated with quadrupled tree rows and north–south direction planting was responsible for decreased forage mass in the SPS over time. Santos *et al*. (2016) observed that the planting of *Eucalyptus* trees in simple lines in an east–west orientation, with a space between groves of 22 m and tree management through pruning and thinning could favour forage production in a SPS.

The observed decrease in forage bulk density the SPS compared with the OP in 2004–2007 is associated with total and green forage mass being lower in the SPS, since canopy height was the same for both systems (Fig. 4*e, f*). Lopes *et al*. (2017) observed a reduction of 18 and 58% in the forage bulk density of the forage mass of signal grass grown with 20 and 70% sunlight respectively. The lower forage bulk densities observed in the SPS with increased shade could decrease the bite mass and forage intake of animals, which would result in compromised animal productivity. Santos *et al*. (2018) observed reductions of

40 and 60% in the forage density of an SPS with increased shade (21.9% for an SPS with 22 m between groves and 39.5% for an SPS with 12 m between groves) relative to full sunlight. According to Sollenberger and Burns (2001), the density of forage is one of the structural characteristics of a pasture that can determine the amount of time animals spend grazing, thereby affecting nutrient intake by interfering with the ingestive behaviour of the animals.

The SPS sward in 2004–2007, 2011–2014 and 2014–2016 presented lower leaf blades mass compared with the OP. The distribution of morphological components in the forage mass – such as vertical structure – influence animal grazing behaviour, thereby affecting forage intake (Carvalho *et al*. 2009). Stem mass and dead material was reduced in the SPS compared with the OP in 2011–2014 and 2014–2016. The lower values observed in the SPS were the result of lower total forage mass observed during this period. Moreover, pastures cultivated in the OP had higher photosynthetic rates than those in shaded conditions, providing accelerated development and tissue senescence. Notably, Neel *et al*. (2016) reported that plants grown in shaded areas tend to have a morphological maturity delay of 4–6 days compared with plants grown in OP. Thus, plants grown in SPS tend to be physiologically younger, which prolongs the vegetative phase and reduces tissue death (Lopes *et al*. 2017).

Nutritive value

The higher CP content observed in the SPS compared with the OP in 2011–2014 and 2014–2016 (Fig. 6*a*) can be attributed to the effect of more intense shade levels during this period (46 and 51% of shade respectively). The increase in CP content in forage in the SPS compared with the OP in 2011–2014 and 2014–2016 was 23 and 30% respectively. This increased CP content with increased shade level is consistent with results from the literature (Soares *et al*. 2009; Kyriazopoulos *et al*. 2013; Paciullo *et al*. 2017; Geremia *et al*. 2018; Santos *et al*. 2018). Such an increase in the CP content of forage in shaded environments may be related to both the direct effect of shade on photosynthesis and the effect of soil N dynamics (Wilson 1996; Peri *et al*. 2007). In addition, signal grass may have benefited from the N fixed by the tree legumes present in the study area, resulting in a higher CP content in the forage. The greater difference in CP over the last two experiments (2011–2014 and 2014–2016) could be the result of altered grazing management. Under continuous stocking, forage samples were cut each 28 days above a canopy height of 30 cm, and practically only leaves with higher CP content were present in this superior portion of pastures. Samples from the two initial experiments (2003–2004 and 2004–2007) when rotational stocking was adopted, were cut after a regrowth of 35 days, adopted a post-grazing stubble height of 20 cm. Therefore, the different managements and sampling strategies may have contributed to the elevated difference in CP content during the last two experimental periods.

The NDF content of forage in the SPS has not presented a well defined pattern, as studies have shown that it may increase, reduce, or even remain constant with increased shade level compared with OP (Lin *et al*. 2001; Paciullo *et al*. 2014; Neel *et al*. 2016; Santos *et al*. 2018). The results obtained were dependent on the forage species, percentage of shade, stage of maturity, and forage management (Neel *et al*. 2008). It is possible that the management grazing strategy during the experiments in both systems prevented the accumulation of fibrous fractions in the forage. The increased IVDMD of forage in the OP – relative to the SPS – in 2011–2014 is contradictory to the results observed by Paciullo *et al*. (2007), where they associated the highest IVDMD with the highest CP content in the forage. Several studies have demonstrated different patterns in the variation of IVDMD in forage grown in SPS; with reduction, similarity and increases in IVDMD among SPS in relation to OP (Sousa *et al*. 2010; Paciullo *et al*. 2011; Neel *et al*. 2016).

Weight gain of heifers

According to the hypothesis of the present study, a decrease in SR was expected with advancing system age, especially in the SPS, due to the progressive increase in competition for available PAR between the forage and tree components. The joint analysis, which characterised the temporal evolution of each system, only showed the tendency for a decrease in the number of heifers ha^{-1}, particularly in the SPS. These results demonstrate the ability of signal grass to adapt to conditions of reduced light intensity, especially in systems with low-input usage.

The higher SR (heifer ha^{-1}) observed in the OP compared with the SPS in 2011—2014 can be explained by the significant fertilisation effect during this period. Fertilisation, especially by N, directly reflects an increase in tiller population density, thereby resulting in a higher availability of forage mass and, consequently, an increase in the carrying capacity of the OP compared with the SPS (Fig. 7*a*).

It was expected that the ADG could be positively influenced by the elevated CP content in the SPS; however, during the four experiments, the ADG remained similar between the systems despite lower forage mass and forage bulk density being observed in the SPS from 2004 to 2016. In fact, the ingestion of forage is directly related to the structural and morphological characteristics of the pasture. Therefore, we can infer that the animals that grazed on the SPS were able to remain over a longer grazing bouts per day to ensure nutrient supply throughout the day, since the forage masses and forage bulk densities were lower in the SPS. Maintenance of the same forage canopy height in both systems during each experiment (but with different densities) may have favoured a greater opportunity for the selection and ingestion of forage in the OP than in the SPS. The higher CP content of forage in the SPS observed in this study, which was associated with microclimatic conditions that were more favourable to the thermal comfort of the animals (Sousa *et al*. 2010), may have compensated for the lower observed masses and forage bulk density in the SPS, thereby contributing to the similar ADG among systems.

Despite similarity in SR and ADG between systems during the experiments, there was a progressive decrease in GPA in the SPS over time, culminating in lower values being observed in 2014–2016. In the OP, a sharp decrease between 2003–2004 and 2004–2007 was observed, though the relative stabilisation of GPA over the period between the experiments (2004–2007 and 2014–2016) is noteworthy. The comparison of systems indicates that there a significant GPA difference in favour of the OP in the last experiment only.

The results of the present study confirmed the expectation of reduced animal productivity by area in the long term SPS. Despite this, the magnitude of differences can be considered small and attributed to forest thinning over time – either by death or the intentional removal of trees – preventing a greater increase in the level of shade in the SPS. It is also emphasised that the extensive management model may have reduced differences between the systems. Considering the results of this long-term SPS study on animal production, it should be expected that income from wood, and its benefits to the environment such as increased the carbon stock in the aerial biomass, will compensate for the lowest animal GPA values from the 17th to 19th years. In addition, the commercialisation of this wood over the long-term represents a method of adding value to the product.

Conclusions

The growth of trees in a SPS over time progressively reduces the PAR available for grass growth. In the present study, the progressive reduction of the PAR negatively impacted the productive characteristics of the pasture in the SPS from the 7th year onwards. However, the liveweight gain of heifers were similar between systems most of the time. To some extent, the higher protein content in the SPS nutritionally compensated for reduced forage mass, leaf mass, and forage bulk density over time. The weight gain per area was lower in the SPS from the 17th to 19th years; however, the difference between systems was relatively minor. Even under intense shade, signal grass presents a high degree of phenotypic plasticity which gives this species a high potential for use in SPS.

Conflicts of interest

The authors declare no conflicts of interest.

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Soil Science/ Scientific Notes

Sampling frequency to estimate cumulative nitrous oxide emissions from the soil

Abstract – The objective of this work was to assess the influence of gas sampling frequency on the cumulative emissions of nitrous oxide (N_2O) from the soil. Gas emissions were assessed over a period of two years (2014–2016), in four systems: eucalyptus forestry, crops, pasture, and native forest. The cumulative emissions of N_2O were calculated at sampling intervals of 7, 14, and 21 days. The sampling intervals did not influence the final results of cumulative N_2O emissions from the soil in the assessed systems.

Index terms: agriculture, emission factor, forestry, greenhouse effect, native forest, N_2O.

Frequência de amostragem para estimativa das emissões acumuladas de óxido nitroso do solo

Resumo – O objetivo deste trabalho foi avaliar a influência da frequência de amostragem de gases na estimativa das emissões acumuladas de óxido nitroso (N_2O) do solo. Foram avaliadas emissões de gases durante dois anos (2014–2016), em quatro sistemas: plantio de eucalipto, lavoura, pastagem e fragmento florestal. As estimativas acumuladas de N_2O foram calculadas para intervalos de 7, 14 e 21 dias. Os intervalos de amostragem não influenciaram os resultados finais de emissões acumuladas de N_2O do solo nos sistemas avaliados.

Termos para indexação: agricultura, fator de emissão, floresta plantada, efeito estufa, floresta nativa, N_2O.

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According to the guidelines for assessing greenhouse gas emissions from the soil using manual static chambers, the adopted sampling frequency depends on the system being evaluated. For natural or agricultural systems, as well as for long-term experiments that do not aim to assess the influence of fertilization, irrigation, sowing, or rainfall on soil N_2O emissions, it is recommended that gas sampling intervals range from 7 to 21 days (Parkin, 2008; Parkin & Venterea, 2010; Klein & Harvey, 2015; Butterbach-Bahl et al., 2016).

For soils with fewer perturbations or when low fluxes are expected, the sampling frequency could be lower, at least every 2 or 3 weeks (Parkin & Venterea, 2010; Butterbach-Bahl et al., 2016); however, this increases error when measuring the cumulative N_2O flux (Parkin, 2008). According to Rochette et al. (2015), gas sampling should be performed twice every week when gas peak fluxes are expected and once during the period of low fluxes. Parkin & Venterea (2010) recommend that sampling should be carried out daily after events that lead to higher fluxes, such as sowing, fertilization, irrigation, and rainfall, and weekly in other events during the crop cycle. For Reeves & Wang (2015), in agricultural systems, sampling should be done at least one time a week, but two times after rain events.

Increasing gas sampling frequency ensures a greater accuracy and representativeness in the estimation of gas emissions from soils (Parkin, 2008). However, an increase in the interval that does not change the final estimates of cumulative emissions can lead to a reduction in research costs: team, field, and laboratory costs. Another difficulty is related to the distance of the area to be evaluated, which makes weekly visits practically impossible due to high costs and difficult sampling logistics, hindering some research on soil gas emission.

The objective of this work was to evaluate the influence of gas sampling frequency on the cumulative emissions of N_2O from the soil.

The research was conducted at the experimental farm of Embrapa Agrossilvipastoril, located in the municipality of Sinop, in the state of Mato Grosso, Brazil (11°51'38"S, 55°36'3"W). From November 2014 to October 2016, soil N_2O emissions were assessed in four systems: 1 ha eucalyptus, 1 ha crops, 2 ha pasture, and native forest fragment. The H13 eucalyptus (*Eucalyptus urograndis*) clone was planted in November 2011, at a density of 952 plants per hectare, with a spacing between plants of 3.0×3.5 m. Since November 2011, the crop system has been cultivated with soybean [*Glycine max* (L.) Merr.] and, after its harvest, with corn (*Zea mays* L.) intercropped with 'Marandu' grass [*Urochloa brizantha* (A.Rich.) R.D.Webster (Syn. *Brachiaria brizantha*) (A.Rich.) Stapf], which works as soil cover after corn harvest. The pasture was formed in November 2011 with 'Marandu' grass. The forest fragment is close to the other systems, approximately 500 m away, and is composed of initial secondary species. The areas with eucalyptus, crops, and pasture were evaluated with six replicates, and the forest, with three. All these systems are on a Latossolo Vermelho-Amarelo distrófico típico of clayey texture (Santos et al., 2018), which corresponds to a Hapludox of clayey texture, in flat relief (Soil Survey Staff, 1999). The main attributes that characterize the 0–10-cm soil layer of the studied areas are presented in Table 1.

Soil N_2O emissions were assessed using the method of vented static chambers, which were rectangular-shaped, with a base of metal and a top of polyethylene. A three-way gas sampling faucet was attached to the center of the top of the chamber, and a tube for internal ventilation was installed on the side of the chamber (Parkin & Venterea, 2010). Gas collections were performed every 7 days, always in the morning, between 8:00 and 11:00 a.m., using a 20-cm^3 syringe. For each chamber, four gas samples were collected at 0, 20, 40, and 60 min after chamber deployment (Parkin & Venterea, 2010). In addition, at the time of gas sampling, the internal temperature of the chamber was also monitored using a digital thermometer.

Gas samples in the syringes were transferred to 20-cm^3 glass vials, which were duly sealed and vacuumed. N_2O concentrations were determined in the GC-2014 gas chromatograph (Shimadzu, Tokyo, Japan), equipped with an electron capture detector, an auto-sampler, and a column system composed of HayeSep 80/100 mesh (1/8" × 2.1 mm) series columns held at 75°C throughout the analysis. Ultrapure nitrogen was used as the entrainment gas at a flux rate of 25 mL min^{-1}, and the injector pressure was maintained at 300 kPa. The injection volume was 1 mL, and the total analysis time was 5 min. The analytical curve used for the estimates of the gas concentrations in the samples was obtained through three known concentrations of N_2O standards – 383, 808, and 2,027 nmol mol^{-1} –, purchased from White Martins (Rio de Janeiro, RJ, Brazil).

Using the analytical results, a linear model was adjusted by the relationship between the variations in N_2O concentrations within the chamber and time, i.e., 0, 20, 40, and 60 min. These data were used to calculate the N_2O flux from the soil to the atmosphere, according to the equation proposed by Hutchinson & Livingston (1993): Flux (μg N m^{-2} h^{-1}) = ($dCdt^{-1}$) × V/A × (mVm^{-1}), where $dCdt^{-1}$ is the change in gas concentration (mol L^{-1}) inside the chamber as a function of time (h), V is the volume of the chamber (L), A is the chamber area (m^2), m is the molar mass (g mol^{-1}), and Vm is the molar volume of the gas (L mol^{-1}).

Flux results were used to estimate the cumulative emissions of the gas during the evaluated period, by the Newton-Cotes (trapezoidal integration) method of numerical integration (Rochette et al., 2015). Sampling intervals of 7, 14, and 21 days were used for integration, which, together with the flux data, represent one of the factors in this calculation. The cumulative N_2O emissions were estimated for two years, i.e., 2014–2016, specifically for the dry and rainy seasons, which contributed to determine the most adequate sampling frequency for each season.

Even after their transformation, the data for two years of soil N_2O emissions did not follow a normal distribution according to the Shapiro-Wilk test; therefore, the standard error of the mean was used to compare the sampling frequency within and between systems.

The cumulative emissions of N_2O from the soil did not differ for the two experimental years, for all gas sampling intervals in all systems (Figure 1). This result may be related, in part, to the great variability of data, leading to a high standard error of the mean, common in gas emission studies (Parkin, 2008; Venterea et al., 2009; Barton et al., 2015).

The sampling interval also did not change the final estimates for cumulative N_2O obtained just for the rainy or dry period (Figure 1). This is indicative that, if greater sampling intervals of 14 or 21 days were used, the cumulative emission would not differ for forest and agricultural systems, even during the period of high soil moisture, when fluxes are higher (Kachenchart et al., 2012; Teh et al., 2017). It should be noted that these results refer only to the final estimates of gas emission and may not be useful for understanding its temporal dynamics, which would include observing the evolution of emissions over time (Rochette et al., 2015). When the goal is to determine flux dynamics rather than cumulative emissions, Barton et al. (2015) pointed out that the sampling frequency should be higher than once every week due to the high variability of soil N_2O data, especially when the intention is to evaluate the effect of agricultural practices on N_2O emissions from the soil.

Because the cumulative emissions were the same for each system evaluated at the sampling intervals recommended by international protocols (Parkin, 2008; Parkin & Venterea, 2010; Klein & Harvey, 2015; Butterbach-Bahl et al., 2016), it may be questioned whether the indicated sampling frequency is adequate for the studied conditions and systems. In this sense, it is necessary to assess if increases in sampling frequency to more than once a week would result in different values of cumulative emissions of N_2O from the soil in different systems, mainly the agricultural ones, which are characterized by greater amounts of soil and more cultural management practices.

The availability of and accessibility to an apparatus with automatic chambers make it feasible to sample gases daily, hourly, or more than once a week in long-term experiments, which enhances accuracy and decreases sampling errors (Fassbinder et al., 2013; Reeves & Wang, 2015). Only in this way, will it be possible to follow recommendations to increase sampling frequency after important events that alter gas emissions, such as rainfall, fertilization, and sowing, among other soil and cultural management practices (Parkin & Venterea, 2010; Reeves & Wang, 2015). However, tests performed by Smith & Dobbie (2001) indicate that there is no significant difference in the cumulative estimate of N_2O by increasing sampling frequency from 7 or 3 days to 8 hours. Likewise, Reeves & Wang (2015) observed that gas sampling thrice or once a week in agricultural systems had the same level of accuracy and did not represent significant losses in the annual estimates of soil N_2O emissions.

Therefore, the obtained data show that cumulative N_2O emissions from the soil for the general evaluation of agricultural and forest systems can be estimated at sampling intervals of 7 to 21 days, without significantly hindering final results. However, it is also important to assess other soil and climatic conditions.

Table 1. Main attributes of the 0–10-cm layer of the Hapludox of the evaluated systems[(1)].

System	pH_{H2O}	C (%)	N (%)	S ($cmol_c\ kg^{-1}$)	V (%)	Clay	Silt	Sand
						-------------------(g kg^{-1})-------------------		
Eucalyptus (*Eucalyptus urograndis*)	5.5	2.4	0.2	1.4	37	520	110	370
Crops	5.8	2.3	0.2	2.3	43	500	120	380
Pasture	5.4	2.6	0.2	1.6	42	490	160	350
Forest	4.6	4.6	0.3	0.5	10	480	110	410

[(1)]C and N, carbon and nitrogen, determined by dry combustion; S, sum of bases, determined by the sum of $Ca^{2+} + Mg^{2+} + K^{+}$; V, base saturation; and clay, silt, and sand determined by the pipette method.

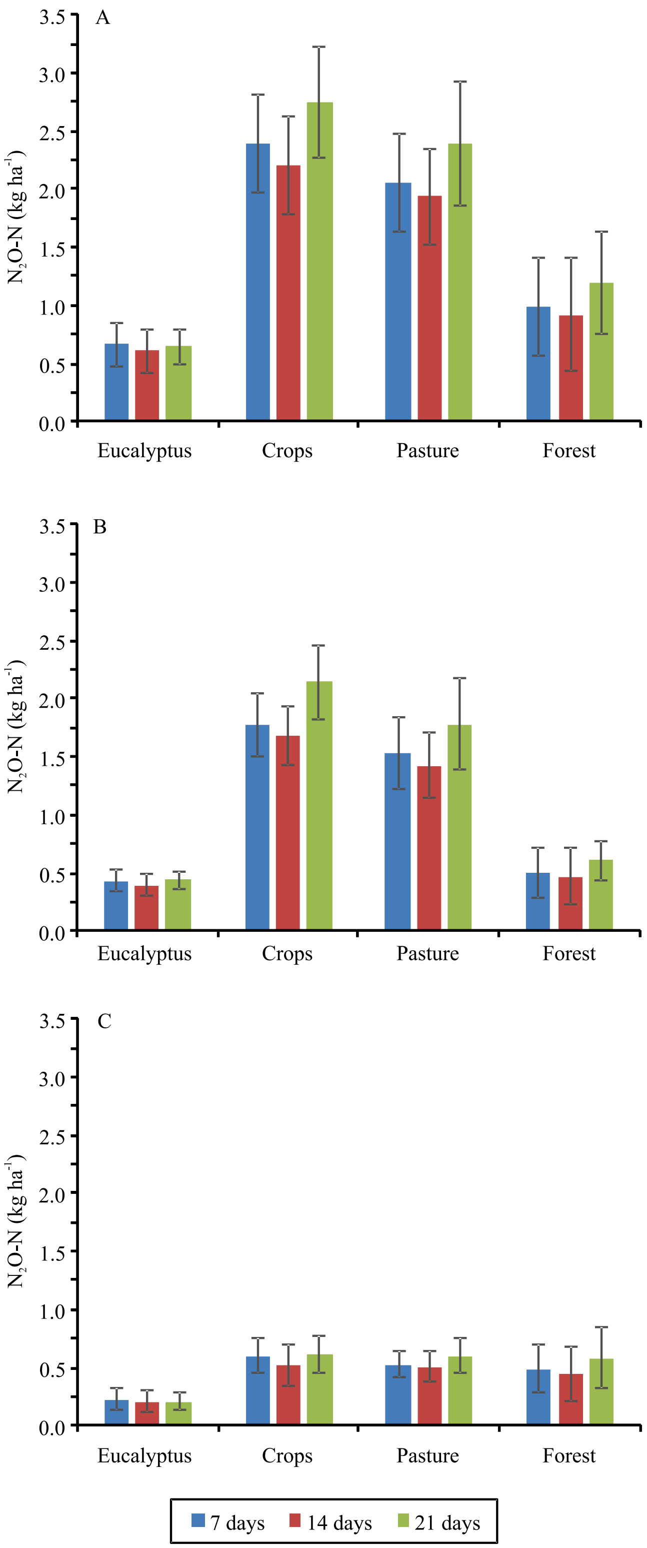

Figure 1. Cumulative N_2O-N emissions from soil under eucalyptus (*Eucalyptus urograndis*), crops, pasture, and native forest, estimated at gas sampling frequencies of 7, 14, and 21 days during two years, i.e., 2014–2016 (A), in the rainy (B) and dry (C) seasons.

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Animal production systems and agribusiness

Attractants for automated emission measurement (Greenfeed®) in pasture-based systems

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ABSTRACT - This study aimed to evaluate the frequency and intensity of GreenFeed (GF) use by Nellore steers using different attractants in pastures of integrated systems. The attractant protein supplement and Tifton bermudagrass pelleted hay flavored with vanilla were evaluated over a period of 15 days. The pelleted hay stimulated the animals to stay longer in the equipment (24.23 s), with 8% more visits in intervals longer than 30 s in contrast to protein supplement. This indicates that pelleted hay flavored with vanilla is a potential attractant to encourage Nellore steers to visit GF in grazing systems.

Key Words: beef cattle, enteric methane, greenhouse gases, integrated systems, mitigation, sustainable intensification

Introduction

Agricultural production systems are frequently criticized because of their significant greenhouse gas (GHG) emissions. However, measurements of gas emissions are influenced by several factors such as climate, soil, animal, and type of equipment used in the evaluations.

In this context, researchers in the last decade have evaluated more accurate measurement techniques (Parkin and Venterea, 2010; Zimmerman and Zimmerman, 2012) in an attempt to develop technologies to mitigate GHG emissions from agricultural areas and livestock production (Lal et al., 1998; Beauchemin et al., 2008; Carvalho et al., 2010; Luo et al., 2010; Balbino et al., 2011).

To evaluate the effectiveness of different systems in terms of reducing GHG emissions, accurate measurements of methane emissions are key. There are several methodologies for measuring daily enteric methane production, such as respiratory chambers (Blaxter and Clapperton, 1965; Pinares-Patiño et al., 2013), sulfur hexafluoride tracer (Johnson et al., 1994; Berndt et al., 2014), and, recently developed, the GreenFeed (GF) system (C-Lock Inc., Rapid City, SD, USA).

The GF system determines daily enteric methane emissions using head- and nose-positioned sensors in combination with decision rules to validate the data obtained (C-lock, 2016; Hammond et al., 2015a). Hereby, the animal voluntarily places its head inside the hood where feed is offered in the form of an attractant to ensure prolonged contact with the equipment, allowing methane measurement (Hammond et al., 2016).

However, to date, the knowledge about animal × GF interaction is still limited, especially regarding pasture-based systems. The most suitable type of attractant and the optimal positioning of the equipment in pastures, ensuring accurate measurements, still need to be found. In this context, the objective of this study was to evaluate frequency and intensity of GF use by beef steers maintained in a crop-livestock-forest integrated system as affected by two types of attractants.

Material and Methods

The experiment was carried out in Sinop, MT, Brazil (11º51' S, 55º35' W, elevation of 370 m), in the Amazon biome. Research on animals was approved by the institutional committee on animal use (case number 008/2015). Measurements with GF were carried out during two periods of 15 consecutive days between July

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and August 2016 on animals maintained in crop-livestock-forest integration systems with beef cattle.

The animals used were two uncastrated Nellore steers, with an average initial weight of 301±3 kg maintained in a 2-ha pasture consisting of *Brachiaria brizantha* (syn. *Urochloa brizantha*) cv. Marandu, established annually for use only in the off-season (July-September). The pasture was planted in consortium with maize (second crop) after soybean harvest and planted with triple rows of eucalyptus *(Eucalyptus urograndis* clone H13), in the arrangement of 3.0 × 3.5 m (270 ha^{-1} trees), with 30-m spacing, in a crop-livestock-forest integration system.

Two attractants were evaluated regarding their ability to encourage animals to visit the GF. In the first evaluation period, a protein supplement (35% crude protein) was offered in powder form. This product is commonly used in farms and the animals are well adapted. The equipment was programmed to offer the attractant at 6-h intervals (duration of the feeding period) with up to eight drops of 60 g (feed supply) distributed in 40-s intervals for up to 5 min in each feeding period. Each day, no more than four feeding periods were allowed, totaling a maximum intake of 1,920 g $animal^{-1}$ day^{-1}.

In the second evaluation period, pelleted Tifton bermudagrass hay (13% crude protein), flavored with vanilla (5 g kg^{-1}), was offered at a maximum quantity of 2,400 g $animal^{-1}$ day^{-1}. This amount could be consumed for up to six feeding periods per day, with a minimum interval of 3 h. At each visit to the equipment, the animal received 50 g of pellets per drop, every 40 s (50 g $drop^{-1}$), for up to 5 min, with a maximum of eight drops per feeding period.

In each evaluation period, the animals were adapted to the attractant for seven days; access to the GF occurred without any restriction in feeding periods and number of drops. To ensure animal visits at the equipment, the GF was allocated near a resting area. In addition, during the first evaluation period, the protein supplement supply was only provided via the GF and not in troughs, in contrast to the usual practice. During the second evaluation period (pelleted hay), protein supplement continued to be supplied in specific troughs.

The GF recorded each visit of each animal by means of an electronic earring, automatically identifying time and duration of the visit, number of drops offered per visit, and feeding period. Concomitant with these measurements, behavioral assessments were performed to determine the intensity of GF use between 6:00 and 18:00 h. Regardless of the time evaluated, when the animals visited the GF, the time they spent with their heads inside the equipment was measured using a digital timer. At the end of each visit, the times were added, characterizing the GF use at each visit and the sum of these visits during the evaluation period, thereby characterizing the GF use over a period of 12 h.

The design was completely randomized with two treatments (protein supplement and pelleted Tifton bermudagrass hay flavored with vanilla) and two sample units (animal) repeated on time (15 days) per treatment (n = 60). Time in the feeder (equipment), number of drops per day, and number of drops per feed period were analyzed using the mixed model method, using the MIXED procedure of the statistical software SAS (Statistical Analysis System, version 9.4) (Littell et al., 2006), considering attractants as fixed and animal as random effects. To choose the covariance matrix, the Akaike information criterion was used. The means of treatments were estimated using LSMEANS; treatments were performed using the probability of difference ("PDIFF") with a significance level of 5%.

Results

For all variables, the greatest values were obtained for pelleted hay. This attractant provided 2.30 feeding periods, with 5.66 s more feeding time compared with the protein supplement (Table 1), which represents an increase of 30% in time for the quantification of methane emission. The intake of drops (day) and drops per feeding period were 163 and 70%, respectively, greater for pelleted hay.

Evaluating the number and percentage of visits to the GF in relation to the length of the stay with head in the feeder, the number of visits shorter than 30 s was greater when the attractant was protein supplement (Table 2). The use of pelleted hay with vanilla increased the number of visits longer than 30 s by 283% compared with protein supplement.

The time each animal remained at the GF, without necessarily keeping the head in a position suitable for methane measurement, was longer for the pelleted hay (138 s) in relation to the protein supplement (70 s) (Figure 1). In addition, over 12 h of evaluation, the frequency of GF use was greater for pelleted hay (738 s) than for the protein supplement (352 s). Equipment use was greatest between

Table 1 - Frequency of GreenFeed use by beef steers in response to two attractants in a crop-livestock-forest integration system

Variable	Protein supplement	Pelletized hay	P-value	CV (%)
Feed time (s)	18.57b	24.23a	0.0032	33.30
Feeding period (number/day)	1.63b	2.30a	0.0031	43.07
Drops (day)	5.63b	14.83a	<0.0001	57.47
Drops per feeding period	3.63b	6.19a	<0.0001	41.42

CV - coefficient of variation.

7:00 and 8:00 h and between 13:00 and 15:00 h, regardless of the attractant.

Discussion

The pelleted hay with vanilla contributed to longer ingestion times of each drop, evidenced by longer feeding times and feeding periods (Table 1). This probably occurred because this attractant, compared with protein supplement, may have contributed to the greater intake (more drops) and number of visits. This is evidenced by the number of feeding periods per day with the use of vanilla (Table 1). As the nutritional composition of the pellets was similar to that of the diet of the animals, the supply of this feed without vanilla would, most likely, not be sufficient to stimulate GF visits because the nutritional requirement could be met by the intake of green forage in the pasture.

The results of this experiment are not in agreement with those observed by Hammond et al. (2016), who indicated that salt could be considered a desirable substitute for pelleted supplement since it does not directly contribute to energy intake and has no direct effects on methane production.

On average, the feeding period per day in feedlot systems was 2.66 (Hammond et al., 2015a; 2015b; Huhtanen et al., 2015), while it was 1.4 in pasture systems (Hammond et al., 2015a; Waghorn et al., 2016). The data obtained in this experiment (Table 1) are close to the values obtained for animals evaluated in feedlots, showing the potential of pelleted hay as an attractant in GF systems in a pasture-based beef cattle production system.

Table 2 - Visits of beef steers at the GreenFeed in response to two attractants in a crop-livestock-forest integration system during 15 days

Length of stay with the head in the feeder (s)	Protein supplement		Pelletized hay	
	Number of visits	% of total number	Number of visits	% of total number
0-30	174	85	408	77
31-60	21	10	78	15
61-90	6.5	3	21	4
91-120	3.5	2	11	2
> 121	0	0	9	2

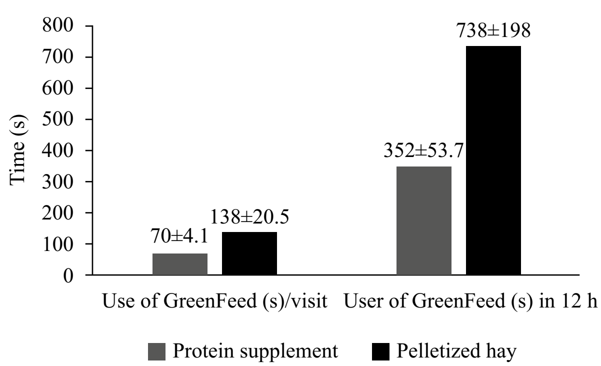

Figure 1 - Intensity of GreenFeed use by beef steers in response to two attractants during 12 h in a crop-livestock-forest integration system.

The recommended minimum time for methane reading by GF is around 30-40 s to reduce (or avoid) the impact of wind speed and direction in the gas sampling (C-lock, 2016). Pelleted hay with vanilla increased by 3.84 times the number of visits over 30 s. This may contribute to more reliable results on methane emissions due to the increased samplings throughout a day (Table 1) and the increased length of stay in the equipment (Table 2).

The physical form of the pelleted hay and the use of flavor could have stimulated the animals to remain longer in the GF (Figure 1). However, in pastoral environments, the number of GF visits are lower than in feedlot systems (Cottle et al., 2015; Gunter and Bradford, 2015; Hammond et al., 2015a). This is explained by the fact that in feedlot systems, much of the diet is provided through the equipment, which encourages animals to visit the GF. However, in grazing systems, the forage is the feed to be evaluated, and any feed offered via the GF system is understood as an attractant to enable enteric methane measurement, which reduces visit frequency.

An alternative to overcome difficulties of methane emission measurement in a grazing production system would be the extension of evaluation periods, thereby increasing the frequency of GF visits. Waghorn et al. (2016), evaluating methane emissions of lactating cows with two stocking rates in perennial ryegrass (*Lolium perennial*) pastures, found that the frequency of GF visits increased by 47% when the evaluation period increased from 1 (8%) to 4 (55%), in which each period corresponded to three weeks of evaluation. This had a positive impact on accuracy and precision of the enteric methane measurement via the GF system.

Conclusions

The use of pelleted hay of Tifton 85 bermudagrass with vanilla is an alternative attractant to encourage Nellore steers to visit GreenFeed systems and may contribute to achieve accurate methane emission measurements in pasture-based systems.

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Artigo

Ciclagem de Nitrogênio em Florestas Tropicais e Plantações de Eucalipto no Brasil no Antropoceno

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Nitrogen Cycling in Tropical Forests and Eucalyptus Plantations in Brazil in the Anthropocene

Abstract: The nitrogen is a macronutrient essential for the functioning of the metabolism of living beings. However, due to the changes that the planet has been passing in the Anthropocene, the nitrogen cycling has been altered. Deforestation combined with changes in land use are primarily responsible for the change in their cycling. Emissions of greenhouse gases such as N_2O were increased due to this deforestation and inadequate soil management practices, and this contributed to the fact that these changes in nitrogen cycling occurred. Considering the importance of nitrogen and the changes that it has undergone in the last decades, this work of revision aims to describe the role of nitrogen and the changes in its cycling due to the processes of land use change that occurred in the Anthropocene in forest areas tropical and eucalyptus plantations in Brazil.

Keywords: Anthropocene; nitrogen cycle; planted forest; nitrogen oxides.

Resumo

O nitrogênio é um macronutriente essencial para o funcionamento do metabolismo dos seres vivos. Porém, devido às mudanças que o planeta vem passando no Antropoceno a ciclagem do nitrogênio vem sendo alterada. O desmatamento aliado às mudanças do uso do solo são os principais responsáveis pela alteração da sua ciclagem. As emissões de gases de efeito estufa como do N_2O foram aumentadas em virtude desse desmatamento e das inadequadas práticas de manejo do solo, e isso acabou contribuindo para que essas mudanças na ciclagem do nitrogênio ocorressem. Visto a importância do nitrogênio e das alterações que ele vem passando nas últimas décadas, este trabalho de revisão tem como objetivo descrever o papel do nitrogênio e as alterações na sua ciclagem devido aos processos de mudança do uso da terra ocorridos no Antropoceno em áreas de florestas tropicais nativas e plantações de eucalipto no Brasil.

Palavras-chave: Antropoceno; ciclo do nitrogênio; floresta plantada; óxidos de nitrogênio.

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Ciclagem de Nitrogênio em Florestas Tropicais e Plantações de Eucalipto no Brasil no Antropoceno

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1. Introdução

Em ecossistemas naturais terrestres, o nitrogênio (N) é um elemento essencial para o desenvolvimento das plantas. Na forma molecular como N_2, é o elemento mais abundante da atmosfera, porém somente está disponível para as plantas quando em formas reativas, principalmente nitrato (NO_3^-) e amônio (NH_4^+),[1] e em menor importância em formas orgânicas.[2] Ao contrário dos demais nutrientes, o N tem grande mobilidade no sistema solo-planta-atmosfera em função dos processos que alteram sua valência química, e consequentemente formas no ambiente. Por isso, desequilíbrios provocados por ações antrópicas podem mudar a intensidade desses processos e levar a impactos negativos no ambiente, tal como acidificação, eutrofização e perda de biodiversidade.[3]

O Antropoceno é marcado por grandes mudanças ambientais, sociais e econômicas a partir de 1950, conhecido como a "Grande Aceleração".[4-6] Fortemente marcado também pela influência do homem no equilíbrio biogeoquímico do Sistema Terra.[4,7] Essa época de intensa ação antrópica trouxe bons resultados como o crescimento econômico no setor agrícola, mas também promoveu danos ambientais ao planeta terra, como alterações na ciclagem de importantes nutrientes como o N, esse efeito pode ser visto no aumento das emissões de gases de efeito estufa (GEE) como o N_2O.[5,6,8,9]

Durante todo o Antropoceno as áreas de florestas foram dando lugar para o crescimento das civilizações. A revolução agrícola, foi um importante marco para o aumento do desmatamento.[6] Durante esta revolução as florestas cobriam a nível global em torno de 6 bilhões ha, em 1998 essa área tinha diminuído para cerca de 4 bilhões ha, a maior parte dessa perda ocorreu nos últimos 50 anos do século XX.[10] Segundos dados mais recentes da Organização das Nações Unidas para a Alimentação e a Agricultura (FAO)[11] estima-se que somente 31 % da superfície terrestre ainda estejam cobertas por florestas, sendo que a maior parte ocorre em regiões tropicais e as principais causas do desmatamento são a abertura de novas áreas para produção agrícola, urbanização e retirada de madeira.

Por outro lado, a necessidade cada vez maior de um contínuo suprimento de produtos de origem florestal, como madeira, lenha e celulose, aliado a crescente preocupação com a preservação ambiental, impulsionou o aumento dos plantios florestais que em parte contribuem para compensar a ocupação das áreas nativas. Entre 2000 e 2010, aproximadamente 130 milhões ha de florestas foram perdidos no mundo, no entanto devido às atividades de reflorestamento com espécies nativas e/ou exóticas uma área de 78 milhões ha foram recuperados.[12]

No Brasil, os plantios florestais são majoritariamente dos gêneros Eucalyptus e Pinus em menor percentagem, espécies exóticas que vem sendo utilizadas, principalmente, para fins industriais, mas também para recomposição de áreas desmatadas. Embora sejam árvores, essas espécies modificam a dinâmica de deposição e decomposição da matéria orgânica do solo (MOS) em relação ao observado originalmente,[13] afetando o ciclo dos nutrientes, como o do N, com possíveis impactos ambientais. Essa preocupação é pertinente tendo-se em conta que a expansão de florestas comerciais é uma realidade no Brasil, e sem dúvida contribui para reduzir a pressão sobre florestas nativas, porém ainda não é claro o quanto modificam a dinâmica de nutrientes, em especial o N.

Desta forma, o objetivo deste artigo de revisão é descrever as alterações no ciclo do N com as mudanças de uso da terra ocorridas no Antropoceno em áreas de florestas tropicais nativas brasileiras, destacando-se o uso com plantações de eucalipto.

2. Antropoceno: Reflexos sob Sistemas Florestais Naturais e Antrópicos

2.1. Florestas tropicais naturais

O Brasil apresenta uma grande diversidade de ecossistemas florestais, dada a sua extensa área física, sua diversidade de climas e de solos. As florestas tropicais e subtropicais brasileiras são constituídas pela Floresta Amazônica, Floresta Atlântica e Florestas de Planalto.[14] Segundo Ministério do Meio Ambiente,[15] a Floresta Amazônica é a maior floresta tropical úmida do mundo e ocupa uma área estimada de 325 milhões de hectares.

Por apresentarem uma alta diversidade florística, a serrapilheira de florestas tropicais é altamente diversificada, consequentemente a comunidade de microrganismos também é diversa. Regiões com florestas tropicais apresentam clima bem definido, com estações de seca e de chuva, elevadas temperaturas e umidade. Essas características promovem uma intensificação na atividade microbiana, contribuindo para um aumento nas taxas de decomposição e mineralização da MOS.[16-18]

Florestas tropicais possuem denso dossel criando uma barreira física de proteção do solo. As copas densas das árvores amortecem o impacto das gotas da chuva favorecendo uma maior infiltração da água no solo e reduzindo a ocorrência de erosões no solo.[19,20] Solos florestais por não passarem por nenhum tipo de manejo, apresentam melhores condições de porosidade, que facilita a infiltração da água, a recarga dos lençóis freáticos e ainda, influência nos estoques e perdas de N via lixiviação e/ou erosão do solo.[21]

O Antropoceno é marcado por atividades que contribuíram para as mudanças na estrutura e funcionamento do planeta Terra.[4] Uma dessas atividades é o desmatamento. Todos os benefícios ambientais promovidos pela floresta acabam sendo prejudicados em função do desmatamento. Essa prática acarreta diversos problemas ambientais e sociais, como a perda de biodiversidade, alteração no ciclo hídrico, o aumento das emissões de gases de efeito estufa (GEE) e a diminuição de territórios de populações tradicionais.[22-24]

Segundo Fearnside,[25] incentivos fiscais dados para grandes fazendeiros entre 1970 e 1980, período este já no Antropoceno, resultou no aumento do desmatamento na região da Amazônia brasileira. O Instituto Nacional de Pesquisas Espaciais (INPE), por meio de imagens via satélite, monitora o desmatamento em várias regiões do Brasil, principalmente na Amazônia Legal. Dados recentes mostram uma redução no desmatamento na região da Amazônia Legal. Em 2004 a taxa de desmatamento foi de 27.772 km^2 já em 2017 essa taxa se reduziu para 6.947 km^2, uma variação de -75 % na taxa de desmatamento.[26] Essa diminuição também é resultado do Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm) do Ministério do Meio Ambiente.[27] Em 2005, as ações do PPCDAm mostraram uma redução da taxa anual do desmatamento de 20.000 km^2 para o atual que varia entre 6.000 – 7.000 km^2. Percentual este menor que o considerando com média de referência da Política Nacional de Mudança do Clima, de 19.625 km^2 (período de 1996 a 2005).[27]

A região de Mata Atlântica também vem mostrando bons resultados no que diz respeito à redução do desmatamento de florestas nativas. A Fundação SOS Mata Atlântica em parceria com o INPE, desde 1985 realizam um monitoramento dos 17 estados que fazem parte do bioma Mata Atlântica. Dados do último relatório técnico de Remanescentes Florestais da Mata Atlântica período 2016-2017 relatou uma queda no desmatamento de 56,8 % em relação ao período anterior (2015-2016), o que significa que no ano de 2017 foram desmatados 125,62 km^2 do bioma e, entre 2015 e 2016, o desmatamento foi de 290,75 km^2.[26]

2.2. Plantações de eucalipto

Para expansão das atividades agropecuárias na época da chamada “Grande Aceleração”, muitas áreas de floresta nativa foram desmatadas, porém, com as mudanças no código florestal brasileiro (Lei nº 12.651, de 25 de maio de 2012)[28] e com uma maior fiscalização e monitoramento nas florestas pelos órgãos responsáveis, o desmatamento ilegal vem sendo reduzido.

No entanto, para que muitos produtores rurais ou empresas pudessem regularizar sua situação perante as novas leis ambientais e/ou cumprir seu passivo ambiental, áreas nativas que foram derrubadas estão sendo recuperadas e reflorestadas com espécies regionais ou exóticas de rápido crescimento como é o caso do eucalipto.

A floresta plantada atualmente é vista com novos olhos. Além de contribuir com a recuperação de áreas degradadas e trazer renda direta e indireta aos produtores e empresas florestais, o plantio de floresta contribui para redução na pressão sobre as florestas nativas.[29]

O país com maior participação em área global de floresta plantada é a China com 27,27 % do seu território ocupado, já o Brasil ocupa o 9º lugar com cerca de 2,67 %. Estima-se que 76 % destas plantações são destinadas para a produção de madeira.[30] No Brasil, segundo o relatório do Instituto Brasileiro de Geografia e Estatística - IBGE,[31] a área de floresta plantada é de 99.000 km², destes, 74,9 % é ocupado por plantação de eucalipto. O Brasil liderou o ranking global de produtividade florestal em 2015, com produtividade média dos plantios de eucalipto de 36 $m^3 ha^{-1} ano^{-1}$.[32]

O gênero *Eucalyptus* spp pertence à família Myrtaceae com cerca de 600 espécies.[33] De origem Australiana, as mudas de eucalipto foram trazidas em 1903, pelo pioneiro Edmundo Navarro de Andrade.[34] Apesar de ser uma espécie exótica, o eucalipto apresentou uma boa adaptação ao clima tropical brasileiro, aliado a avançada tecnologia da silvicultura, contribuiu para a elevação da produtividade nacional de madeira, sendo maior que as de muitos países de clima temperado. [35]

No Brasil, florestas plantadas de eucalipto têm sido largamente utilizadas na prática de recuperação de áreas degradadas.[36] Essas florestas promovem benefícios ao ecossistema tais como, regulação do ciclo hídrico, sequestro de carbono e conservação da biodiversidade local.[37] Nas indústrias, o eucalipto é utilizado para a produção de madeira para serraria, mourões, postes, energia, celulose, laminados e extração de óleos e resinas.[38,39]

Desta forma, o plantio de florestas contribui para diminuição na retirada de madeira de áreas naturais, e aumenta o fornecimento de madeira, fibra, combustível e produtos florestais não madeireiros de áreas de florestas plantadas.[29]

3. Nitrogênio: Funções e Importância

O N foi descoberto em 1772 pelo médico e químico Daniel Rutherford. É um macronutriente essencial para o funcionamento do metabolismo dos seres vivos, pois é necessário para a formação de diversas moléculas como, adenosina trifosfato (ATP), ácidos nucleicos (DNA e RNAs), aminoácidos, proteínas entre outros.[40-44]

O N na litosfera encontra-se distribuído nas rochas, nos sedimentos e no fundo dos oceanos, representando 98 % do N existente.[40] Já na atmosfera terrestre, 78 % dos gases correspondem ao N em sua forma molecular diatômica (N_2).[40] O óxido nitroso (N_2O) é a segunda forma de N mais abundante na atmosfera possuindo um tempo de meia-vida de 130 a 150 anos.[45]

Os processos de ciclagem de nutrientes, acúmulo e decomposição da MOS, são responsáveis pelo equilíbrio existente dos ecossistemas naturais.[46] A ciclagem do N no ecossistema terrestre é fortemente influenciada pelas características físicas e químicas da área tais como, qualidade do solo, quantidade e tipo de serrapilheira, vegetação, microrganismos, água, temperatura e O_2.[47-49]

Embora o N seja um elemento abundante na atmosfera, o seu uso pelas plantas é muito limitado, pois só conseguem absorver o N nas formas dos íons amônio (NH_4^+) e nitrato (NO_3^-).[50,51] A transformação do N_2 molecular nesses íons inorgânicos ocorre pela reação química chamada de fixação de N que pode acontecer por fontes naturais ou industrial.[51] A ciclagem do N envolve três etapas, a primeira de entrada do N no ecossistema terrestre, sua transformação e por último sua saída.

O N_2 pode ser fixado na atmosfera antes de ser transportado para o ecossistema terrestre, por meio da ação de relâmpagos. Essa fixação ocorre pela dissociação térmica do O_2 por descargas elétricas.[50] Já a entrada de N no ecossistema terrestre pode ser, via deposição atmosférica, fixação biológica de N (FBN) e aplicação de fertilizantes nitrogenados, e ainda sua transformação ocorre via decomposição da MOS, da mineralização, dos processos de nitrificação e desnitrificação e, as saídas do N retornando para atmosfera podem ser via emissão de óxidos de N (N_2O, NO) e emissão de N_2 (Figura 1).[16,49,52,53]

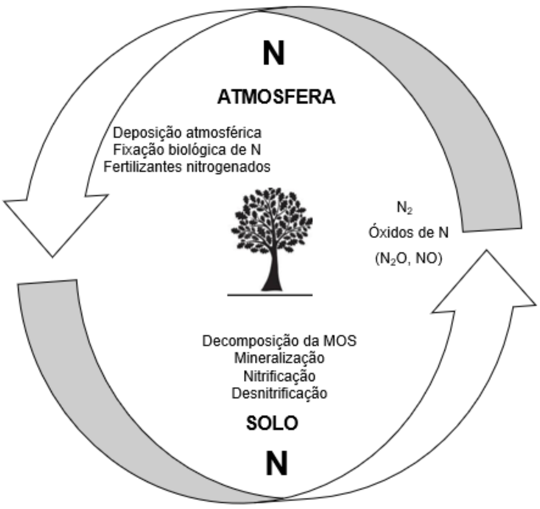

Figura 1. Ciclagem do N no sistema terrestre

A entrada do N via deposição atmosférica é constituída pelas formas úmidas e secas, que juntas são chamadas de deposição total (*bulk deposition*).[54] A forma úmida compreende a retirada dos gases e das partículas atmosféricas, tais como NH_4^+, NO_3^-, nitrogênio orgânico dissolvido (NOD) via precipitação, neblina e neve.[55] A deposição seca é constituída pela deposição de gases (NH_3; HNO_3) e de partículas atmosféricas chamadas de aerossóis, tais como: sulfato de amônio ($(NH_4)_2SO_4$) e nitrato de amônio (NH_4NO_3). Os aerossóis possuem composições, concentrações e formas diferentes, podendo ser desde poeira do deserto até poluição urbana e, a velocidade de deposição vai depender do tamanho das partículas.[56,57]

A fixação biológica do N (FBN) ocorre pela associação simbiótica entre plantas leguminosas e grupos específicos de bactérias diazotróficas, por associações não simbióticas, normalmente por bactérias presentes na rizosfera ou mesmo endofíticas, e a FBN em microrganismos de vida-livre. O grupo dos rizóbios (*Rhizobium, Bradyrhizobium, Sinorhizobium, Mesorhizobium* entre outros) é o mais conhecido entre as bactérias fixadoras de N, contribuindo largamente para a nutrição nitrogenada de leguminosas como o feijoeiro, a soja, a ervilha entre outras. O gênero *Azospirillum* é exemplo de bactéria comum na rizosfera das plantas capaz de fixar N_2, além de produzir hormônios que estimulam o crescimento de raízes. Além das bactérias, o gênero *Frankia* é um actinomiceto capaz de nodular as casuarinas, mostrando a ampla diversidade de diazotróficos na natureza.[16,49,58]

A FBN compreende uma reação de redução catalisada pela enzima nitrogenase, que realiza a quebra da tripla ligação do N_2 produzindo o NH_3, molécula que é rapidamente incorporada como aminoácido pela planta no caso dos sistemas simbióticos.[59] As plantas que não realizam simbiose com bactérias diazotróficas, assimilam N através dos íons de NH_4^+ excretados no meio pelas bactérias.[49]

Uma vez incorporado na forma orgânica, o N volta a ficar disponível para as plantas via o processo de amonificação (mineralização), que é a conversão do N orgânico em NH_4^+.[40] Nesse processo, os organismos decompositores do solo que possuem enzimas extracelulares como a celulase, protease e a urease causam a degradação da MOS tornando o N orgânico dissolvido e em seguida convertendo à íons de NH_4^+, que pode ser assimilado pelas plantas ou ainda imobilizado (absorção) pelos microrganismos.[60,61]

A fonte antrópica de N para o solo é por meio da fertilização nitrogenada.[62,63] Os dados do IBGE,[31] relatam que o fertilizante nitrogenado mais utilizado pelos agricultores é a ureia, seguido do sulfato de amônio e do nitrato de amônio, com produção em 2014 de 830, 302 e 278 mil toneladas respectivamente. Visando uma maior produtividade, muitos produtores aplicam uma quantidade maior que o necessário de fertilizantes nitrogenados e isto pode contribui para o aumento das perdas de N no meio ambiente nas formas de NH_3, NH_4^+, óxidos de nitrogênio (NOx), N_2O e NO_3^-.[64] No setor de mudança do uso da terra, as práticas de manejo e os sistemas de irrigações inadequados para a área, são responsáveis por alterações nas propriedades físicas do solo e, essas alterações podem promover a perdas de nutrientes, como a perda de NO_3^- via lixiviação. [48,65]

Toda essa mudança de uso que o solo é submetido acaba por alterar e prejudicar a ciclagem de muitos nutrientes, principalmente do N. Sendo sua ciclagem intensamente influenciada pelas características físicas e químicas do ecossistema local. Visto isso, o tópico a seguir abordará a influência da mudança do uso da terra no Antropoceno, e como essas mudanças podem alterar a ciclagem do N em áreas de florestas nativas tropicais e em áreas com florestas plantadas de eucalipto.

4. Mudanças do uso da Terra no Antropoceno: Influências Sob a Ciclagem do Nitrogênio

4.1. Entradas de N

Como já relatado, as formas de entrada de N ao ecossistema terrestre podem ser por meio da deposição atmosférica (úmida ou seca), fixação biológica ou ainda por aplicação de fertilizantes nitrogenados. Essas formas de entrada de N no sistema terrestre têm sido submetidas a diversas alterações, segundo Galloway e colaboradores,[66] a produção de alimentos e energia tem sido o impulsionador para a alteração do ciclo N e isso é o reflexo do disparado crescimento populacional do Antropoceno.

Dados do último relatório das Organizações da Nações Unidas (ONU),[67] relata que a população mundial triplicou de 1950 até meados de 2017, período da chamada a “Grande Aceleração”.[4] A população que era de 2,5 bilhões de habitantes em 1950 saltou para 7,5 bilhões em 2017. Segundo estimativas da ONU, a população mundial aumentará pouco mais de um bilhão de pessoas nos próximos 13 anos, chegando a 8,6 bilhões em 2030, e aumentará ainda mais em 2050 com 9,8 bilhões e 11,2 bilhões até 2100.[67]

Tendo em vista este cenário, fica a pergunta “Como o setor industrial e agropecuário conseguirão acompanhar esse crescimento populacional, fornecendo produtos (alimentícios/não alimentícios) de qualidade sem que haja aumento no desmatamento e emissão de GEE e ainda consiga trabalhar de forma sustentável para atender toda essa demanda?”.

O uso de sistemas consorciados de produção entre espécies fixadoras de N (leguminosas) e não fixadoras possibilitam o aumento nos estoques de N e C no solo e também da redução das emissões de GEE.[68] Santos e colaboradores,[69] observaram que os tratamentos consorciados (eucalipto+acácia) apresentaram maiores teores de N na serrapilheira em relação aos monocultivos de eucalipto, com teores de 225 kg N ha^{-1}, contra uma média de 115 kg N ha^{-1} respectivamente. Esses resultados mostram que sistemas consorciados podem contribuir para o aumento dos estoques de nutrientes no solo, principalmente do N e este pode colaborar para reduzir as quantidades de adubos aplicado na área. Segundo Cooper & Scherer,[68] bactérias fixadoras de N do grupo Cyanobactéria que são encontradas nas superfícies das folhas em área de floresta tropical podem fixar cerca de 90 kg N ha^{-1} ano^{-1}.

Assim como o N aplicado via fertilizante, o N que entra no sistema terrestre via deposição atmosférica também vem apresentando alterações no período do Antropoceno. O aumento da urbanização e industrialização, acarreta num incremento nas emissões e deposições de N para as regiões tropicais do planeta.[57,66,70]

Allen e colaboradores,[57] estimaram o fluxo de deposição seca de partículas nitrogenadas atmosféricas de áreas próximas a cultivos de cana-de-açúcar no sudeste do Brasil. Para área de floresta tropical os fluxos de deposição seca foram de 0,54 e 8,04 kg N ha^{-1} ano^{-1} para o NH_4^+ e NO_3^- respectivamente, já para as regiões mais afastadas dos canaviais e com floresta de eucalipto e pinus, o fluxo de NH_4^+ foi 0,28 kg N ha^{-1} ano^{-1}, e de 2,89 kg N ha^{-1} ano^{-1} para NO_3^-. Os autores reforçam que a queima de biomassa oriunda da cana-de-açúcar é uma das causas responsáveis pela deposição de aerossóis atmosféricos nas áreas rurais do sudeste brasileiro.

Souza e colaboradores,[70] observaram uma deposição total anual de N maior nas áreas costeiras, área mais próxima ao perímetro urbano, com 17,2 e 15,4 kg N ha^{-1} ano^{-1}, contra 15,1 e 12,1 kg N ha^{-1} ano^{-1} em áreas de floresta, que se encontram mais distante do perímetro urbano.

4.2. Acúmulo de serrapilheira e estoques de N

A serrapilheira é a principal fonte de nutrientes para o solo, e a ciclagem e disponibilidade desses nutrientes estão fortemente ligadas as condições do ecossistema local,[71,72] além de serem fortemente afetadas pela ação antrópica. Essa ação pode causar alterações nos ciclos biogeoquímicos, como do N e, acabam por prejudicar a disponibilidades desses nutrientes para o solo e para a planta.[40,66]

Visto a importância da serrapilheira para a disponibilidade de nutrientes para o solo e para a planta, trabalhos relacionados com a avalição das quantidades de serrapilheiras e teores de nutrientes, principalmente do N estão cada vez mais sendo realizados. Vital e colaboradores,[72] observaram a ciclagem de nutrientes em uma vegetação da Mata Atlântica, cuja produção de serrapilheira foi de 10.647 kg $ha^{-1}ano^{-1}$ já, o retorno dos macronutrientes dessa serrapilheira foi de 521 kg ha^{-1} e destes 218 kg ha^{-1} correspondia ao N.

Resultados semelhantes foram encontrados por Pinto e colaboradores,[73] ao trabalharem em áreas com estágio de crescimento diferentes. Na floresta em estágio inicial, a produção anual de serrapillheira foi de 6.310 kg ha^{-1} e o conteúdo de N foi de 137 kg $ha^{-1}ano^{-1}$. Já na vegetação madura, a produção de serrapilheira e o conteúdo de N foram maiores, com 8.800 kg $ha^{-1}ano^{-1}$e 180 kg ha^{-1} ano^{-1}, respectivamente. Valores próximos também foram observados em uma Floresta Ombrófila Mista Montana.[47] Os autores relataram um acúmulo médio de serrapilheira de 8000 kg $ha^{-1}ano^{-1}$ desses, o conteúdo médio de N foi de 96 kg N ha^{-1} ano^{-1}.[47]

Já em uma área de Floresta Ombrófila Densa, foi observado um acúmulo de serrapilheira em povoamento de eucalipto de 13.500 kg $ha^{-1}ano^{-1}$ e na mata nativa de 10.100 kg ha^{-1} ano^{-1}.[74] Os autores explicam que esse maior acúmulo de serrapilheira no eucalipto possivelmente está relacionado a baixa qualidade nutricional da serrapilheira o que promove menores taxas de decomposição. A serrapilheira de eucalipto apresenta maiores relações de C/N, lignina/N e (lignina + celulose) /N ocasionando uma lenta decomposição do resíduo vegetal.[74] Além disso, a idade da vegetação, a taxa de crescimento, as condições climáticas e as propriedades do solo também influenciam nos processos de decomposição da serapilheira,[75,76] isso explica os menores teores de N encontrados na serrapilheira do eucalipto que foram de 165 kg N ha^{-1} ano^{-1} contra 229 kg N ha^{-1} ano^{-1} na serrapilheira mata. Em contrapartida, o tempo de permanência do N na serrapilheira de mata nativa é menor em virtude da maior taxa de mineralização que ocorre nessas áreas.

Maiores resultados foram encontrados por Gama-Rodrigues e colaboradores,[39] onde o acúmulo de serrapilheira foi de 37.600 kg ha^{-1} ano^{-1} e 22.500 kg ha^{-1} ano^{-1} para uma área de plantio de eucalipto e de floresta de Mata Atlântica respectivamente. Já os teores de N total na serrapilheira foram maiores na mata, com valores de 377 e 304 kg N ha^{-1} ano^{-1} para o povoamento de eucalipto. Esse maior acúmulo de serrapilheira no povoamento de eucalipto possivelmente está relacionado com a relação C/N de 62 contra 30 da mata nativa. Segundo O'Connelle e Sankaran,[75] em determinados locais da América do Sul, a serrapilheira acumulada em florestas tropicais podem variar de 3.000 a 16.500 kg ha^{-1}.

Rangel & Silva,[77] ao trabalharem sob diferentes sistemas de uso e manejo do solo encontraram valores estatisticamente iguais nos estoques de N no solo para as áreas de floresta nativa e plantio de eucalipto. Na profundidade de 0-10 cm os estoques foram de 2790 kg N ha^{-1} para mata nativa e 2510 kg N ha^{-1} para o plantio de eucalipto. Já na profundidade de 0-40 cm os estoques de N foram maiores com 7980 e 8890 kg N ha^{-1} para a mata nativa e o plantio de eucalipto respectivamente.

O tipo de solo também pode contribuir para maiores estoques de N no solo. Plantações de eucalipto em áreas de solos argilosos conseguem absorver maiores quantidade de N devido ao maior estoque de N e MOS.[36,78] Esse comportamento foi observado por Eaton,[79] ao trabalhar em área de floresta subtropical com solos com altos teores de argila. O autor observou que no período de chuva, os solos apresentaram um incremento no C orgânico e na taxa de nitrificação. O mesmo sugere que essa matéria orgânica em decomposição estava adsorvida à argila do solo tornando-se disponíveis a comunidade microbiana por um longo período de tempo.

4.3. Saídas de N

O ciclo do N é fechado com o retorno do N para atmosfera. Porém, assim como as demais etapas do ciclo do N, em virtude do aumento das atividades antrópicas e crescimento populacional no Antropoceno,[6] esse retorno do N para atmosfera não está ocorrendo de forma equilibrada, pelo contrário, está havendo um aumento nas perdas de N principalmente na forma do gás N_2O.

Desde o século XIX, a produção de energia e alimentos vêm aumentando não apenas as emissões de C, mas também de N para atmosfera, onde, a queima de combustíveis fósseis é o principal emissor de óxidos de N ($NOx = NO + NO_2$).[53,55,64] Além dos combustíveis fósseis, o uso de fertilizantes sintéticos, a queima de biomassa e de dejetos de animais também são responsáveis por aumentar as perdas de N via volatilização da NH_3.[53,64,80,81]

A substituição da mata nativa por outras culturas altera as condições físicas e químicas do solo,[82] esse fato resulta na mudança da estrutura do solo podendo alterar a atividade microbiana do solo e aumentar as emissões de GEE. Solos que sofrem intenso revolvimento podem ter sua estrutura modificada, tornando-os mais compactados criando assim condições com baixas concentrações de O_2, ambiente propício para a ocorrência do processo de desnitrificação, responsável pela produção e emissão de N_2O para atmosfera.[40,83]

Os processos de nitrificação e desnitrificação são os responsáveis pela produção de N_2O, e estes podem ser acelerados em função da temperatura e da saturação do solo por água. Segundo Neill e colaboradores,[84] em solos florestais, as emissões de N_2O são baixas quando o solo possui < 30 % do espaço poroso preenchido por água, em contrapartida, quando a saturação do solo é > 30 % essa emissão de N_2O para atmosfera é aumentada. O pH do solo também pode alterar a produção de N_2O, quando o pH está acima de 5,5 predomina o processo de nitrificação, já quando o solo apresenta um pH entre 4 e 5,5 o processo que ocorre é o de desnitrificação.[40]

As emissões de N_2O podem variar de uma cultura para outra. Coutinho e colaboradores,[82] avaliaram a emissão de N_2O em área de pastagem que foi substituída por mata secundária e plantação de eucalipto. Os maiores fluxos foram observados na área de mata, onde também foram encontradas as maiores concentrações de NO_3^-. Os fluxos de N_2O na mata e no eucalipto foram de 0,560 kg N ha^{-1} ano^{-1} e 0,422 kg N ha^{-1} ano^{-1}, respectivamente. Os autores explicam que essa maior emissão na mata está associada a qualidade da serrapilheira, que por apresentar menor relação C/N, a mineralização da MOS é mais rápida resultando em maiores teores de NO_3^- e consequentemente um incremento na emissão de N_2O do solo.

Já em um trabalho de revisão sobre as emissões de N_2O em solos da floresta Amazônica, foi observado uma variação nas emissões entre 1,4 e 2,4 kg N $ha^{-1}ano^{-1}$.[85] Em termos mundiais, os autores relatam, que as emissões de N_2O em florestas tropicais podem variar de 0,3 a 6,7 kg N $ha^{-1}ano^{-1}$. Valores semelhantes de N perdido via N_2O foram encontrados em diferentes sistemas de plantios em uma região de transição entre os biomas Cerrado e Amazônia.[86] Os maiores picos de emissão de N_2O foram relatados na estação chuvosa, onde as emissões foram de forma crescente nos tratamentos de eucalipto, seguido da pastagem, integração lavoura-pecuária-floresta (ILPF) e lavoura, com uma emissão média acumulada de 0,165; 0,298; 0,367 e 1,401 kg N $ha^{-1}ano^{-1}$ respectivamente.[86] Fialho,[87] também avaliou a emissão de N_2O solo sob áreas de plantios de eucalipto. O trabalho foi realizado em três regiões distintas e sob diferentes fontes de fertilizantes nitrogenados. A emissão média de N_2O nas três regiões foi de 1,22 kg N $ha^{-1}ano^{-1}$.

Outra forma de perda da N para atmosfera é via volatilização da amônia, e este fato está vinculado a aplicação de fertilizantes, principalmente ureia. Quando a ureia é a aplicada no solo e sem incorporação, a mesma sofre processo de hidrólise, e o N pode ser perdido por meio da volatilização da NH_3.[88] Porém, em plantações de eucalipto, os fertilizantes mais recomendados são aqueles que possuem em sua composição os elementos NPK e, o adubo com a fonte de N via sulfato de amônio é o mais recomendado.[38]

O uso inadequado dos fertilizantes também contribui para a perda de N do solo via lixiviação. Entre os íons que são lixiviados mais facilmente está o NO_3^-.[89] Sua fácil lixiviação ocorre porque este íon não é adsorvido pelos componentes das frações do solo, facilitando seu deslocamento na solução do solo, podendo ser absorvidos pelas raízes das plantas e translocadas às folhas ou ainda, podem ser perdidas por lixiviação para os lençóis freáticos mais profundos.[90,91] Segundo Gonçalves,[38] a maioria das áreas de reflorestamento com eucalipto estão sob solos com altos níveis de intemperização e lixiviação, consequentemente, solos pobres em nutrientes. A lixiviação em áreas de eucalipto pode estar atrelada ao fato de as copas das árvores terem pouca área foliar em comparação a mata nativa, permitindo assim que mais água da chuva atinja o solo, acarretando maior erosão e perda de nutrientes pela lixiviação.[92]

Com objetivo de avaliar essa perda de N via lixiviação do NO_3^- Silva e colaboradores,[78] monitoraram um povoamento de eucalipto que recebeu 80 kg N ha^{-1} de NPK (adubo que contém nitrogênio, fósforo e potássio). Os autores observaram que no primeiro ano após o plantio houve uma perda de N-NO_3^- via lixiviação de 32 kg ha^{-1} ano^{-1}. Já no segundo ano após o plantio a quantidade de N-NO_3^- perdido foi de 8,6 kg ha^{-1} ano^{-1}. Esse resultado colabora com a conclusão de Denk e colaboradores,[59] como o NO_3^- não é adsorvido pelos argilominerais do solo ele pode ser facilmente perdido pelos processos de lixiviação do solo.

Os resultados de todos esses trabalhos apontam para a corroboração da hipótese de que as mudanças que o planeta vem passando no Antropoceno em relação à sua estrutura e funcionamento estão refletindo para alterações dos ciclos biogeoquímicos, principalmente no ciclo no N.

5. Desafios e Medidas para Minimizar os Impactos Sob o Ciclo do Nitrogênio no Antropoceno

O investimento em pesquisa, monitoramento e fiscalização no setor de mudança do uso da terra e florestas é imprescindível para que o país possa crescer de forma sustentável, e uma das estratégias que o Brasil criou para minimizar os impactos sobre o ciclo do N por meio da redução das emissões de GEE visando também a sustentabilidade dos setores foi a criação do "Plano Setorial de Mitigação e de Adaptação às Mudanças Climática para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura", também denominado de "Plano ABC" (Agricultura de Baixa Emissão de Carbono). Esse plano foi criado para que o Brasil consiga cumprir com o compromisso voluntário que ele assumiu na 15ª Conferência das Partes (COP 15) que ocorreu em 2009 em Copenhague na Dinamarca.[93]

O compromisso que o Brasil assumiu foi o de reduzir de 36,1 % a 38,9 % das emissões de GEE entre eles o N_2O até 2020, essa porcentagem equivale uma redução em torno de um bilhão de toneladas de CO_2 equivalente. Para que o país consiga atingir essa meta o Plano ABC é composto por sete programas, seis deles referentes às tecnologias de mitigação que são: Recuperação de Pastagens Degradadas; Integração Lavoura-Pecuária-Floresta; Sistema Plantio Direto; Fixação Biológica de Nitrogênio; Tratamento de Dejetos Animais e Florestas Plantadas e ainda um programa com as ações de adaptação às mudanças climáticas.[93]

O Brasil está entre os países que mais se preocupara em participar e colaborar com as discussões internacionais referente a mudanças climáticas, como ocorreu na 21ª Conferência das Partes (COP21) também conhecida como Acordo de Paris que ocorreu em 2015 na França, na cidade de Paris. Segundo o Ministério do Meio Ambiente,[94] após a ratificação do Acordo pelo Congresso Nacional em setembro de 2016, as metas brasileiras de redução das emissões de GEE deixaram de ser pretendidas e tornaram-se compromissos oficiais. Sendo assim, a NDC (Contribuições Nacionalmente Determinadas) assumidas pelo Brasil foi de reduzir as emissões de GEE em 37 % abaixo dos níveis de 2005, em 2025, e ainda reduzir as emissões de GEE em 43 % abaixo dos níveis de 2005, em 2030. Para isso, o país se comprometeu a aumentar a participação de bioenergia sustentável na sua matriz energética para aproximadamente 18 % até 2030, restaurar e reflorestar 12 milhões de hectares de florestas, bem como alcançar uma participação estimada de 45 % de energias renováveis na composição da matriz energética em 2030.

Nessa mesma conferência, o Brasil anunciou sua Estratégia Nacional para REDD+, a ENREDD+. O REDD+ é um instrumento econômico desenvolvido no âmbito da Convenção-Quadro das Nações Unidas sobre Mudança do Clima (UNFCCC), da qual o Brasil é membro. O objetivo desse instrumento é fornecer incentivos financeiros a países em desenvolvimento por seus resultados no combate ao desmatamento e à degradação florestal e na promoção do aumento de cobertura florestal.[95] O ENREDD+ tem como objetivo geral contribuir para a mitigação da mudança do clima por meio da eliminação do desmatamento ilegal, da conservação e da recuperação dos ecossistemas florestais e do desenvolvimento de uma economia florestal sustentável de baixo carbono, gerando benefícios econômicos, sociais e ambientais.

Esses compromissos assumidos pelo governo brasileiro perante a sociedade internacional na UNFCCC aliadas as fiscalizações e monitoramento realizado pelo Ministério do Meio Ambiente em parceria com o INPE e o Ministério da Ciência e Tecnologia e Inovação das áreas de florestas nativas brasileira, são medidas que juntas, podem minimizar os danos que a crescente urbanização e industrialização do Antropoceno estão causando para o sistema terrestre, prejudicando e alterando os ciclos biogeoquímicos, principalmente do nitrogênio.

6. Considerações Finais

O nitrogênio é o elemento que possui um dos ciclos mais complexos no meio ambiente, e a mudança do uso do solo é uns dos fatores que mais contribui para a alteração da sua ciclagem no ecossistema terrestre. A retirada da mata nativa para implantação de outra cultura como do eucalipto acaba por alterar as condições físicas, químicas e principalmente biológicas do solo, sendo esse último de extrema importância para os processos de decomposição e mineralização da MOS, consequentemente para a ciclagem dos nutrientes.

As áreas de mata apresentam maiores emissões de N_2O em relação a plantios de eucaliptos, porém, esse fato está atrelado a maior qualidade, diversidade e quantidade de vegetação quando comparado ao um monocultivo, como do eucalipto, porém isso não quer dizer que se deve retirar a floresta e plantar eucalipto, pelo contrário, a floresta apesar da forte pressão do desmatamento que passam no Antropoceno, exercem importante papel no sequestro de CO_2 reduzindo assim grandes concentrações de GEE da atmosfera contribuindo para amenizar futuros problemas com o desequilíbrio biogeoquímico do Sistema Terrestre.

Conferências como as realizadas pela UNFCCC são de grande valia para que os países que fazem parte desse tratado possam rever seu sistema de produção (energético, agrícola, industrial etc) e como eles podem contribuir para reduzir as emissões de GEE no Antropoceno. O setor de mudança de uso do solo e floresta são grandes responsáveis por essas emissões, e o investimento em tecnologias sustentáveis que contribuam para diminuir os danos ambientais causados pelas inadequadas práticas de manejo são de suma importância para mitigação das emissões desses gases.

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Artigo

Dinâmica do Nitrogênio em Sistemas Agrícolas e Florestais Tropicais e seu Impacto na Mudança do Clima

Rodrigues, R. A. R.;* de Mello, W. Z.; da Conceição, M. C. G.; de Souza, P. A.; Silva, J. J. N.

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Nitrogen Dynamics in Tropical Agricultural and Forest Systems and their Impact on Climate Change

Abstract: Nitrogen is the most abundant element of the atmosphere, being present in the constitution of several atmospheric gases, among them nitrous oxide (N_2O). The N_2O is one of the most powerful greenhouse gases, due to its high potential for global warming. In Brazil, the sector that emits more N_2O to the atmosphere is Agriculture, due to the high amounts of nitrogen fertilizers applied in the field. However, the country has an advanced public policy of adopting agricultural technologies that contribute to the reduction of this problem. The present review aims to show the dynamics of Nitrogen in agricultural and forest systems, the role of Nitrogen in the economy and present the main mitigation strategies in greenhouse gas emissions in agriculture.

Keywords: Biogeochemical nitrogen cycle; greenhouse gas mitigation; nitrous oxide; nitrogen emissions from agriculture.

Resumo

O nitrogênio é o elemento mais abundante da atmosfera, estando presente na constituição de vários gases atmosféricos, entre eles o óxido nitroso (N_2O). O mesmo está entre os principais gases de efeito estufa, em função do seu alto potencial de aquecimento global. No Brasil, o setor que mais emite N_2O para atmosfera é o agropecuário, em função das altas quantidades de fertilizantes nitrogenados aplicados no campo. No entanto, o país possui uma avançada política pública de adoção de tecnologias agrícolas que contribuem para a redução desse problema. A presente revisão pretende mostrar a dinâmica do Nitrogênio em sistemas agrícolas e florestais, o papel do Nitrogênio na economia e apresentar as principais estratégias de mitigação nas emissões de gases de efeito estufa na agricultura.

Palavras-chave: Ciclo biogeoquímico do nitrogênio; mitigação de gases de efeito estufa; óxido nitroso; emissões de nitrogênio pela agricultura.

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Dinâmica do Nitrogênio em Sistemas Agrícolas e Florestais Tropicais e seu Impacto na Mudança do Clima

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1. Introdução

O nitrogênio (N) é o elemento químico mais abundante da atmosfera, onde se encontra predominantemente como nitrogênio molecular (N_2), uma forma gasosa e quimicamente muito estável. Sua razão de mistura no ar seco é 78,08 % e sua massa na atmosfera é 3,98 x 10^{21} g de N_2. Dos gases constituídos pelo nitrogênio, o óxido nitroso

(N_2O) é o segundo mais abundante na atmosfera[1].

É um gás muito estável na troposfera (camada que se estende da superfície até em média 15 km de altitude) da Terra. Sua decomposição se dá na estratosfera (camada da atmosfera de 15 a 50 km de altitude) predominantemente por fotólise, ao absorver radiação solar de comprimento de onda inferior a 300 nm (10^{-9} m), e, em menor parcela, por reação com o átomo de oxigênio eletronicamente excitado, representado por $O(^1D)$.[1]

Sua estabilidade química na troposfera lhe confere uma razão de mistura atual de 330 ppb (partes por bilhão; 10^{-9} mol de N_2O por mol de ar) e um tempo de vida na atmosfera de aproximadamente 120 anos. Os demais compostos gasosos de nitrogênio são mais reativos e menos abundantes, com razões de mistura na escala de ppt (partes por trilhão; 10^{-12} mol por mol de ar), podendo, entretanto, atingir de dezenas a poucas centenas de ppb no ar de grandes áreas urbanas e industrializadas, e seus arredores.[1]

Ainda menos abundantes e termicamente instáveis, há uma série de compostos orgânicos, como os nitratos de alquila de baixa massa molecular, peroxialquila e peroxiacila, dos quais o nitrato de peroxiacetila (PAN), $CH_3C(O)O_2NO_2$, é o mais conhecido. A amônia (NH_3) é a forma gasosa de nitrogênio reduzida (nox = -3) mais abundante na atmosfera, com razões de mistura na escala de ppt nos ambientes não poluídos até algumas dezenas de ppb nos ambientes poluídos. Sob a forma de partículas (solúveis em água) em suspensão no ar, os compostos de nitrogênio mais abundantes são os sais inorgânicos de amônio e nitrato. Na água da chuva predominam os íons nitrato (NO_3^-) e amônio (NH_4^+) e em menor abundância o nitrito (NO_2^-). Além destes, tanto no material particulado atmosférico quanto na água da chuva, uma série de compostos nitrogenados orgânicos estão presentes, como ureia, aminas, aminoácidos, nitrofenóis, alquilamidas, alcaloides N-heterocíclicos e nitratos orgânicos.[2]

Globalmente, em média um terço (1/3) do nitrogênio total dissolvido na água da chuva são formas de nitrogênio orgânico.[3] Há evidências recentes de que fração de nitrogênio orgânico solúvel na atmosfera é constituída principalmente de nitrogênio reduzido.[2] Em estudo realizado no sudeste do Brasil, foi verificado que a ureia, $(NH_2)_2CO$), representa de 40 a 100% do nitrogênio orgânico dissolvido, em amostras de água de chuva coletadas com coletores de deposição total (*bulk deposition samplers*).[4]

Os compostos de nitrogênio presentes na natureza subdividem-se em não-reativos e reativos.[5] O primeiro é representado exclusivamente pelo N_2, face à sua elevada estabilidade química. Os reativos (Nr) são aqueles considerados biologicamente, fotoquimicamente e radiativamente ativos na atmosfera e biosfera de nosso planeta. Estes compostos e grupos de compostos de nitrogênio são todos aqueles supracitados.[1,2]

O presente artigo tem como objetivo fazer uma revisão geral, a partir de documentos científicos e políticos, do papel do Nitrogênio em sistemas agrícolas e florestais, bem como na economia, no contexto da mudança do clima e nas políticas públicas brasileiras de mitigação de emissões de gases de efeito estufa.

2. Histórico da negociação internacional sobre mudança do clima

Os gases de efeito estufa existem naturalmente na atmosfera e são responsáveis por manterem a Terra mais quente do que ela seria sem a existência desses gases. Os principais gases de efeito estufa naturais são o vapor d'água, o dióxido de carbono (CO_2), o ozônio (O_3), o metano (CH_4), o óxido nitroso (N_2O). Esse efeito estufa natural tem mantido a atmosfera da Terra por volta de 30°C mais quente do que ela seria na ausência dele, possibilitando a existência da vida como é conhecida no planeta.

No entanto, as ações provenientes das atividades humanas – como geração de energia, produção agrícola e urbanização – têm acentuado a concentração desses gases na atmosfera, gerando um aumento na absorção do calor e consequente aumento da temperatura.

Por isso, em 1988, o Programa das Nações Unidas para o Meio Ambiente (PNUMA) e a Organização Mundial de Meteorologia (OMM) estabeleceram o Painel Intergovernamental sobre Mudança do Clima (IPCC), com o objetivo de avaliar cientificamente o conhecimento em mudança do clima e os possíveis impactos socioeconômicos e ambientais, e formular estratégias realistas para lidar com o problema. Esse foi um dos passos mais importantes no reconhecimento do efeito dos gases de efeito estufa (GEE) no sistema climático.

A partir do conhecimento científico produzido pelo IPCC, houve um movimento político internacional para criação de mecanismos eficientes de combate à mudança do clima. Esse processo culminou na Conferência das Nações Unidas sobre o Meio Ambiente e o Desenvolvimento (também conhecida como Rio92 ou Eco92).

Dessa Conferência nasceu, dentre outras medidas, a Convenção-Quadro das Nações Unidas sobre Mudança do Clima (CQNUMC ou em inglês, *United Nations Framework Convention on Climate Change* – UNFCCC). A UNFCCC é atualmente, a maior Convenção da Organização das Nações Unidas, com 195 países e constitui a base para o mecanismo jurídico-político multilateral de combate à mudança do clima. A UNFCCC tem como princípio a decisão por consenso, onde cada país membro representa uma "Parte" da Convenção. Por esse motivo, a reunião anual da Convenção, que teve sua primeira edição em 1995, em Berlin, se chama "Conferência das Partes" (COP).

Em 2009, durante a COP15, o Brasil apresentou um compromisso voluntário de redução de emissões de 36,1% a 38,9% das emissões projetadas para o ano de 2020, deixando assim de emitir cerca de 1 bilhão de toneladas de CO_2 equivalente (tCO_2eq). Esse constitui o maior esforço de redução de emissões do planeta. As propostas apresentadas em Copenhagen foram internalizadas por meio da Lei 12.187/09 que instituiu a Política Nacional sobre Mudança do Clima. Em 2010 foram criados os Planos Setoriais para o atingimento desse compromisso voluntário.[6]

Com a finalidade de reduzir emissões de gases de efeito estufa (GEE) do setor agrícola, disseminar e financiar boas práticas agrícolas, o Governo Federal lançou em 2010 o Plano ABC. Sendo composto por sete programas, seis deles referentes às tecnologias de mitigação, e ainda um último programa com ações de adaptação às mudanças climáticas: Recuperação de Pastagens Degradadas; Integração Lavoura-Pecuária-Floresta (ILPF) e Sistemas Agroflorestais (SAFs); Sistema Plantio Direto (SPD); Fixação Biológica de Nitrogênio (FBN); Florestas Plantadas; Tratamento de Dejetos Animais; Adaptação às Mudanças Climáticas.[6]

Além desse compromisso assumido na COP 15, o Brasil apresentou à UNFCCC sua pretendida Contribuição Nacionalmente Determinada (*intended Nationally Determined Contribution* – iNDC), durante a COP 21 em Paris.[7]

Na iNDC, o Brasil propôs ações de mitigação de emissões de GEE e ações de adaptação aos efeitos da mudança do clima, assim como meios para implementar essas ações no país e em outros países em desenvolvimento, por meio de cooperação Sul-Sul. Em relação à mitigação, o Brasil se comprometeu a reduzir as emissões de GEE em 37% abaixo dos níveis de 2005, em 2025, além de uma contribuição indicativa subsequente de reduzir as emissões de GEE em 43% abaixo dos níveis de 2005, em 2030.[7]

No setor agrícola, os iNDCs visam fortalecer a estratégia para a intensificação sustentável na agricultura, por meio da restauração adicional de 15 milhões de hectares de pastagens degradadas e pelo incremento de 5 milhões de hectares de sistemas de integração lavoura-pecuária-floresta (ILPF) até 2030.[7]

Esse novo compromisso, adicional ao proposto pelo Brasil na COP15, reforça amplamente a consolidação da Agricultura de Baixo Carbono como uma forma real de alcançar a intensificação sustentável da produção agrícola. Essas tecnologias contribuem para a mitigação das emissões de gases, aumento da produtividade e da renda, aumento dos benefícios sociais dos produtores e para a consolidação do desenvolvimento sustentável.[7]

O governo brasileiro percebeu que é necessário a implementação de boas práticas agrícolas, que visem a redução da emissão de GEE, o aumento da incorporação de carbono no solo e diminuir a pressão sobres as florestas nativas. Práticas de uso da terra, como agricultura e reflorestamento, possuem grande impacto no fluxo de GEE da superfície do solo e no incremento de carbono no solo.[8,9] Essas mudanças podem alterar substancialmente a dinâmica do carbono do solo e afetar as trocas de gases de efeito estufa entre o solo e a atmosfera.[10,11]

3. Ciclo do Nitrogênio

O ciclo global natural do N tem sido severamente alterado por atividades antrópicas relacionadas à produção de alimentos e a geração de energia.[5] A entrada do N reativo nos ecossistemas terrestres (florestas e áreas de cultivo) mais que dobrou nos últimos dois séculos e vem contribuindo para o aumento das descargas fluviais de N nos corpos hídricos.[12,13] O Nr desempenha ainda papel crítico nos aspectos relacionados às mudanças climáticas (incluindo as questões de mitigação, adaptação e impacto) devido ao crescimento contínuo (*ca.* 0,3 % por ano) das emissões antrópicas globais de N_2O desde o período Pré-Industrial, sendo atribuído principalmente a expansão de áreas agrícolas e ao aumento do uso de fertilizantes.[14]

A ciclagem do N envolve os processos de entrada, via deposições atmosféricas (como formas dissolvidas de N orgânico e inorgânico) e, de saída, via escoamento fluvial (como formas dissolvidas e particuladas de N orgânico e inorgânico), infiltração da água no solo até ao lençol d'água subterrânea (principalmente como NO_3^-) e emissões de óxidos de N (N_2O e NO) para atmosfera resultante das atividades biológicas no solo,[15,16] assim como as transferências internas (ciclagem dentro do próprio sistema) entre plantas, micro–organismos (decompositores e consumidores) e o meio–ambiente.[15,17] A biogeoquímica do N é quase que inteiramente dependente das reações de oxirredução, mediada por processos físicos, químicos e biológicos.

Nestes ecossistemas a ciclagem do N engloba os seguintes processos: fixação biológica de N, amonificação, assimilação, nitrificação, desnitrificação e redução dissimilatória de nitrato a amônio (RDNA). Entretanto, as taxas de transformação de N (processos) podem variar de um ecossistema para o outro, uma vez que são controlados por uma série de fatores abióticos (água, temperatura, oxigênio e solo) e bióticos (comunidade de plantas e micro-organismos, qualidade da matéria orgânica, disponibilidade de nutrientes).

A fixação biológica do N (FBN) consiste em outra importante via de entrada de N, principalmente, em área de cultivo. Somente alguns grupos específicos de bactérias (bactérias dos gêneros *Frankia e Rhizobium)* e arqueias (micro-organismos estruturalmente similares embora evolutivamente distintas das bactérias) têm a capacidade de fixar diretamente o N_2 atmosférico. Isto é possível, uma vez que eles possuem a nitrogenase, um complexo enzimático que promove a catálise (quebra da tripla ligação entre os átomos de N) e redução da molécula do N_2 atmosférico a NH_3 (ou NH_4^+) conforme a reação 1:[17]

$$N_2 + 8H^+ + 8\bar{e} + 16\,ATP \xrightarrow{\text{nitrogenase}} 2NH_3 + 16ADP + 16PO_4^{3-} + H_2 \qquad (R1)$$

As demais plantas adquirem N através da assimilação (pelas raízes) dos íons NH_4^+ e NO_3^- dissolvidos no solo. O fornecimento de NH_4^+ é dependente do processo de amonificação (ou mineralização do N). Este processo inicia-se com a ação de enzimas extracelulares (*i.e.*: celulase, protease e urease) dos organismos decompositores, que promovem a degradação do N orgânico particulado contido na matéria orgânica do solo (derivada de folhas caídas no solo, raízes mortas e de material microbiano e animal) em Nitrogênio orgânico dissolvido (aminoácidos, ureia e ácidos nucleicos) e subsequente conversão à íons NH_4^+ (R2), disponível para a assimilação por plantas e imobilizado (absorção) por microorganismos.[17,16] Eventualmente, o NH_4^+ é adsorvido nos minerais presentes na fração argila do solo (<0,02 mm).[16]

$$R\text{–}NH_2 + 2H_2O \rightarrow R\text{–}OH + NH_4^+ + OH^- \qquad (R2)$$

Os íons NH_4^+ provenientes da degradação da matéria orgânica estabelecem uma reação de equilíbrio com o NH_3 da solução do solo. Em condições de pH alcalino pode ocorrer a volatilização da NH_3. O aumento da temperatura do solo e da velocidade do vento também favorece a razão NH_3/NH_4^+ e consequentemente, a volatilização da NH_3.[18]

No solo o NH_4^+ é biologicamente oxidado a NO_3^- durante a fixação do CO_2. O processo de nitrificação é iniciado com a oxidação do NH_4^+ a NO_2^- (R3) por bactérias do gênero *Nitrosomonas*, tendo como produto intermediário a hidroxilamina (NH_2OH), seguido da oxidação do NO_2^- a NO_3^- por bactérias do gênero *Nitrobacter* (R4). Os gases N_2O e NO são subprodutos desta reação. As bactérias nitrificadoras são obrigatoriamente aeróbicas e utilizam o O_2 como aceptor de elétrons.[16]

$$NH_4^+ + 3/2O_2 \xrightarrow{\textit{Nitrosomonas}} NO_2^- + H_2O + 2H^+ \qquad (R3)$$

$$2NO_2^- + O_2 \xrightarrow{\textit{Nitrobacter}} 2NO_3^- \qquad (R4)$$

O NO_3^- disponível é assimilado por plantas e imobilizado por micróbios, mas não fixados nos argilominerais do solo. Portanto, é facilmente lixiviado, movimentando–se livremente pelo perfil do solo até as águas subterrâneas (infiltração), ou então, escoado lateralmente pelo solo até as águas fluviais[19].

Em condições de esgotamento de O_2 (condição anóxica) e disponibilidade de matéria orgânica (representada como CH_2O; reação 5), as bactérias desnitrificadoras, principalmente as do gênero *Pseudomonas*, realizam a redução do NO_3^- (ou NO_2^-) sequencialmente a NO, N_2O e N_2, por processo conhecido como desnitrificação. Essas bactérias utilizam nitrato como aceptor, e carbono orgânico como doador de elétrons.

$$4NO_3^- + 5CH_2O + 5H_2O \rightarrow 2N_2 + 5CO_2 + 8H_2O + 4OH^- \quad (R5)$$

A produção biológica de N_2O por nitrificação e desnitrificação é regulada por fatores ambientais tais como disponibilidade de O_2, temperatura, umidade, pH e textura do solo, disponibilidade e qualidade da matéria orgânica.[16, 20,21] As práticas de manejo e uso do solo favorecem a acumulação de C e N e a atividade de micro-organismos anaeróbicos e influenciam a capacidade de desnitrificação e alterações nas taxas de emissão de N_2O do solo para a atmosfera.[22]

O NO_3^- também pode ser reduzido dissimilarmente (redução sem que ocorra assimilação) a NH_4^+ por bactérias fermentadoras estritamente anaeróbicas. A redução dissimilatória do NO_3^- a NH_4^+ (RDNA) requer condições similares ao processo de desnitrificação: matéria orgânica, disponibilidade de NO_3^- e condições anóxicas. Entretanto, a RDNA parece ser favorecida em condições mais redutoras. Este processo foi reportado em solos de florestas tropicais e representa um importante mecanismo de retorno de N inorgânico (na forma de NH_4^+) para o ambiente.[23,24]

4. Uso do Nitrogênio nos diferentes setores da economia

A intensificação das atividades econômicas humanas, se iniciou com a Revolução Industrial e se delonga até os dias de hoje. Essas atividades são grandes responsáveis pelo incremento das emissões dos GEE à atmosfera, principalmente do CO_2, CH_4 e do N_2O.[6]

O N é um elemento utilizado em diversas atividades econômicas. Como já mencionado anteriormente, depois de passar por uma série de processos químicos ou biológicos, o N pode ser perdido para atmosfera via N_2O. No setor da agricultura o N é utilizado para fabricação de fertilizantes nitrogenados.[25,26]

Os dados do Anuário estatístico do Brasil / IBGE de 2015,[27] relatam a produção bruta de fertilizante em 2014 (Tabela 01). Por meio deste, é possível observar que o fertilizante mais utilizado pelos agricultores em geral é a ureia. Já em relação às exportações, a Associação Nacional para Difusão de Adubos, relata que em 2016, a exportação de fertilizantes e formulações NPK foi de 549.444 em toneladas de produto.[28]

Tabela 1. Produção bruta de fertilizantes nitrogenados em 2014 segundo o Anuário estatístico do Brasil/IBGE de 2015

Produção de Fertilizantes (2014)	Quantidade toneladas
Ureia	830.374
Nitrato de amônia	278.586
Sulfato de amônio	302.551

O uso irregular de fertilizantes na agricultura é o principal responsável pela contaminação das águas subterrâneas e superficiais. Esse uso inadequado aumenta as perdas de N no ambiente, nas formas como amônia (NH_3), amônio (NH_4), óxidos de nitrogênio (NO_x), óxido nitroso (N_2O) e nitrato (NO_3).[5] A nível mundial, o setor da agricultura e da pecuária, são responsáveis pela emissão de 2/3 do N_2O para atmosfera.[29]

Segundo IPCC,[30] em menos de 10 anos, as emissões de GEE via fertilizantes sintéticos se tornarão a maior fonte de emissões em relação às de dejetos depositados em pastagens e a segunda maior de todas as categorias de emissões agrícolas.

Outro setor da economia que contribui

significativamente com as emissões de GEE e também utiliza N durante seu processo de produção é o setor de energia. O carvão mineral de origem fóssil foi uma das primeiras fontes de energia utilizadas em larga escala pelo homem. Ele era usado para gerar vapor e movimentar as máquinas e, no fim do século XIX, esse vapor produzido era utilizado na produção de energia elétrica.[31,32] O carvão mineral é considerado uma das formas mais agressivas ao meio ambiente, segundo a Agência Nacional de Energia Elétrica,[32] o dano mais severo em relação ao uso do carvão mineral é a emissão de partículas com nitrogênio (NO_x), enxofre (SO_x) e também de CO_2.

Dados do relatório de emissões de GEE, do Observatório do Clima,[33] mostram que 71% das emissões de gases do setor de energia em 2014 foram oriundas da queima do petróleo, seguido do gás natural com 17% e por último o carvão mineral com 6% das emissões.

Os processos industrias também são setores da economia que acabam por emitir GEE para atmosfera e, a indústria química é um exemplo disso. Dentre as emissões deste subsetor, as de maiores importâncias são as emissões de CO_2 resultantes da produção de amônia, as emissões de N_2O e NO_x que ocorrem durante a produção de ácido nítrico e as emissões de N_2O, CO e NO_x resultantes da produção de ácido adípico.[34] O ácido adípico é a matéria prima para fabricação de fibras sintéticas, plásticos, lubrificantes sintéticos e, o mais importante ácido alifático dicarboxílico, usado na fabricação de poliéster e nylon 6.6.[35]

Porém, devido a projetos no âmbito do Mecanismo de Desenvolvimento Limpo (MDL), de 2005 a 2011, a indústria de produção de ácido adípico e ácido nítrico, apresentaram reduções significativas em relação a suas emissões de GEE.[36] Em 1990, as estimativas das emissões gerais de gases da indústria química era de 7.500 Gg CO_2eq e, em 2012 novas estimativas relataram que houve uma redução nas emissões, elas caíram para 3.446 Gg CO_2eq.[36]

A mudança do uso da terra também se enquadra entre os setores que mais emitem GEE no Brasil. O setor de mudança e uso da terra e de florestas, respondem por mais de 2/3 das emissões brutas de CO_2eq do Brasil, deste volume, 2/3 correspondem ao desmatamento e o restante a produção agrícola e pecuária.[37] As mudanças no uso e cobertura do solo podem influenciar na dinâmica dos ciclos de C, do N e ainda, nas mudanças dos padrões dos fluxos de GEE.[38-40] A matéria orgânica do solo é a principal fonte de N, logo com a alteração e remoção da superfície do solo, aumenta-se os processos de erosões e, consequentemente acabam contribuindo com uma maior perda de N do solo.[38]

O relatório de 2014, do Observatório do Clima,[41] referente a evolução das emissões de gases no Brasil de 1990 a 2012, relata que a durante esse período, esse setor foi responsável pela emissão de 28 bilhões tCO_2eq, correspondendo as 61% do total das emissões brasileira nesse período. O relatório de MCTI,[36] aborda as estimativas das emissões em CO_2eq referente a 2012 para o setor mudança e uso da terra nos diferentes biomas. Segundo o relatório, o Bioma Cerrado ocupa a primeira posição com emissão de 109 TgCO_2eq, em segundo lugar está o bioma Amazônia com 33 TgCO_2eq e o terceiro lugar está ocupado pelo bioma Pampa, responsável pela emissão de 16TgCO_2eq.

Também durante o período de 1990 a 2012, o setor de resíduo brasileiro, foi responsável pela emissão de 883 milhões de TCO_2eq. Nesse período as emissões passaram de 28,6 MtCO_2eq para 46,9 MtCO_2eq, um incremento de 64% em 22 anos.[42] Os aumentos dessas emissões estão vinculados ao crescimento da população urbana e consequente aumento da produção de vários tipos de resíduos sendo que, muitos deles são descartados no meio ambiente sem tratamento adequado. Os resíduos sólidos das industrias de couro é um exemplo de rejeito com altas concentrações de N em sua composição e, que acaba contaminando o meio ambiente devido à falta de um processo de reciclagem apropriado.[43]

Os dejetos e a urina de animais também apresentam altos teores de N orgânico em sua composição e, por meio dos processos de nitrificação e desnitrificação, acabam por produzir e emitir grandes quantidades de N_2O para atmosfera, como é o caso dos dejetos da criação de porcos, de vacas leiteiras entre outros.[44-46]

5. Deposição atmosférica de Nitrogênio

As deposições atmosféricas de nitrogênio, bem como de outros elementos, ocorrem basicamente de duas formas, seca e úmida. A primeira representa o processo de transferência de material particulado em suspensão e de substâncias gasosas da atmosfera para a superfície do planeta. Esse processo depende de uma série de variáveis de controle, em destaque a composição química da partícula ou do gás, sua solubilidade em água, tamanho da partícula, velocidade do vento e características da superfície de deposição, que irão definir a velocidade de deposição. O produto da concentração da partícula ou do gás pela velocidade de deposição resulta no fluxo de deposição expresso em unidade de massa por área e tempo.

A deposição úmida representa tudo que é transferido da atmosfera para a superfície através da água da chuva. Nesse caso, o fluxo de deposição é o produto da concentração da substância dissolvida na água da chuva pela altura pluviométrica (espessura de chuva precipitada). A deposição seca de nitrogênio inorgânico recentemente estimada para a toda a superfície continental global é de 34,3 Tg N ano^{-1} (T = 10^{12}), dos quais 65% são atribuídos à amônia, e o restante, nessa ordem, ao dióxido de nitrogênio (NO_2), ácido nítrico (HNO_3), amônio e nitrato.[47]

Regionalmente, a deposição seca de nitrogênio inorgânico na América do Sul foi estimada em 3,31 Tg N ano^{-1}, dos quais, nesse caso, 54 e 34% foram atribuídos à amônia e ao dióxido de nitrogênio. Considerando a área da América do Sul (1,78 x 10^9 ha), em média, o fluxo de deposição de nitrogênio inorgânico é de 1,85 kg N ha^{-1} ano^{-1} neste continente. Globalmente, em média, os fluxos de deposição seca de NH_3, NO_2, HNO_3, NH_4^+ e NO_3^-, estimados foram 1,64, 0,45, 0,27, 0,11 e 0,02 NH_3, NO_2, HNO_3, NH_4^+ e NO_3^-, respectivamente.[47] Os valores mais elevados, considerando os cinco compostos de nitrogênio, foram estimados para o leste da China, na faixa de 50-55 kg N ha^{-1} ano^{-1}.

A deposição atmosférica total (seca e úmida) global de nitrogênio estimada é de 10^6 Tg N ano^{-1}, distribuídos em 56% nos ambientes continentais, 19% costeiros e 25% oceânicos.[48] Com base no mapa de deposição total gerado, os fluxos de deposição úmida nas regiões tropicais variam de 1 a 4 kg N ha^{-1} ano^{-1}, e na maior parte do Brasil,[48] especialmente nas regiões nordeste, sudeste e centro-oeste a faixa é de 2 a 4 kg ha^{-1} ano^{-1}. A média global da deposição atmosférica de N sobre os ecossistemas terrestres é 3,5 kg N ha^{-1} ano^{-1}.

No Brasil, o aporte atmosférico de nitrogênio inorgânico (NH_4^+, NO_3^-), diretamente medido por meio de coletores automáticos ou de deposição total, varia de 5,0 a 20 kg N ha^{-1} ano^{-1} em áreas extensamente afetadas por queima de biomassa e nos arredores dos grandes centros urbanos.[4,49-52] Em áreas mais preservadas do país, como a bacia Amazônica,[53,54] o aporte atmosférico de nitrogênio inorgânico tende a ser inferior a 5,0 kg N ha^{-1} ano^{-1}. No setor litorâneo do nordeste do Brasil os valores são ainda mais baixos. De Ilhéus à Itabuna (cerca de 40 km da costa), na Bahia, foi verificado que o aporte de nitrogênio inorgânico fica na faixa de 2 a 3 kg N ha^{-1} ano^{-1}.[55]

Em diversas regiões do mundo, o aporte atmosférico de nitrogênio vem aumentando em virtude do crescimento contínuo da fixação do N_2 atmosférico (transformação de N_2 em formas de Nr), através de processos relacionados a algumas atividades humanas.

Esses processos transformam o N_2 da atmosfera em (1) amônia pelo processo Haber-Bosch (em escala industrial desde a segunda década do século XX), destinada principalmente à produção de fertilizante, (2) amônia pelo processo de fixação biológica do nitrogênio (FBN) por microorganismos e (3) óxidos de nitrogênio durante a queima de combustíveis fósseis (principalmente) e biocombustíveis. Em razão disso,[56] foi estimado, comparativamente, os valores do aporte atmosférico de nitrogênio em 34 biomas do planeta potencialmente suscetíveis a impactos provocados por excesso de nitrogênio.

Estes autores estimaram que em meados da década de 1990 estas áreas já recebiam em média um aporte atmosférico de nitrogênio 50% superior à média global e que em 2050 poderá mais que dobrar. No caso da Mata Atlântica, verificaram que, em meados da década de 90, aproximadamente um terço da área total remanescente recebia um aporte atmosférico superior a 10 kg N ha^{-1} ano^{-1}. Já para 2050, o cenário é de que 95% e dois terços da área total remanescente estarão recebendo aportes superiores a 10 e 15 kg N ha^{-1} ano^{-1}, respectivamente.

6. Emissão de N_2O dos solos agrícolas e florestais

As atividades antropogênicas contribuem para o desequilíbrio do N no sistema terrestre, e estas vêm causando sérias consequências ambientais, em particular relacionado com as mudanças climáticas, através da liberação de N_2O para atmosfera.[57] O N_2O pode ser emitido para atmosfera por meio de processos naturais do solo e dos oceanos, ou ainda, por fontes antrópicas, como aplicação de fertilizantes e queima de biomassa.[57]

Como já mencionado, as maiores emissões de N_2O de solos agrícolas, estão relacionadas à aplicação de fertilizantes nitrogenados, aplicação de dejetos de animais e manejo inadequado do solo.[26,58]

A rotação de leguminosas com cultura agrícola é uma das estratégias para redução da emissão de GEE, principalmente do N_2O. Essa rotação reduz a aplicação de fertilizantes nitrogenados liberando maiores teores de N mineral no solo oriundos dos resíduos da cultura e, ainda contribui com um aumento no estoque de carbono no solo.[59,60]

Além das aplicações de fertilizantes, as práticas agrícolas podem influenciar na produção de N_2O para atmosfera. O manejo agrícola pode causar alterações nas propriedades físico-químicas do solo e consequente impacto nas emissões de N_2O do solo.[61] Com o manejo agrícola, a textura do solo acaba sofrendo alterações, e este influencia na maior ou menor capacidade de retenção de água no solo. A umidade associada à temperatura, são importantes fatores que influenciam na velocidade dos processos de nitrificação e desnitrificação.[18,20] A ocorrência da nitrificação ou da desnitrificação é resultado do nível de oxigênio do solo logo, com um manejo inadequado, a textura do solo acaba sofrendo alterações e podem influenciar no teor de umidade e oxigênio do solo, e consequente aumento da produção de N_2O.[62-64]

Já em áreas florestais, existem dois cenários relacionados à emissão de GEE do solo. No primeiro, áreas florestais sejam elas nativas ou plantadas, também ocorre de forma natural os processos de nitrificação e desnitrificação no solo e consequente produção de N_2O. Estudos relatam uma maior emissão de N_2O em solos de floresta nativa em relação a floresta plantada.[65]

Esses estudos relatam que a matéria orgânica do solo da mata nativa apresenta baixa relação C/N, o que estimula o processo de mineralização, liberando mais NO_3^-, e este tende a entrar nas vias de formação do N_2O no solo. Já solos de florestais tropicais em função das altas temperaturas e umidade, apresentam uma taxa decomposição da matéria orgânica do solo mais rápida. Isso leva a uma maior perda de nutrientes via processos de mineralização.[66,67]

O segundo cenário está relacionado ao serviço ambiental que a floresta presta ao meio ambiente como um todo. Segundo a FAO,[68] as florestas são consideradas importantes sumidouros de carbono, pois as árvores e vegetação em geral, no processo de fotossíntese, absorvem CO_2 da atmosfera e o armazenam na forma de carbono, reduzindo assim as emissões de CO_2 para atmosfera. Em áreas de floresta nativa ou plantada, existe uma grande massa de serapilheira depositada sobre o solo. Esse resíduo florestal acaba por contribuir com uma maior estocagem e ciclagem de nutrientes no meio ambiente.[69] Em estudo realizado após três anos de monitoramento em uma área com monocultivos e cultivos mistos de Eucalipto e Acácia, foi relatada um incremento no conteúdo de C e N do solo.[70]

Segundo os dados da Associação Brasileira de Celulose e Papel,[71] o setor de base florestal tem um papel importante em relação à mitigação de GEE, pois as atividades de reflorestamento contribuem com o sequestro de CO_2 da atmosfera e com os estoques de C nas áreas de plantio e de reservas florestais. A associação discorre que nos anos de 2009 e 2010 o setor de papel e celulose contribuiu com a redução de 8,28% das emissões de CO_2eq para atmosfera.

Em geral, as florestas contribuem para a mitigação da mudança do clima, pois a mesma é envolvida em atividades de florestamento e reflorestamento, redução de desmatamento, manejo florestal e de produtos florestais, matéria prima para produção de bioenergia e ainda, melhoria genética das espécies afim de aumentar sua produtividade em biomassa.[72]

7. Medidas de mitigação das emissões de N_2O na agricultura

São muitas as possiblidades de mitigação das emissões de GEE (sistema plantio direto, recuperação de pastagens, manejo de dejetos, integração lavoura-pecuária-floresta (ILPF), fixação biológica de nitrogênio (FBN), plantio de florestas, redução das queimadas, dentre outras) para o setor agrícola que impactam diretamente nas emissões de N_2O. Aqui serão abordadas as medidas de mitigação propostas no Plano ABC.

7.1. Integração Lavoura-Pecuária-Floresta (ILPF)

O sistema ILPF consiste na implementação de diferentes sistemas de produção de grãos, fibras, carne, leite, bioenergia e outros na mesma área, em consórcio, plantio sequencial ou rotacionado, buscando efeitos sinérgicos entre os componentes do agroecossistema, contemplando a adequação ambiental, a valorização do homem e a viabilidade econômica.[73-75] O Plano ABC prevê a expansão de 4,0 milhões de hectares, com um potencial de mitigação de 18-22 milhões $MgCO_2$eq.

Os benefícios de sistemas integrados, como a ILPF, incluem o aumento da fertilidade do solo, devido ao acúmulo de matéria orgânica,[76] melhoria da ciclagem de nutrientes e melhoria na agregação do solo.[76-78] A rotação de culturas, como acontece em sistemas de ILPF, também pode ajudar a diminuir pragas, doenças e ervas daninhas, reduzindo assim os custos de produção, aumentando os resultados econômicos e ambientais.[79,80]

7.2. Sistema Plantio Direto – SPD

A técnica de sistema plantio direto na palha consiste na eliminação da movimentação do solo por meio do uso de arados e grades, priorizando a rotação de culturas e a manutenção da cobertura vegetal durante todo o ano.[81] De acordo com Plano ABC, o Governo Federal prevê um aumento de área de 8,0 milhões de hectares com este tipo de manejo, com um potencial de mitigação de 83 – 104 milhões $MgCO_2eq$. Um dos efeitos dessa técnica sobre as emissões de GEE é a redução, a cada safra, em quase 50% ou algo próximo de 90 quilos de dióxido de carbono por hectare, devido à eliminação das operações de aração e gradagem.[82]

Para exemplificar o uso do SPD para acúmulo de carbono e nitrogênio no solo, estudos de longo prazo conduzidos no Brasil, localizados na região tropical e subtropical, observaram que foi possível aumentar de forma significativa o estoque de carbono orgânico do solo (COS) sob SPD quando comparados com cultivos sob preparo convencional. Isso ocorre devido ao fato da rotação de culturas incluir leguminosas de alta eficiência para fixação biológica de nitrogênio (FBN) e da permanente cobertura de resíduos vegetais, oriundos das culturas, no solo. Segundo estimativas,[83-86] a conversão de áreas de plantio convencional para o sistema plantio direto acarretaria aumento médio de acumulação de carbono no solo da ordem de 0,5 Mg por hectare ao ano.

7.3. Recuperação de Pastagens Degradadas

A degradação das pastagens ocorre devido à falta de manejo adequado, com uso de queimadas, uso de espécies não adaptadas, superpastejo, dentre outras. Esse quadro leva à queda de suporte das pastagens, elevação dos custos de produção (carne e/ou leite), com consequente aumento da pressão por novas áreas de produção (aumento do desmatamento). O Plano ABC prevê a recuperação de 15 milhões de hectares de pastagens degradadas, cujo potencial de mitigação é da ordem de 83-104 milhões $MgCO_2eq$.

As leguminosas desempenham um papel importantíssimo nas pastagens, que é a incorporação do nitrogênio atmosférico ao sistema solo planta animal.[87-90] A redução da disponibilidade de nitrogênio no solo com o envelhecimento de pastagens sem leguminosas, que não recebem adubação nitrogenada, é um dos principais fatores responsáveis pela queda da produtividade e pela degradação destas pastagens. O uso de leguminosas forrageiras em consórcio pode contribuir para manter a produtividade da pastagem e, ao mesmo tempo, incrementar a fertilidade do solo e disponibilizar mais proteína aos animais, além de aumentar os estoques de carbono e nitrogênio no solo.[87-92]

7.4. Fixação Biológica de Nitrogênio - FBN

O uso de fertilizantes na agricultura emite muito GEE em função de sua industrialização, distribuição e utilização nos sistemas de produção. Após a aplicação em áreas agrícolas, os fertilizantes à base de P ou K não promovem, pelo menos diretamente, emissões de GEE, ao contrário do que ocorre com os nitrogenados, que emitem N_2O devido aos processos biológicos de nitrificação e desnitrificação.

A FBN desempenha papel importante no aporte de N aos ecossistemas agrícolas. Estima-se que no mundo a FBN em áreas cultivadas contribua com 32 Tg ano^{-1} de N, o que corresponde a 30% do N produzido na forma de fertilizantes. Sendo assim, o Plano ABC tem como objetivo aumentar em 5,5 milhões de hectares o uso da FBN, cujo potencial de mitigação e da ordem de 10 milhões Mg CO_2eq. O caso mais eficiente é a simbiose de Bradyrhizobium com soja no Brasil.

Algumas culturas, como a soja, dispensam integralmente a adubação nitrogenada.[93] Isso porque, com a FBN é possível suprir as necessidades nutricionais da planta. É importante ressaltar que, a FBN para outras culturas importantes, como o feijoeiro e o amendoim, não consegue, com a tecnologia atualmente disponível, suprir totalmente a demanda por N dessas culturas, mas permite reduzir as doses de N aplicadas como fertilizantes químicos.[94] Alguns estudos indicam a possibilidade de se reduzir as doses de fertilizante nitrogenado, atualmente recomendadas, em até 50%, no caso da cana-de-açúcar, milho e trigo com o uso deste tipo de manejo.[93,95]

7.5. Florestas Plantadas

O governo federal espera ampliar em 3 milhões de hectares, as áreas com florestas comerciais (Plano ABC) até 2020. O plantio de florestas para a produção de madeira, celulose e papel, e carvão vegetal se apresenta como alternativa tecnológica que viabiliza a geração de renda e o aumento do sequestro de carbono da atmosfera, contribuindo para atenuar os efeitos das mudanças climáticas. Além das reduções de emissões, as florestas proporcionam a conservação do solo e água, manutenção das bacias hidrográficas, aumento dos estoques de carbono, redução do desmatamento de florestas nativas, dentre outros.[6]

7.6. Tratamento de Dejetos Animais

Cerca de 20% dos resíduos produzidos por animais, bovinos e suínos, são aplicados diretamente sobre os solos, sendo assim uma das maiores fontes de N_2O na agricultura. O Plano ABC prevê a ampliação no tratamento de 4,4 milhões de m^3 de dejetos de animais, cujo potencial de mitigação é de 6,9 milhões Mg CO_2eq. Os biodigestores para dejetos de suínos vêm sendo cada vez mais utilizados por produtores integrados a grandes corporações contribuindo com grandes reduções de GEE. Uma vez que esses biodigestores são usados para geração de energia e/ou queima de CH_4 e N_2O emitindo CO_2.[6]

8. Conclusões

O grande aumento das emissões de gases de efeito estufa, responsável pela mudança do clima atual foi severamente agravada nos últimos 100 anos e hoje o quadro está muito próximo de se tornar irreversível, mesmo em longo prazo.

Nesse cenário, o nitrogênio representa um papel de grande relevância, especialmente sob a forma do gás N_2O, largamente emitido pelo setor industrial e pela agropecuária. Por outro lado, o N é absolutamente essencial para esses importantes setores da economia. Desta forma, produzir mais e melhor com o menor impacto possível ao meio ambiente tornou-se imprescindível.

Entender o ciclo do N e quais setores da economia contribuem para emissão de N_2O são fundamentais para o direcionamento de políticas públicas e ações de mitigação que visem a redução da emissão desse gás para a atmosfera.

Nesse contexto, o Brasil tem se mostrado um ator extremamente relevante e proativo nas negociações internacionais. Ações de mitigação para reduzir a emissão desse gás, já são implementadas e estimuladas pelo governo brasileiro. Para o setor agrícola essas ações são internalizadas principalmente pelo Plano ABC. As tecnologias adotadas pelo Plano ABC são, em grande parte, dependentes do manejo adequado do N nos sistemas agrícolas e florestais. O uso racional dos fertilizantes nitrogenados e o manejo adequado dos dejetos animais são de fundamental importância para o estabelecimento da intensificação sustentável da agricultura.

No entanto, apesar de todo esse protagonismo do Brasil em ações de mitigação, muito ainda precisa ser feito no setor agrícola, como a recuperação de uma grande área de pasto degradados, que além de pouco produtivas contribuem para o agravamento do efeito estufa; o aprimoramento, o desenvolvimento, a transferência e a adoção de tecnologias agrícolas sustentáveis; o monitoramento das ações de implementação das políticas públicas; a certificação de propriedades que adotam essas tecnologias; a capacitação adequada da assistência técnica e extensão rural no país e o estabelecimento de mecanismos de pagamento por serviços ambientais para os produtores que adotam as tecnologias.

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Short-term effect of *Eucalyptus* plantations on soil microbial communities and soil-atmosphere methane and nitrous oxide exchange

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Soil greenhouse gas (GHG) emissions are a significant environmental problem resulting from microbially-mediated nitrogen (N) and carbon (C) cycling. This study aimed to investigate the impact of *Eucalyptus* plantations on the structure and function of a soil microbial community, and how resulting alterations may be linked to GHG fluxes. We sampled and monitored two adjacent *Eucalyptus* plantations—a recently logged site that harbored new seedlings and an adult plantation—and compared them to a site hosting native vegetation. We used 16S rRNA gene sequencing and qPCR amplifications of key nitrogen and methane cycle genes to characterize microbial structure and functional gene abundance and compared our data with soil parameters and GHG fluxes. Both microbial community attributes were significantly affected by land use and logging of *Eucalyptus* plantations. The genes *nosZ* and archaeal *amoA* were significantly more abundant in native forest than in either young or old *Eucalyptus* plantations. Statistical analyses suggest that land use type has a greater impact on microbial community structure and functional gene abundance than *Eucalyptus* rotation. There was no correlation between GHG fluxes and shifts in microbial community, suggesting that microbial community structure and functional gene abundance are not the main drivers of GHG fluxes in this system.

Emissions of greenhouse gases (GHG) through human activities represent a pressing issue today, contributing to global climate change and ecosystem destabilization[1]. Atmospheric concentrations of the three main GHGs—carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4)—have increased by 144%, 256% and 121%, respectively, since the first Industrial Revolution[2]. Although N_2O and CH_4 are less concentrated in the atmosphere than CO_2, they represent major GHGs as their global warming potentials are respectively 296 and 25 times higher than CO_2 over a 100-year period[3].

Agriculture, forestry and other land uses are the third-highest sources of anthropogenic GHG emissions (24% of total GHG emissions[4], mainly through crop cultivation and tropical deforestation. Owing to high levels of deforestation, land use change, and improper land use practices, Brazil has been ranked as the fourth-highest emitter of GHGs in the world[5].

Planted forests cover 7.8 million ha in Brazil[6], and they are thought to play many positive roles in the context of climate change and deforestation through restoration of degraded land, soil conservation, CO_2 sequestration, and protection of biodiversity. Their appropriate use in many industrial applications also reduce pressures on native forests[7].

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Of these Brazilian planted forests, 5.56 million ha are dedicated to *Eucalyptus*. *Eucalyptus* are fast-growing trees with high carbon sequestration potential during development[8,9]. *Eucalyptus* plantations have been reported to be a source of N_2O and CO_2 and a sink of CH_4 in semi-arid and subtropical climates, as observed for most forest ecosystems[10,11]. However, GHG fluxes in *Eucalyptus* plantations have not yet been well described in the tropics, so a greater understanding of the impacts of *Eucalyptus* plantation management on these fluxes is still needed.

Soil behaves as both source and sink for GHGs[12], as it represents the living space for the microbial communities responsible for nutrient cycling[13]. Accordingly, microbial activities in the N and C cycles are central to GHG fluxes in soil.

The link between soil microbial communities and GHG fluxes has previously been described[14]. Soil microbial processes are particularly impacted by land use practices, which can deregulate nutrient cycles and thereby increase or reduce GHG emissions[15,16]. Some studies have revealed a correlation between the abundance and/or expression of functional genes involved in N and C cycles and GHG fluxes in forest soils[16–18]. However, until now, no study has focused on the link between a microbial community and the GHG fluxes in the soil of *Eucalyptus* plantations.

To address this topic, we studied GHG fluxes and the microbial community associated with *Eucalyptus* plantations at two growth stages (i.e., one with new seedlings and one with 6-year-old trees), and with a native Brazilian tropical forest (Atlantic Forest). We hypothesized that: (1) replacement of native vegetation by *Eucalyptus* plantation or *Eucalyptus* plantation rotation would lead to changes in microbial community structure and functional gene abundance; and (2) changes in microbial community would alter GHG flux dynamics at each site.

We employed two different experimental strategies to test these hypotheses. Firstly, we performed 16S ribosomal RNA (rRNA) gene sequencing to compare the composition of soil microbial communities among the three treatments (i.e., young and old *Eucalyptus* plantations, as well as native forest). Secondly, we measured by quantitative PCR (qPCR) the abundances of the following key functional genes involved in the methane and N cycles: *nifH* (nitrogen fixation), archaeal and bacterial *amoA* (nitrification), *nirK* (denitrification), *nosZ* (N_2O reduction) and *mcrA* (CH_4 production). We then compared our 16S rRNA sequencing and qPCR data with soil physicochemical properties and measurements of GHG fluxes.

Materials and Methods

Field site description. The experimental field site is located in Belo Oriente, Minas Gerais, Brazil (18–20°S, 42–44°W, 300 m elevation), in an area that belongs to the Celulose Nippo-Brasileira (CENIBRA) company. The climate is classified as Aw (tropical with a dry winter and a rainy season during summer, Köppen classification), with an annual mean temperature varying from 22 °C to 27 °C (maximum = 32 °C, minimum = 18 °C). Annual mean precipitation varies from 701 to 1,500 mm. The soil is classified as loamy red-yellow Ferralsol. The experimental area is highly sloping, with a slope of 26 degrees.

The experimental field was originally covered by Atlantic Forest, a native tropical forest. Since 1960, CENIBRA has managed *Eucalyptus* plantations in this area and adopts regular rotation cycles of 7 to 9 years between planting seedlings and tree-cutting. Part of the area has been retained as native vegetation, in accordance with Brazilian law, which allowed us to compare adjacent areas covered by native forest or *Eucalyptus* plantation. Planted seedlings are clones of *Eucalyptus urograndis* produced by the company.

We chose an area under *Eucalyptus* plantation since 1978, immediately adjacent to a fragment of Atlantic Forest to perform this study. The most recent *Eucalyptus* rotation started in 2011, with trees in the 6th year growth in the beginning of 2017. To understand the short-term impact of a new rotation, we manually logged approximately half of this 6-year-old *Eucalyptus* plantation in February 2017 and replanted it immediately with new *Eucalyptus* seedlings. Sampling for our analyses was conducted at the end of March 2017.

Experimental Design. Three adjacent areas under contrasting use were considered for this study:

i. Atlantic Forest fragment (NF) – native Brazilian tropical forest fragment (Atlantic Forest);
ii. Old *Eucalyptus* (OE) - *Eucalyptus* plantation with 6-year-old trees;
iii. Young *Eucalyptus* (YE) - *Eucalyptus* plantation in which 6-year-old trees had been removed from the field, and new seedlings were planted one month before sampling.

We compared the *Eucalyptus* plantations at the beginning (YE) and at the end of the rotation cycle (OE), with the Atlantic Forest (NF) fragment acting as a reference. OE and YE areas comprised 470 and 680 *Eucalyptus* trees, respectively, which had been planted in lines with a spacing of 3 × 2.5 m.

GHG sampling. Gas sampling was done daily, during four days, from 14 to 17 March 2017. Nitrous oxide and methane fluxes were manually quantified using closed static chambers, similar to those described by Alves *et al.*[19]. The top-base chambers had a base composed of a rectangular steel frame (40 cm × 60 cm), which was deployed between rows of *Eucalyptus* trees or randomly in the Atlantic Forest fragment. The base was inserted into the soil to a depth of 6–7 cm, before attaching a polyethylene lid (of the same lateral dimensions as the base) to it, generating an internal chamber space 12–15 cm above the soil surface. Soft rubber was fixed to the rim of the lid to satisfactorily seal it to the base. Air accumulating in the chamber headspace was withdrawn through a three-way valve connected to the lid using a polypropylene syringe. Approximately 30 mL of this air was sampled and transferred to 20 mL chromatography vials crimped with chlorobutyl septa. Just before gas transfer, each vial was evacuated to approximately −100 kPa by using an electric vacuum pumping system. The chamber lid was covered with a 2-cm-thick foam layer and reflective adherent mantle for thermic insulation. The bases of the chambers remained in their respective areas throughout the monitoring period. After chamber closure an air sample was immediately taken from chamber headspace. Subsequent samples were taken at 20, 40 and 60 min, after which lids were removed. Gas sampling was always performed in the morning between 08 h and 10 h[19].

Gas analyses were performed using a gas chromatograph (GC 2014, Shimadzu, Japan). For each sampling run, N_2O and CH_4 standards were used to build an analytical curve to transform the integrated areas of each sample peak into gas concentrations.

Gas fluxes were calculated by the equation $F = (\Delta C/\Delta t)(V/A)M/Vm$, where $\Delta C/\Delta t$ is the slope of a linear function fitted to the gas concentration of samples taken at 0, 20, 40 and 60 min after chamber closure; V and A are the volume of the chamber and the area of soil covered by the chamber, respectively; M is the molecular weight of atoms of the elements N and C, respectively, in molecules of N_2O and CH_4; and Vm is the molecular volume at the sampling temperature.

Biogeochemical characteristics of the soil. We sampled approximately 500 g of soil from nearby each of the gas chambers described in the previous section (around 10 cm from the chamber) to measure clay content, pH, total carbon, total nitrogen, available P, and amounts of $H^+ + Al^{3+}$, Ca^{2+}, Mg^{2+} and Al^{3+}. Each sampling point served as an independent replicate, resulting in five replicates per treatment, which were used to assess correlations with the respective gas fluxes calculated for each chamber.

Soil samples were air dried, sieved (2 mm) and analysed chemically. Total carbon and total nitrogen were determined using a CHN elemental analyser (PerkinElmer, USA). Exchangeable nutrients: Ca^{2+}, Mg^{2+} and Al^{3+} were extracted by 1 M KCl; P, Na and K by Mehlich-1 extractant $-0.05\,mol\,L^{-1}$ in HCl in $0{,}0125\,mol\,L^{-1}$ H_2SO_4) and pH (soil:water, 1:10); Potential acidity: H + Al extracted with calcium acetate 1 N (pH 7), titrated with 0.0125 NaOH N. Inductively coupled plasma apparatus for Ca^{+2}, Mg^{+2} and Al^{+}, flame emission (K and Na) and photocolorimeter (for P) were used to nutrient determinations. Soil granulometry was determined using the aerometer method, after chemical dispersion. All these soil characteristics were measured according to Embrapa[20].

Soil moisture and concentrations of NO_3^- and NH_4^+ were measured according to Morais *et al.*[21]. Determinations were made from samples taken from another four randomly selected points in each of the three areas. The inorganic N content was extracted from fresh soil with 60 mL 2M KCl after 1 h on a rotary shaker at 220 rpm. The supernatant was filtered and the NO_3^- and NH_4^+ concentrations were determined in the resultant solution respectively by flow injection (FIA) technique using Cd reduction and nitrite analysis and by the salicylate reaction adapted for FIA. We used averages of the four values obtained for soil moisture and NO_3^- and NH_4^+ concentrations.

Soil sampling for microbial analyses. Soil samples were taken from five points in each treatment area (YE, OE and NF), approximately 10 cm away from each gas flux chamber, resulting in five replicates per treatment. To extract each soil sample, we placed a steel tube probe of 1.5 cm diameter (previously sterilized at 180 °C for 3 h to remove contaminants and nucleases) into the soil to a depth of 7 cm. The harvested soil was immediately put in a sterile 50 mL propylene tube for mixing, before being separated into two subsamples and placed in liquid nitrogen until we conducted DNA extractions.

Analysis of bacterial community structure. DNA was extracted from approximately 500 mg of each soil sample using the Fast DNA Spin Kit for Soil (MP Biomedicals, USA). The extracted DNA was dark in color due to a high level of humic material, so it was then purified using the last steps of the NucleoSpin Soil kit (Macherey-Nagel, Germany) protocol. DNA concentration and quality were measured using a NanoDrop (Thermo Fisher, USA). Soil bacterial diversity were assessed by next generation sequencing of the V4 variable region of the 16S rRNA gene using the primers 515FB (GTGYCAGCMGCCGCGGTAA) and 806RB (GGACTACNVGGGTWTCTAAT)[22,23].

PCR reactions with a barcode on the forward primer were used in a 28-cycle PCR using the HotStarTaq Plus Master Mix Kit (Qiagen, USA) under the following conditions: 94 °C 3 min; 28 cycles of (94 °C 30 s, 53 °C 40 s, 72 °C 1 min); 72 °C 5 min. Following PCR amplification, PCR products were checked in 2% agarose gels to determine the success of PCR and the relative intensity of resulting bands. Multiple samples were pooled in equal proportions based on their molecular weight and DNA concentrations. Pooled samples were purified using calibrated Ampure XP beads (Beckman Coulter, USA). The pooled and purified PCR products were then used to prepare an Illumina DNA library.

Sequencing was performed by MR DNA (www.mrdnalab.com, Shallowater, TX, USA) on a MiSeq (Illumina, USA) paired-end 2 × 250 sequencing system, following the manufacturer's guidelines. Raw data were downloaded from Basespace and analysed using Mothur v1.39 software[24]. Forward and reverse paired sequences were merged into contigs after checking for the presence of barcodes and primers in the sequences. Merged sequences of less than 240 base pairs (bp) or greater than 300 bp, containing any ambiguities, or containing more than 8-mer homopolymers were removed.

Sequences were then aligned using a modified Silva database (generated by a virtual PCR using the same primers as those used for our samples) as reference[25], and the resulting alignment was submitted to screen.seqs and filter.seqs (Mothur v1.39) to remove badly aligned sequences and uninformative columns in the alignment. The sequences where then pre-clustered using the command pre.cluster (Mothur v1.39.5) with parameter diffs = 2. Chimeras were detected using the command chimera.vsearch (Mothur v1.39.5) and then eliminated. We classified sequences using the classify.seqs (Mothur v1.39.5) command, with the Ribosomal Database Project[26] as reference and a bootstrap threshold of 80. Sequences identified as being from chloroplasts, mitochondria, Eukarya or Archaea and those not assigned to any kingdom were removed. The resulting sequences were used as input for the dist.seqs (Mothur v1.39.5) command.

Target gene	Primer names	Forward primer sequence	Reverse primer sequence	Fragment size (bp)	Annealing temperature	References
16S rRNA	341 f/534r	5′-CCTACGGGAGG CAGCAG-3′	5′-ATTACCGC GGCTGCTGG-3′	193	53 °C	51,52
nifH	PolF/PolR	5′-TGCGAYCCSA ARGCBGACTC-3′	5′ATSGCCATCATYT CRCCGGA-3′	360	55 °C	53
Archaeal *amoA*	19 F/CrenamoA616r48x	5′-ATGGTCTGGCT WAGACG-3′	5′-GCCATCCABC KRTANGTCCA-3′	624	55 °C	54,55
Bacterial *amoA*	amoA1F/amoA2R	5′-GGGGTTTCTAC TGGTGGT-3′	5′-CCCCTCKGSA AAGCCTTCTTC-3′	491	55 °C	56
nirK	F1aCu/R3Cu	5′-ATCATGGTS CTGCCGCG-3′	5′-GCCTCGATCA GRTTGTGGTT-3′	473	62 °C	57,58
nosZ	nosZ1F/nosZ1R	5′-WCSYTGTTCMT CGACAGCCAG-3′	5′-ATGTCGATCA RCTGVKCRTTYTC-3′	259	62 °C	42
mcrA	qmcrAf/qmcrAr	5′-TTCGGTGGAT CDCARAGRGC-3′	5′-GBARGTCGWA WCCGTAGAATCC-3′	140	58 °C	59,60

Table 1. Primers and protocols used for PCR and qPCR of targeted genes.

Finally, we clustered the sequences into operational taxonomic units (OTUs), with a 3% dissimilarity threshold. To avoid bias due to sampling effort, the samples were randomly normalized to the same number of sequences (35028). We employed a taxonomic summary to assess the bacterial composition of each sample.

Differences in the relative frequencies of phyla and classes among treatments were tested using analysis of variance (ANOVA) followed by Tukey's test. Before performing ANOVA, we checked the homoscedasticity among treatments and normality of distributions (Shapiro-Wilk's test) for all values, and data was transformed (log or Box-Cox transformation) accordingly if necessary before performing ANOVA. The Shannon index was also analysed by ANOVA followed by a pairwise Tukey's test.

The distribution of OTUs was used as input for a non-metric multidimensional scaling (NMDS) ordination with the Bray-Curtis similarity index to assess relationships among samples. We performed a PERMANOVA test, followed by Bonferroni correction ($p < 0.05$), to assess differences in structural composition among treatments. All aforementioned statistical analyses were conducted in Past3[27]. To determine if the treatments had a significant effect on specific bacterial OTUs, we undertook a blocked Indicator Species Analysis (ISA) (YE vs OE and YE + OE vs NF) using Mothur v1.39.5. The ISA, proposed by Dufrêne and Legendre[28], is based on the relative frequency of a specie (OTU in our case) within and inter treatments. It gives provides an indicator value ranging from 100 (perfect indicator) to 0 (no indicator). The perfect indicator species would be the one found in high abundance in all samples of a given treatment and absent in all other treatments. It also uses a randomization test to evaluate the significance of the specie distribution.

Nucleotide sequence accession numbers. The data generated were deposited in the NCBI Sequence Read Archive (SRA) and are available under Bioproject accession numbers PRJNA471919.

Gene quantification by qPCR. Genes were chosen based on their involvement in the soil nitrogen and methane cycles. Primers were selected according to the literature and assessed with the Primer blast tool of the National Center for Biotechnology Information (NCBI) (https://www.ncbi.nlm.nih.gov/tools/primer-blast/). We chose primers with the highest number of results and lacking non-specificity (Table 1).

The standards were constructed by amplifying each gene from DNA extracted from soil or activated sludge, ligating them into plasmids (CloneJET PCR Cloning Kit, Thermo Fisher Scientific, USA), and transforming them into *E. coli* DH5alpha plasmid (heat shock method, Froger and Hall, 2007). The plasmids were recovered using the PureYield Plasmid Miniprep system (Promega, USA). Based on the size of each gene, the weight of one nucleotide, and the plasmid concentration, we generated ten-fold serial dilutions in RNase- and DNase-free water for each plasmid to reach 10^{10} to 10^{2} gene copies per reaction.

qPCR reactions were carried out using the GoTaq® qPCR Master Mix (Promega, USA) on DNA (DNA amount ranged from 56 to 106 ng) in a 7500 Real-Time PCR system (Applied Biosystem, USA) with the SybrGreen excitation setting.

Each sample was quantified twice (technical replicate) in a 20 µl reaction volume. The following program was used: 50 °C 2 min; 95 °C 5 min; 40 cycles of (95 °C 30 s, annealing temperature (Table 1) 45 s, 72 °C 1 min); 72 °C 5 min; 95 °C 15 s; 60 °C 1 min; 95 °C 15 s; 60 °C 15 s. Fluorescence was read during the elongation step of each qPCR cycle. An absolute quantification was realized based on the standard curve generated by the plasmid dilutions. The copy number of each sample was normalized to the weight of soil used for DNA extraction to take into account the difference in soil DNA abundance among treatments. qPCR efficiencies were calculated using the formula $E = 10^{(-1/\text{slope})} - 1$, (where slope is the slope of the standard curve), with $E = 1$ corresponding to 100% efficiency.

Each qPCR reaction result was subjected to ANOVA followed by a pairwise Tukey's test. We ran an NMDS ordination based on soil characteristics, using qPCR reaction results and gas fluxes as correlating parameters. Spearman correlations were generated between gene amounts, gas fluxes and soil characteristics. We only present significant correlations ($p < 0.05$).

Soil characteristics	YE	OE	NF
Clay content ($g.kg^{-1}$)	600 (14)	592 (23)	600 (20)
Humidity factor (%)	32.8 (3.78) a	24.6 (1.49) b	24.5 (2.86) b
pH (water)	4.00 (0.23) a	4.26 (0.05) ab	4.3 (0.15) b
Total carbon (%)	3.77 (1.03)	3.81 (0.67)	3.02 (0.90)
Total nitrogen (%)	0.22 (0.04)	0.21 (0.04)	0.22 (0.04)
C:N ratio	16.9 (1.65) a	17.5 (0.76) a	13.3 (1.62) b
Available P ($mg.kg^{-1}$)	19 (23)	7 (1)	3 (1)
N:P ratio	221 (109) a	312 (86.7) a	663 (98.7) b
NO_3^- ($ugN.g^{-1}$ of dry soil)	44.6 (14.6) a	3.7 (1.27) b	4.4 (1.3) b
NH_4^+ ($ugN.g^{-1}$ of dry soil)	37.9 (16.1)	27.7 (2.89)	26.4 (2.86)
$H^+ + Al^{3+}$ ($cmolc.dm^{-3}$)	16.3 (2.2)	16 (1.1)	14.5 (1.8)
Ca^{2+} ($cmolc.dm^{-3}$)	0.95 (0.47) a	0.38 (0.07) b	0.31 (0.12) b
Mg^{2+} ($cmolc.dm^{-3}$)	0.29 (0.1) a	0.14 (0.01) b	0.28 (0.04) a
Al^{3+} ($cmolc.dm^{-3}$)	1.86 (0.41)	2.06 (0.22)	1.57 (0.26)

Table 2. Soil characteristics of the three treatment areas: young Eucalyptus plantation (YE), old Eucalyptus plantation (OE), and native forest (NF). Total C and N are expressed as % weight. Values represent means ($n = 5$, except $n = 4$ for humidity, NO_3^- and NH_4^+), followed by the standard deviation inside brackets. Different letters mean significant differences among treatments according to Tukey's test ($p < 0.05$).

Gas flux	YE	OE	NF
CH_4 ($\mu g\ CH_4\ m^{-2}\ h^{-1}$)	−22.3 (7.3)	−25.2 (10.9)	−34.8 (18.1)
N_2O ($\mu g\ N_2O\ m^{-2}\ h^{-1}$)	9.4 (4.8)	4.8 (3.6)	5.3 (2.7)

Table 3. Gas fluxes in the three treatment areas: young Eucalyptus (YE), old Eucalyptus (OE), and native forest (NF). Values represent means ($n = 5$), followed by the standard deviation in brackets. No significant differences were found among treatments according to Tukey's test ($p < 0.05$).

Results

Soil characteristics.

Our soil texture analysis revealed similar clay contents among all three studied areas (Table 2). However, we did identify some differences in soil characteristics among treatments, especially lower soil pH in area YE than NF, and higher NO_3^- content in areas YE than OE compared to NF. Area YE exhibited higher intra-sample heterogeneity than OE and NF. Despite high spatial variability, the low levels of available phosphorus in soil under native vegetation (area NF) reveal the importance of fertilization to achieve better wood production in high weathering soils. Fertilization resulted in considerable differences in the N:P soil ratio.

Gas fluxes.

All three treatment areas exhibited similar GHG flux dynamics (Table 3) over the short experimental period. All three areas acted as a sink for CH_4, with average fluxes ranging from −22 to −35 $\mu g\ m^{-2}\ h^{-1}$. All three areas acted as sources of N_2O, with average fluxes ranging from 4.8 to 9.4 $\mu g\ m^{-2}\ h^{-1}$. These fluxes did not differ significantly among treatments.

Impact of land use change and *Eucalyptus* logging on microbial community structure.

We assessed a total of 525,420 sequences (35,028 per sample) after applying quality filters and data normalization, clustered into 6,831 OTUs (3% dissimilarity threshold). Rarefaction curves show that our sequencing effort describes well the diversity of each sample (Supplemental Fig. 1). Bacterial richness (represented by numbers of OTUs) was significantly different among treatments, being highest in YE, followed by OE, and lastly NF (Table 4). Shannon diversity indices also differed significantly among treatments, being higher in YE and OE than in NF (Table 4). No significant difference was found between the two *Eucalyptus* plantations.

Taxonomic assignments revealed that all treatment areas were dominated by the same phyla, but with significant differences in the abundances of some phyla among treatments (Fig. 1A). Eight phyla were found in all treatments: Proteobacteria, Acidobacteria, Actinobacteria, Verrucomicrobia, Chloroflexi, Firmicutes and Bacteroidetes. The three most dominant phyla (Proteobacteria, Acidobacteria and Actinobacteria) represented at least 74% of the communities in each of the three treatments. We could classify approximately 88% of sequences into 16 different classes (Fig. 1B). Alphaproteobacteria were dominant in all treatments, representing 25 to 32% of the entire bacterial community.

Most significant differences in the relative abundances of bacterial taxa were observed between the native forest treatment (NF) and the two *Eucalyptus* plantations (YE and OE). However, there were also significant differences in the microbial community between the YE and OE treatments.

A global analysis of the distribution of the 6,831 OTUs indicated that, overall, microbial community structure was significantly affected by treatments, with all treatments differing from one another (PERMANOVA, $p < 0.001$). To identify the main bacterial groups responsible for the structure change, the abundances of the

Richness and diversity index	YE	OE	NF
Number of OTUs	2039 (308) a	1933 (156) ab	1623 (182) b
Shannon index	5.67 (0.18) a	5.54 (0.19) a	4.94 (0.18) b

Table 4. Richness and diversity index values for the soil bacterial community in the three treatment areas: young Eucalyptus (YE), old Eucalyptus (OE), and native forest (NF). Values represent means (n = 5), followed by the standard deviation in brackets. Different letters mean significant differences among treatments according to Tukey's test ($p < 0.05$).

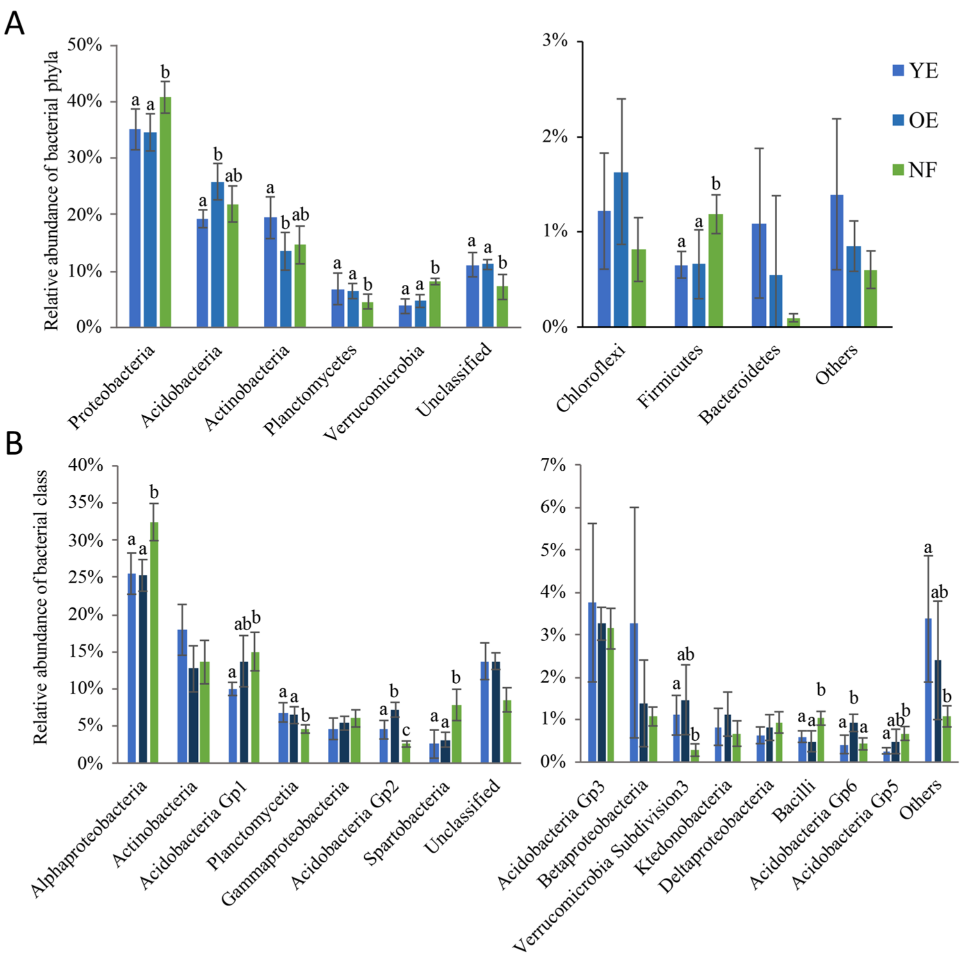

Figure 1. Relative abundances of bacterial phyla (**A**) and classes (**B**) found in soils under Young Eucalyptus (YE), Old Eucalyptus (OE) and Native forest (NF). Taxonomic assignment was based on the RDP database, with an 80% bootstrap threshold. Different letters mean significant differences among treatments according to Tukey's test ($p < 0.05$).

50 most abundant OTUs (representing 56% of the entire community) were tested by a ISA, which allowed us to identify 23 OTUs that were significantly different between the YE + OE and NF treatments. The 23 OTUs identification and their relative abundances in each treatment were shown in Fig. 2A. Additionally, the ISA performed on the 50 most abundant OTUs present in both *Eucalyptus* treatments revealed only six OTUs that were significantly different between them. The six OTUs identification and their relative abundances are shown in the Fig. 2B.

Quantification of abundances of C and N cycle functional genes. Our qPCRs were efficient in terms of quantifying functional gene copy numbers (Fig. 3). Dissociation curves indicated that the reactions were specific for all genes (data not shown), with R-squared values of the standard curves ranging from 0.98 to 0.99.

Copy numbers of the 16S rRNA gene were very similar among treatments (approx. 10^{10} copies). No significant differences were observed among treatments for the genes *nifH* (approx. 10^9 copies), *nirK* (approx. 10^7 copies), bacterial *amoA* (approx. 10^9 copies), or *mcrA* (approx. 10^7 copies). However, copy numbers of the genes *nosZ* and archaeal *amoA* were significantly affected by land use, with both being lower in the two *Eucalyptus* plantations than in native forest. There were no significant differences between YE and OE for these two genes. Archaeal

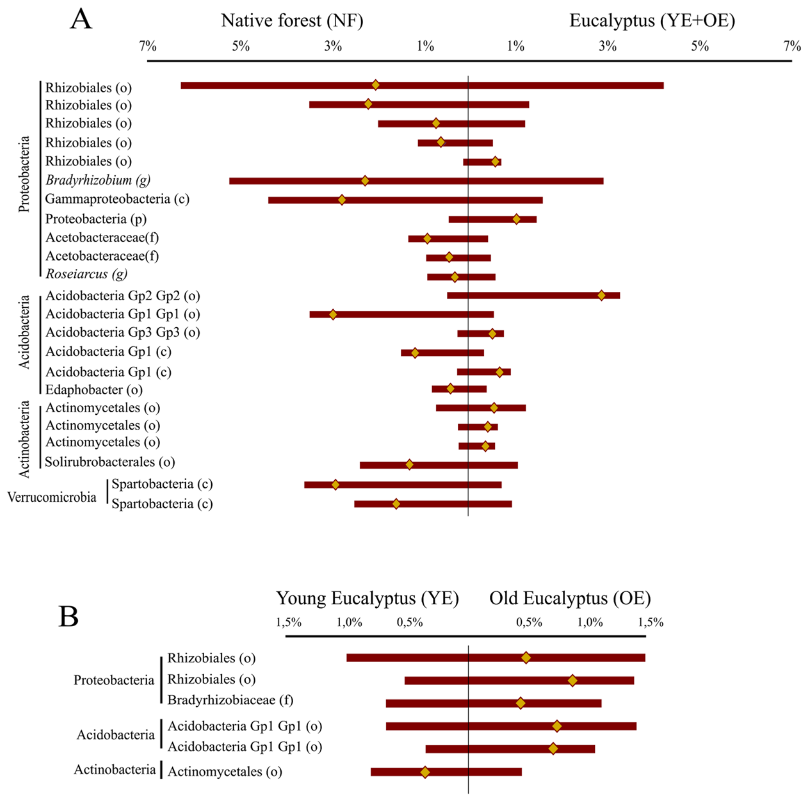

Figure 2. Comparison of the relative abundances of the top 50 OTUs between soils under native forest and Eucalyptus plantations (**A**), and between soils under Young Eucalyptus and Old Eucalyptus. (**B**) Only OTUs with significant differences are represented. Bars represent the average relative abundance of each OTU, extending to the left of the midpoint for one treatment and to the right for the other treatment. The yellow diamonds represent the differences in abundance between the treatments. In the left, the identification of each OTU. o - order, g - genus, f - family, c – class.

amoA, bacterial *amoA*, *nifH* and *nosZ* (approx. 10^9 to 10^{10} copies) were more abundant compared to *nirK* and *mcrA* (approx. 10^7 to 10^8 copies).

Correlations between abundances of N cycle genes, microbial community composition, soil characteristics, and gas fluxes. To more clearly understand how microbial activities are related to soil physicochemical characteristics, we generated correlations between abundances of N cycle genes (quantified by qPCR) and soil characteristics using Spearman correlations. Three genes exhibited correlations with soil characteristics—*nifH*, archaeal *amoA* and *nosZ* (Table 5)—all of which were correlated with the N:P ratio and available P, whereas archaeal *amoA* and *nosZ* were both also correlated with humidity, NH_4^+ and the C:N ratio. We also employed Spearman correlations to investigate the factors linked with gas fluxes in the three treatments, but there were no correlations between N_2O and CH4 fluxes and N cycle gene abundances or any soil characteristic.

We ran non-metric ordinations (NMDS) to better visualize the data structure and differential relationships in terms of microbial community composition (OTUs) and functional gene abundance (qPCR). The ordination based on soil characteristics revealed that all treatments differed from each other and that the difference between the YE and OE treatments was more pronounced than the difference between the OE and NF treatments (Fig. 4A). This ordination also revealed higher variability within the YE treatment. An ordination based on the distribution of OTUs (Fig. 4B) indicated that differences between the NF and YE + OE treatments were stronger than those between YE and OE. These differences were correlated with gene copy numbers of archaeal *amoA* and *nosZ* (both of which were higher in the NF treatment) and with gene copy number of *nirK*, total C content and the C:N ratio (higher in the two *Eucalyptus* treatments). Moreover, the higher graphical dispersion for the YE and OE treatments compared to the NF treatment on the NMDS ordination indicates higher beta diversity in the *Eucalyptus* treatments than in the NF treatment.

Discussion

The main phyla we found in the soil samples of the three treatments are common in soils, either from cultivated or native forests[29–33]. A dominance of Proteobacteria has also previously been reported for many types of soils[30,31,33]. Despite the apparent homogeneity in microbial composition across treatments, the PERMANOVA on OTUs indicated that microbial community structure is significantly affected by both land use change (from native forest to *Eucalyptus*) and at the start of a new *Eucalyptus* rotation (the transition from the OE to YE treatment). Conversion of native forest to other land uses—such as silviculture, agriculture or pasture—has previously

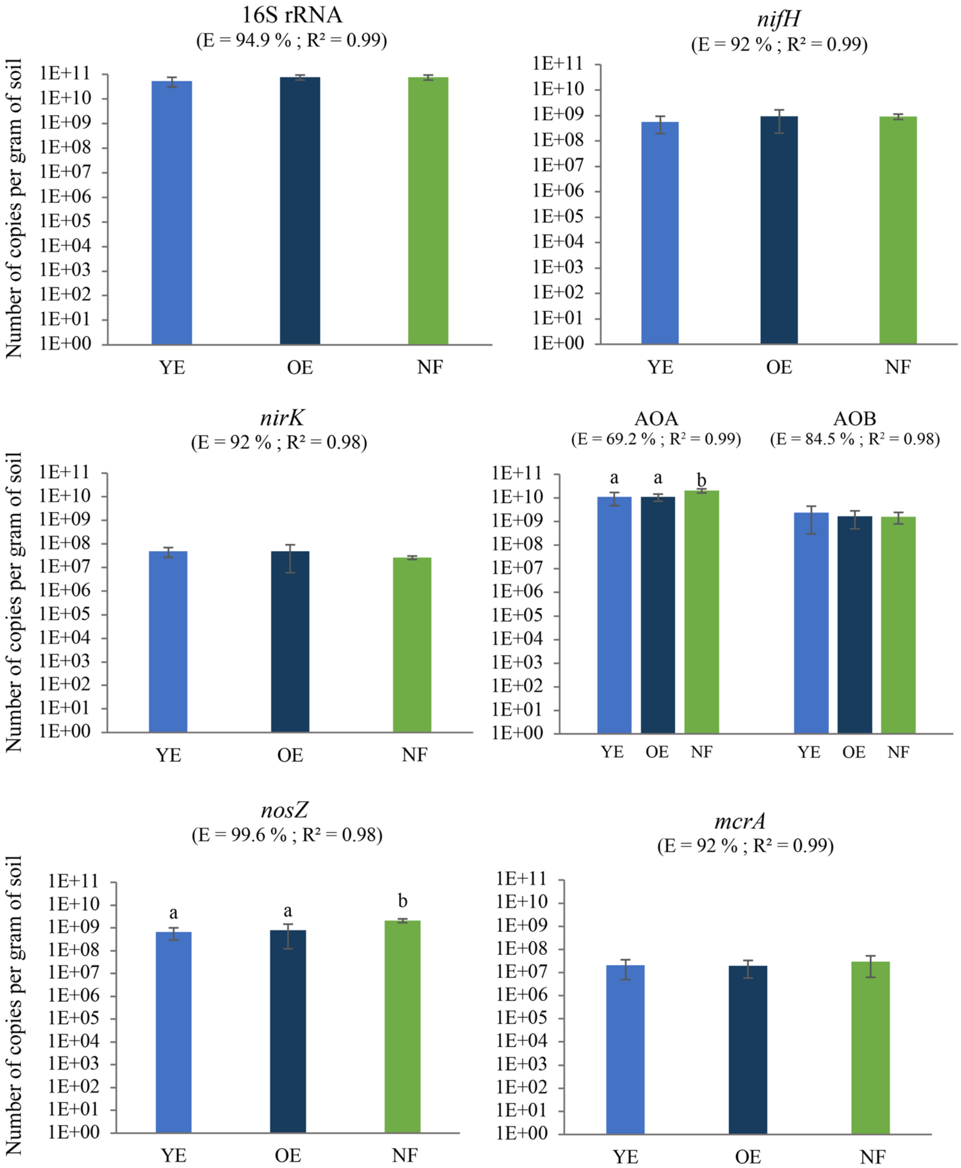

Figure 3. Quantification of 16S rRNA and nitrogen and carbon cycle functional gene abundance in soils under Young Eucalyptus (YE), Old Eucalyptus (OE) and Native forest (NF). The average copy number per gram of soil is plotted (logarithmic scale) for each condition ($n = 5$). Error bars represent standard deviation. AOA = archaeal amoA; AOB = bacterial amoA. E = significant reaction efficiency. Different letters over the bars represent significant differences according to ANOVA followed by Tukey's test ($p < 0.05$).

Soil parameter	*nifH*	Archaeal *amoA*	*nosZ*
Humidity	NS	$p = 0.01$ $R = -0.62$	$p = 0.007$ $R = -0.66$
C:N ratio	NS	$p = 0.003$ $R = -0.71$	$p = 0.002$ $R = -0.74$
NH_4^+	NS	$p = 0.01$ $R = -0.62$	$p = 0.007$ $R = -0.66$
Available P	$p = 0.01$ $R = -0.61$	$p = 0.001$ $R = -0.71$	$p = 0.001$ $R = -0.74$
N:P ratio	$p = 0.04$ $R = 0.53$	$p = 0.01$ $R = 0.64$	$p = 0.01$ $R = 0.64$

Table 5. Spearman correlations ($n = 15$) between N cycle gene abundances (measured by qPCR) and soil characteristics. Spearman correlations with p-values < 0.05 are shown. NS means lack of significant correlation. Genes and soil characteristics not shown in this table lacked any correlation. Correlations with ion abundances (K^+, Na^+, $H^+ + Al^{3+}$, Ca, Mg and Al) were not tested.

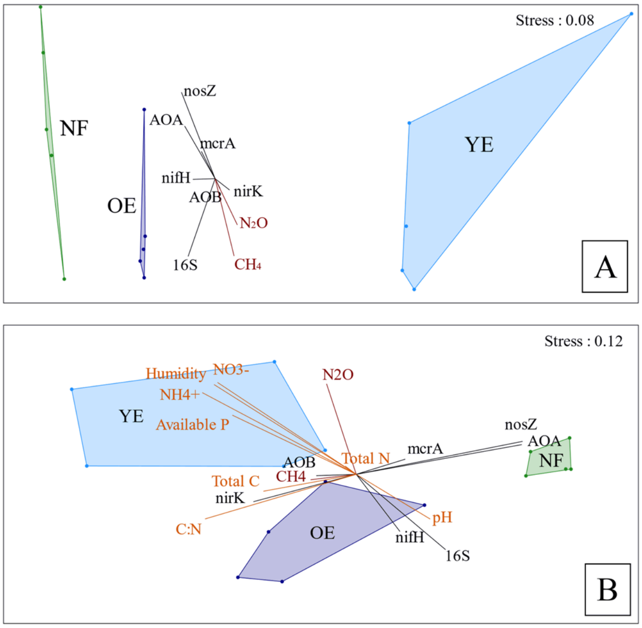

Figure 4. Non-metric multidimensional scaling (NMDS) ordination using Bray-Curtis similarity index of soil characteristics (**A**) and OTU distribution (**B**) for soils under Young Eucalyptus (YE), Old Eucalyptus (OE), and Native forest (NF). Environmental factors are plotted as vectors. AOA = archaeal *amoA*; AOB = bacterial *amoA*. Genes (abundances) are shown in black, gas flux data in red, and soil characteristics are in orange. Stress is expressed in a scale ranging from 0 to 1.

been shown to have an impact on global soil microbial community structure[34,35], but we are the first to report a short-term impact (within one month) of *Eucalyptus* plantation logging.

Our results suggest that the main driver of the observed differences in microbial community structure is land use type, as opposed to management practices (i.e., plantation logging and initiation of new rotations) or soil characteristics. Indeed, our NMDS analyses showed that OE and NF treatments were more similar to each other in terms of soil characteristics (Fig. 4A) relative to the YE treatment, but that the microbial community structure of OE was more similar to that of the YE treatment than the NF treatment, meaning that the overlying plant coverage was more effective than soil characteristics in driving microbial community structure (Fig. 4B). A similar outcome has been reported in other studies[36–38], which indicate that this scenario is more likely to occur when soil pH varies little between treatments, as found in this study. Moreover, our comparison of relative abundances of specific OTUs between the YE + OE treatments and the NF treatment (Fig. 2A) evidence that *Eucalyptus* plantations considerably influence the soil microbial community, including for specific groups of bacteria. High level selection of specific fungal groups by *Eucalyptus* trees has previously been reported[39].

The higher bacterial alpha diversity (Table 4) and beta diversity (Fig. 4B) of the two *Eucalyptus* treatments compared to the native forest is unexpected considering the greater tree biodiversity of the latter treatment. Interestingly, increased alpha diversity was also reported for an Amazon forest zone 4 months after deforestation[35]. We postulate that microbial richness might increase under these circumstances to adapt to the disturbance caused by deforestation, which is supported by the higher diversity of the YE area in our study given that its tree coverage was removed one month before soil sampling.

However, the higher microbial diversity in the OE area cannot be linked to short-term disturbance, since the trees had been growing there for 6 years before sampling. Higher primary productivity in *Eucalyptus* plantations compared to native forest might explain the higher microbial diversity under *Eucalyptus*, perhaps leading to higher fluxes of root exudates into the soil. The higher soil beta diversity under *Eucalyptus* plantations relative to native forest might be explained by heterogeneous perturbations due to management practices, such as fertilization and the physical consequences of tree-cutting and -dragging before starting a new rotation.

The phyla we identified as being impacted by the three treatments (Proteobacteria, Acidobacteria, Actinobacteria, Planctomycetes, Verrucomicrobia; Fig. 1A) have previously been highlighted as being affected by altered land use, i.e., from forest cover to deforested[34,35,40]. The decreased relative abundance of Proteobacteria we observed between native forest and *Eucalyptus* plantations is consistent with other studies. A similar outcome was observed 20 to 30 years after native forest had been converted to oil palm plantation[34], and also 2 to 3 years after an Amazonian forest soil lost its forest coverage[40]. Interestingly, both Acidobacteria and Actinobacteria were affected by starting a new *Eucalyptus* rotation (YE vs OE) but not by altered land use (NF vs YE + OE). This result suggests that plantation management practices may have their own inherent impact on microbial community structure.

We found the relative abundance of Acidobacteria to be significantly reduced in the YE treatment compared to that of the OE area. This phylum has previously been shown to be affected by deforestation[40]. Although relative abundances of Acidobacteria (particularly subdivision 1) are considered to be mainly driven by pH[41], our results suggest that other factors can influence Acidobacteria abundance, as we did not find pH to be significantly correlated with Acidobacteria abundance (data not shown).

The homogenous distribution of 16S rRNA gene sequence abundances among treatments demonstrates that the size of the prokaryote population is not significantly different among treatments. Moreover, the abundance of 16S rRNA gene fragments in our study is within the range usually measured in soil[42]. The higher archaeal *amoA* gene copy number compared to bacterial *amoA* could be linked to the acidic soil pH (<4.5 in all treatments)[43]. This phenomenon has been widely observed in previous soil studies, and may be explained by the fact that NH_3 content is reduced at lower pH and ammonia-oxidizing Archaea have a higher affinity for NH_3 than ammonia-oxidizing bacteria[18].

Since significant differences in gene abundances were only observed between native forest and *Eucalyptus* treatments, and not between the *Eucalyptus* treatments themselves, it seems that land use change and not starting a new rotation has an impact on microbial processes linked to the N and C cycles. Only the archaeal *amoA* and *nosZ* genes were significantly more abundant in soils under native forest than those under *Eucalyptus*. These differences are likely due to the specific soil characteristics of each treatment regime, since both archaeal *amoA* and *nosZ* gene abundances were strongly correlated with certain soil characteristics (Table 5).

The negative correlation between archaeal *amoA* abundance and humidity might be due to the aerobic character of ammonia-oxidizing Archaea, even though these bacteria have been previously shown to tolerate a broad range of oxygen concentrations[44]. The negative correlation between the C:N ratio and archaeal *amoA* abundance seems logical, given that a lower C:N ratio means higher N abundance, so there is more substrate for ammonia-oxidizing Archaea[45]. However, a negative correlation was observed between NH_4^+ and archaeal *amoA* abundance, suggesting that higher NH_4^+ levels are more a consequence of low nitrifier activity than a cause of higher rates of nitrification[46].

A similar process has been suggested to explain a negative correlation between soil NO_3^- levels and *nirK* gene abundance[38]. However, the correlations we report between levels of NH_4^+ and NO_3^- and humidity should be viewed with caution, as these factors were not measured specifically at each soil-sampling site, but at four sites randomly distributed in the three treatment areas. Thus, the correlations are based on average values for each treatment area, which could lead to spurious correlations.

The negative correlation between *nosZ* gene copy number and humidity is unexpected, because nitrous oxide oxidase has been reported to be highly sensitive to O_2, even being inhibited by low oxygen levels[47]. However, another study found a higher gene copy number of *nosZ* in wetlands than dry areas[48], and a negative correlation between levels of *nosZ* and NH_4^+ has been observed in wetlands[48]. This correlation might mean that lower NH_4^+ levels are a consequence of higher NH_4^+ oxidation activity from high levels of nitrous oxide reductase. It is important to note that we measured gene copy number, and not gene expression, in this study. Gene copy number is not always an effective means of reporting microbial activity as it provides no information about gene expression or protein activity.

The negative correlation we revealed between available P and the *nifH*, archaeal *amoA* and *nosZ* genes suggests an important link between P availability and N cycle functioning. However, this finding is not consistent with previous data, which suggest increased P availability promotes nitrification, denitrification and nitrogen fixation[49]. Analysing the bacterial community structure (Fig. 4) we can speculate that this correlation is more likely to be occurring indirectly. The microbial community structure of YE (highly disturbed) is positively correlated with P availability and negatively correlated with *nifH* and *nosZ* and *AOA*. Therefore, the disturbance could be the main factor controlling these correlations.

The absence of a correlation between levels of functional genes and gas fluxes is surprising because correlations between the *nosZ*, archaeal *amoA*, and bacterial *amoA* genes and N_2O fluxes have previously been described in forest systems[16–18]. The quantification results for *pmoA* may explain CH_4 fluxes, as this gene has been shown to be positively correlated to CH_4 emissions from soil[17]. Moreover, we only conducted gene quantification for a single time-period, so we cannot rule out a correlation between gene abundances and gas fluxes over time. Despite the absence of an overall link between microbial structure and functional gene abundance and gas fluxes, it is important to note that our study focused solely on bacterial activities (apart from the archaeal *amoA* gene). It would be interesting to also analyse Archaea and fungi, both of which play important roles in N cycling in soils, especially in forest soils[50].

In conclusion, we demonstrate that soils under *Eucalyptus* plantations can harbour a distinct and more diverse bacterial community compared to soils under native forest and that this community responds very quickly to environmental disturbances, such as implementation of a new plantation rotation. However, the short-term changes we observed arising from plantation management practices were qualitative and not quantitative, and they did not result in significant changes in terms of greenhouse gas fluxes from soil.

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Study conception and design: C.T.C.C.R., F.C.B., R.A.R.R. and B.J.R.A.; Field experiment: C.C., F.C.B., J.J., E.S. and C.T.C.C.R. Laboratory analysis: C.C., J.J. and E.S. Bioinformatics and statistical analysis: C.C. and C.T.C.C.R. Drafting of the manuscript C.C. and C.T.C.C.R. Critical revision: All Authors; Financial support: R.A.R.R., B.J.R.A. and C.T.C.C.R.

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Structural and functional shifts of soil prokaryotic community due to *Eucalyptus* plantation and rotation phase

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Agriculture, forestry and other land uses are currently the second highest source of anthropogenic greenhouse gases (GHGs) emissions. In soil, these gases derive from microbial activity, during carbon (C) and nitrogen (N) cycling. To investigate how *Eucalyptus* land use and growth period impact the microbial community, GHG fluxes and inorganic N levels, and if there is a link among these variables, we monitored three adjacent areas for 9 months: a recently planted *Eucalyptus* area, fully developed *Eucalyptus* forest (final of rotation) and native forest. We assessed the microbial community using 16S rRNA gene sequencing and qPCR of key genes involved in C and N cycles. No considerable differences in GHG flux were evident among the areas, but logging considerably increased inorganic N levels. *Eucalyptus* areas displayed richer and more diverse communities, with selection for specific groups. Land use influenced communities more extensively than the time of sampling or growth phase, although all were significant modulators. Several microbial groups and genes shifted temporally, and inorganic N levels shaped several of these changes. No correlations among microbial groups or genes and GHG were found, suggesting no link among these variables in this short-rotation *Eucalyptus* study.

The greenhouse effect is a natural process responsible for the maintenance of Earth's mean temperature. Greenhouse gases (GHGs) absorb solar radiation and trap it in Earth's atmosphere, which increases the planet's heat budget[1]. Atmospheric increases of 40% in carbon dioxide (CO_2), 150% in methane (CH_4) and 20% in nitrous oxide (N_2O) were observed from 1750 to 2011[2]. The increase in the concentrations of these gases is now causing ecological issues[3] and extreme weather and climate events[1].

Even though they are lower in atmospheric concentrations, CH_4 and N_2O have 28 and 265 times the global warming potential of CO_2, respectively, in a 100-year period. They contribute, respectively, to approximately 17% and 6% for the positive radiative forcing of the GHG[4]. N_2O also acts as the main ozone-depleting particle in the stratosphere[5].

Agriculture, forestry and other land uses represented 23% of global GHG emissions from 2007 to 2016. The emissions during this period consisted of 13% CO_2, 44% CH_4 and 82% N_2O[6]. Land use change currently contributes to 44% of the GHG emissions in Brazil, mainly through deforestation[7]. Brazil currently ranks sixth in global emissions[8].

The increasing demand on raw material has driven deforestation, which has caused the decrease of 129 million hectares of the global forest area in a 25-year period, especially in South America[9]. Planted forests are an alternative for this demand, since they supply materials including wood pulp, charcoal, and lumber for industry. In Brazil, planted forests cover 7.83 million hectares. These forests are responsible for 1.3% of the country's gross income and the planted trees are a stock of approximately 1.7 billion tons of CO_2 equivalent. As mandated by

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Brazilian law, the involved companies conserve 5.6 million hectares of native land, which stocks approximately 2.5 billion tons of CO_2 equivalent[10].

The genus *Eucalyptus* comprises approximately 73% of the planted forests in Brazil. They are preferred because of their fast growth, high productivity and adaptation to many regions, as revealed from studies of *Eucalyptus* silviculture[11–13]. Soils from *Eucalyptus* plantations behave as atmospheric sinks for CH_4 and as sources of CO_2 and N_2O[14–18]. However, as they occupy marginal soils, with low fertility (and fertilisation regime) and high acidity, the fluxes could be considered low compared with other ecosystems[19]. The short-rotation plantation has two growth phases in terms of nutrient demand and cycling: a juvenile phase up to canopy closure and another phase up to harvest[20]. How the plantation phase affects the dynamics of GHG fluxes is unclear.

Microorganisms play an important role in the emission and removal of GHGs by soils, as they cycle nitrogen (N) and carbon (C) molecules in soil environments[21]. Soil CH_4 is produced under anaerobic conditions by methanogenic archaea and is consumed under aerobic conditions by methanotrophic bacteria[22]. Release of N_2O from soils mainly derives from the escape of this molecule during nitrification or denitrification steps of the N cycle[23]. Understanding the correlation among specific microbial groups or the abundance of functional genes with underlying abiotic factors (*e.g*., temperature, humidity, nutrients, vegetation, land cover and land use)[24] linked with GHG fluxes could lead to the development of microbial indicators that correctly assess these processes, and development of mitigation options[25].

A previous study evaluated how *Eucalyptus* logging impacts soil microbial communities and GHG fluxes[18]. Significant changes in soil bacterial community structure and the abundance of specific genes suggested that forestry management interferes with microbial communities in the short-term. However, this study involved a single sampling, and provided no information on the impact in the longer-term. The present study was undertaken to clarify how: i. the growth period, ii. land use change and iii. seasonality impact the GHG fluxes and inorganic N levels in tropical *Eucalyptus* planted forests. Additionally, we investigate how these variables modulate microbial communities and whether there is a link between the microbial community and the GHG fluxes or the inorganic N levels.

To accomplish these goals, we selected three adjacent areas: a recently logged *Eucalyptus* forest area with 1-month seedlings (juvenile phase), a fully developed *Eucalyptus* forest with 6-year old trees near the end of the rotation cycle and a native forest area. We surveyed these areas for 9 months, sampling for GHG and inorganic N levels, and used 16 S rRNA gene sequencing and quantitative polymerase chain reaction (qPCR) of key genes involved in the CH_4 and N cycles to examine the research questions. Our hypothesis was that key microbial groups and gene abundances would correlate with GHG fluxes in a 9-month period, and that the land use or the *Eucalyptus* trees growth phase would recruit specific microbial groups.

Methods

Sampling area. All samplings were performed in an area belonging to the Celulose Nippo-Brasileira (CENIBRA) company, located in Belo Oriente, Minas Gerais State, Brazil (19°18′54′S, 42°23′48′W; 300 m altitude). The company has rotated *Eucalyptus* plantations in the area since 1960, with a 7 to 9-year period of tree growth before harvesting. The planted seeds are clones of *Eucalyptus urograndis*, a hybrid from *E. grandis* and *E. urophylla*. In compliance with Brazilian law, a section of native forest is maintained inside the company's area.

The predominant vegetation of the region is the Atlantic forest. The climate is defined as Aw (tropical with a dry winter) according to the Köppen climate classification. The annual mean temperature varies from 22 °C to 27 °C, and the annual mean precipitation varies from 701 to 1,500 mm. The landscape comprises a high slope of 26°. To avoid the effect caused by the differences in relation to the slope, we divided the area into 4 quartiles, perpendicular to the direction of the slope. Samples were taken over the entire length of the second quartile (from top to bottom).

The soil is defined as red-yellow Ferralsol (high metal oxides contents, low fertility, and a medium to a loamy texture). The physical-chemical contents of the soil were previously measured[18] (Supplementary Table 1).

Experimental design. To understand both the effects of *Eucalyptus* establishment and its growth phase (juvenile and adult) as compared to native forest soils, an area undergoing *Eucalyptus* rotations since 1978 was chosen for study. In 2017, trees in this area were 6-years-old, and approximately half of them were logged and seedlings were planted. The study area was divided into three treatments. The first was an area of adult (6-years-old) *Eucalyptus* (OE), representing a plantation at its last management year. This area contained 470 trees planted in rows and spaced by 3 × 2.5 m. At the end of the sampling, the trees were 7-years-old and ready to be harvested. At this stage (end of rotation), a large mass of litterfall (organic matter and nutrients) has returned to soil and is mineralized, representing the key process to providing nutrients to the stand.

The second area was young *Eucalyptus* (YE). It was a 1-month-old seedlings area, planted approximately 1 week after *Eucalyptus* logging, representing a standard *Eucalyptus* forest renewal. This area contained 680 seedlings planted in rows and spaced by 3 × 2.5 m. At the end of the sampling, the trees were 10-months-old and approximately 2.5 m height. At this stage, crop residues are the main supplier of nutrients to plants.

The third area was native forest (NF). It was an Atlantic forest remnant maintained by CENIBRA, representing a closer condition to the region's original state.

To check for temporal shifts, four campaigns for GHG sampling, four for inorganic N content sampling and two for microbiological soil sampling (beginning and end of the period) were performed in March 2017 (summer, wet season; Time 1), June 2017 (fall, dry season; Time 2), September 2017 (winter, dry season; Time 3) and December 2017 (spring, wet season; Time 4) (Supplementary Fig. 1).

GHG quantification. To quantify N_2O and CH_4 fluxes, five closed static chambers were deployed in each area. The static chamber design was previously described[26]. The chambers had a steel frame base (40 cm × 60 cm), mounted at a depth of 6 to 7 cm, 20 cm from a randomly chosen *Eucalyptus* tree, seedling or a NF tree. The base was left in the same position during the whole experiment. Polyethylene lids were attached and sealed to the base with soft rubber and covered with a foam layer and a reflective adherent mantle. The lid of the mounted chamber was approximately 13 cm above the soil surface. A three-way-tap at the lid permitted 30 mL gas samples to be withdrawn from inside the chambers with a polypropylene syringe. The syringe air was transferred to 20 mL chromatography vials that been previously depressurized close to −100 kPa. Sampling was performed 0, 20, 40 and 60 min after chamber closure, always between 8 a.m. and 10 a.m.[26].

Gas flux quantification was carried out by gas chromatography using a GC 2014 apparatus (Shimadzu, Japan). Soil N_2O and CH_4 fluxes were calculated based on analytical curves of standards. The fluxes were used to transform the integrated area of each sample peak into gas concentrations. The flux (*F*) was calculated as:

$$F = (\delta C/\delta t) \times (V/A) \times M/Vm$$

where δC/δt is the slope of a linear function fitted to the gas concentration of samples, V is the volume (L) of the chamber, A is the area covered by the chamber in m^2, M is the molecular weight and Vm is the molecular volume at the sampling temperature.

Inorganic N quantification. Four soil samples were randomly collected inside the three areas. Collection was done at the beginning and at the end of the sampling campaign to quantify nitrate (NO_3^-) and ammonium (NH_4^+) in soil extracts. The mineral N content was extracted from 20 g of fresh soil with 60 mL of 2 M KCl after 1-h of rotary shaking at 220 rpm, and the supernatant was filtered[27]. The resultant solution was used to determine NO_3^- by ultraviolet spectrometry and NH_4^+ by salicylate reaction[28]. The arithmetic mean of the four values was used for both contents.

Soil samples for microbial analysis. Five soil samples were taken per area in each sampling time approximately 10 cm apart from the different gas flux chambers. Each point was considered as a replicate. At each sampling time a 1.5 cm diameter steel tube probe that had been previously sterilised at 180 °C for 3 h to remove contaminants, especially nucleases, was inserted approximately 7 cm into the soil. Collected soil was deposited in a sterile 50 mL propylene tube, mixed and subdivided into two subsamples. Samples were frozen in liquid nitrogen in the field and maintained until DNA or RNA extraction.

DNA and RNA extraction. DNA was extract from approximately 500 mg of each soil sample using the Fast DNA Spin Kit for Soil (MP Biomedicals, USA). The DNA was purified using the NucleoSpin Soil Kit (Macherey-Nagel, Germany) from the sixth step of its extraction protocol, due to residual presence of humic acids after the final step of extraction.

RNA was extracted from approximately 2 g of soil using the RNA Power Soil – Total RNA Isolation Kit (Mobio, USA) according to the manufacturer's protocol. After the RNA extraction, 7 μL were treated with RQ1 RNase-Free DNase (Promega, USA) to remove any DNA contamination.

Nucleic acid purity and concentration was assessed using a NanoDrop 1000 device (Thermo Fisher Scientific, USA) and a Qubit 3.0 fluorometer (Thermo Fisher Scientific, USA), respectively.

16S rRNA gene sequencing and analysis. DNA extracted from soil samples was examined using 16S rRNA gene sequencing to understand shifts in bacterial communities due to land use, *Eucalyptus* growth phase, and temporality. Soil samples from time 1 had their sequencing performed as previously described[18]. Time 4 soil samples were sequenced by the StarSeq Company (www.starseq.com, Germany) on MiSeq equipment using paired-end runs (2 × 250) according to the manufacturer's guidelines. The primers used were 515FB (GTG YCA GCM GCC GCG GTA A)[28] and 926 R (CCG YCA ATT YMT TTR AGT TT)[29]. These primers target the V4-V5 regions of the 16S rRNA gene. Sequencing error tax rate was assessed by the coincident use of the ZymoBIOMICS Microbial Community DNA Standard (Zymo Research, USA) with the samples. The error tax rate from this sequencing was 0.08% per base, as assessed by the positive control.

Bioinformatics analysis were done using Mothur software v. 1.41.3[30]. Forward and reverse paired sequences were grouped into contigs and their barcodes and primers were removed from sequences. Sequences containing ambiguities (N-base) or containing more than 8-mer homopolymers were removed. All sequences presenting inconsistent sizes with what was expected for the amplicon were also removed. Unique sequences were grouped through the unique.seqs command. A virtual PCR was done in the Silva database[31] using the 515FB and 926 R primers. The sequences were then aligned with the database. Badly aligned sequences and non-informative columns were eliminated. All sequences were trimmed to fully overlap and unique sequences were again grouped. Pre-clustering of the sequences with a difference threshold of 2 bp was done. The chimeras were checked and removed using the chimera.vsearch command[32]. Virtual PCR was performed on the Ribosomal Database Project[33] using the 515FB and 806RB (GGA CTA CNV GGG TWT CTA AT)[34] primers for the V4 hypervariable region (in common among time 1 and 4 sequencings). The resulting reference file was used to classify our sequences using an 80% bootstrap threshold. Sequences from mitochondria, chloroplasts, Eukarya, Archaea and unknown domain were removed. Sequences from our samples that matched those at the negative control were also removed. In addition, OTU clustering was performed with a 3% similarity cutoff and singletons were removed. We normalized all samples based on the size of the smallest one (16,745 sequences) by random subsampling. Rarefaction curves, alpha diversity indexes, relative abundance of taxa, and an OTU distribution matrix were exported from the software.

To assess archaeal community structure, an exact sequence variant (ESV) clustering methodology was carried out using the Deblur algorithm[35] in Mothur v1.41.3 during the pre-clustering step. After chimera removal, our sequences were classified according to the RDP database. Sequences from mitochondria, chloroplasts, Eukarya, Bacteria and unknown domain sequences were removed. ESVs from unique sequences were then removed. Because of the low number of sequences after the error correction steps, we had four samples removed at our subsample step (OE1.4, OE3.4, NF1.4, YE2.4; <225 sequences).

Raw sequence data were deposited in the NCBI Sequence Read Archive (SRA) and are available under Bioproject accession numbers PRJNA471919 (time 1) and PRJNA591370 (time 4).

RT and qPCR reactions. The construction of the standard curves and the qPCR reactions of the time 1 samples were performed as previously described[18], except for *nir*S and *pmo*A genes.

Time 4 samples were analysed by qPCR for the selected genes using the GoTaq qPCR Master Mix (Promega, USA) on extracted DNA, and were quantified with the QuantStudio 3 device (Applied Biosystems, USA) using the SybrGreen excitation setting. The analyses were performed with the QuantStudio Design & Analysis Software v1.4.3 (Applied Biosystems, USA). Each reaction was 12 µL and contained 2 µL DNA, 0.48 µL (0.4 µM) of each primer, 0.24 µL of formamide (2%; for *nir*S and *nir*K reactions only), 6 µL of GoTaq qPCR Master Mix (2×) and nuclease-free water to the final volume of 12 µL. All the reactions were performed in triplicate along with a -RT control (without reverse transcription, for RT-qPCR only), eight plasmid dilutions (ranging from 10^9 to 10^2 copies), and a no-template control (NTC) in a MicroAmp Optical 96-Well Reaction Plate (Thermo Fisher Scientific, USA). The following protocol (fast setting) was used: 95 °C for 20 s; 40 cycles of 95 °C for 3 s, annealing temperature (Supplementary Table 2) for 20 s and 72 °C for 45 s; 95 °C for 1 s, 60 °C for 20 s and 95 °C for 1 s (melting curve analysis). Fluorescence was read during the elongation step of each cycle.

RT-qPCR reactions were done using the GoTaq 2-Step RT-qPCR System kit (Promega, USA) with the same protocol as for qPCR of time 4 samples.

Absolute quantifications based on the standard curve created with the plasmid dilutions were performed. The quantified number of copies were normalised to a nanogram of extracted RNA and to a gram of soil for DNA. Reactions efficiencies were calculated as:

$$E = -1 + 10^{\left(-\frac{1}{slope}\right)}$$

and quantities were normalised as gene/16S ratio to minimize extraction bias.

Statistical analyses. The gene/16S ratios, N_2O and CH_4 fluxes, NO_3^- and NH_4^+ measurements, alpha diversity indexes and relative abundances of bacterial taxa were tested for differences among treatments by two-way analysis of variance (two-way ANOVA) using treatment and time of sampling as independent variables, followed by Tukey's post hoc test. All data were checked for normality of distribution by Shapiro-Wilk's test and homoscedasticity among treatments by the Levene test. If the data failed both assumptions, a Box-Cox transformation was executed. For GHG and inorganic N plots, the standard error of the mean (SEM) was used instead of the standard deviation (SD). Spearman's correlations among gene/16S ratios and the 49 most abundant bacterial OTUs (>0.5% relative abundance) with gas fluxes and inorganic N contents were generated and the p-values were Bonferroni corrected.

A non-metric multidimensional scaling (nMDS) ordination was performed from the OTU distribution of treatments with the Bray-Curtis dissimilarity index and using GHG fluxes and inorganic N contents as correlating parameters. A two-way permutational multivariate analysis of variance (two-way PERMANOVA) followed by Bonferroni correction for p-values was performed, to test for the impact of time and treatments on OTU distribution. All statistical tests were done using Past3.24 software[36].

We then performed a blocked Indicator Species Analysis[37] based on the 49 most abundant bacterial OTUs (>0.5% relative abundance) using the following parameters: YE × OE and YE + OE × NF. Only the OTUs that were significantly impacted ($p < 0.05$) and had an indicator value > 60 are demonstrated. This analysis was conducted with PC-ORD 6.0 software[38].

For all boxplots, whiskers represent the minimum and maximum values and box the interquartile range (Q1-Q3, line representing Q2, *i.e.*, the median).

Results

GHG fluxes and inorganic N contents. All areas were CH_4 sinks and N_2O sources during the year. A statistical difference was evident between the sampling time factor for CH_4 and N_2O, but not between areas (Fig. 1A,B). Time 2 (June) showed lower net negative CH_4 fluxes from the *Eucalyptus* areas, and a slightly net positive CH_4 flux in NF, but without statistical difference to time 4 (December). Times 1 (March) and 3 (September) showed the greatest net negative CH_4 fluxes. For N_2O fluxes, time 4 had the greatest means (except for YE), with no statistical difference to time 1. Times 2 and 3 had lower net N_2O fluxes than the others (although time 2 did not differ from 1), with two events of net negative fluxes.

Regarding the inorganic N contents, NH_4^+ and NO_3^-demonstrated differences among treatments and times according to two-way ANOVA (Fig. 2A,B). Soil NH_4^+ concentrations seemed to increase from time 1 to 4, with times 3 and 4 differing from time 1. YE was statistically different from the other groups. For NO_3^-, YE had evidently higher values over the other two treatments throughout the year. NF showed higher values than OE. Time 2 showed the higher results, followed by times 3 and 4, which were not statistically different.

Structural profile of microbial communities. A total of 502,350 sequences were obtained after the quality filtering and random subsampling, resulting in 16,745 sequences per sample. Good coverage of our samples was obtained, as evident by the rarefaction curves (Supplementary Fig. 2). We clustered the sequences into 7,754 OTUs (with a 3% dissimilarity threshold). Surprisingly, higher richness (indicated as number of OTUs) and

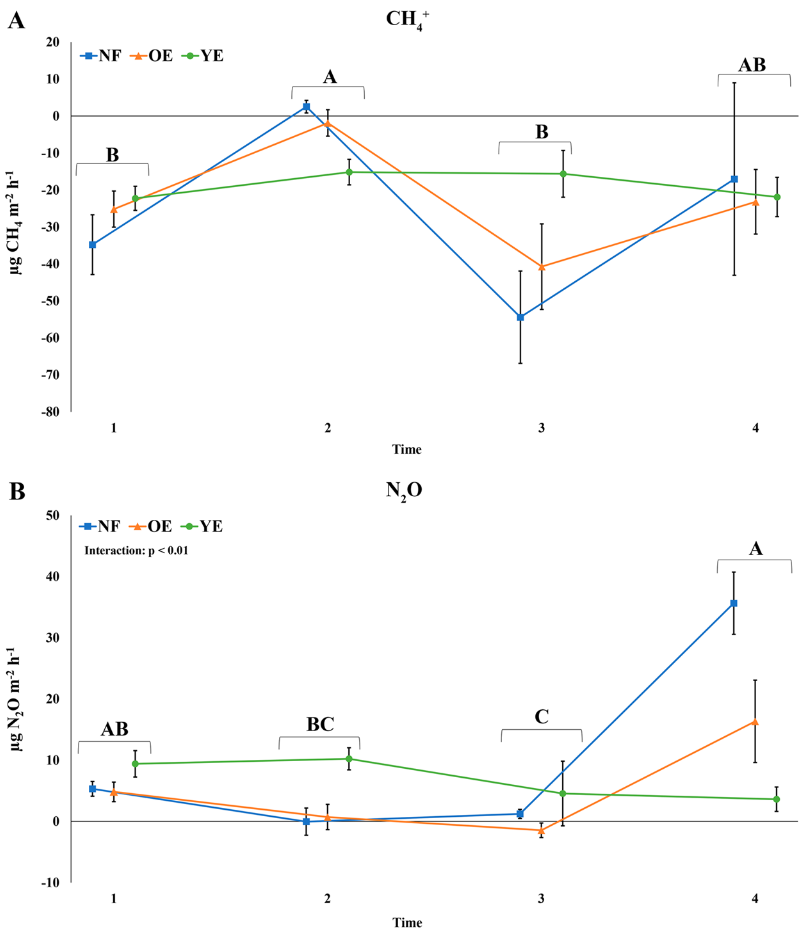

Figure 1. GHG fluxes (**A**: CH_4; **B**: N_2O) in the native forest (NF), old *Eucalyptus* (OE), and young *Eucalyptus* (YE) areas at times 1 (March), 2 (June), 3 (September), and 4 (December). Values represent means with the vertical error bars denoting SEM. Statistical differences are expressed as different upper-case letters for the time factor. No statistical differences were found for the treatment factor (two-way ANOVA followed by Tukey's test; $p < 0.05$).

diversity (indicated as Shannon index) values were observed inside *Eucalyptus* areas (OE and YE) than in the NF area (Table 1). Statistical testing supported the difference in means. No statistically significant difference among *Eucalyptus* treatments or between times 1 and 4 for richness and diversity were found.

Regarding the bacterial composition at the phylum level, the following taxa were shared among all treatments: Proteobacteria, Acidobacteria, Actinobacteria, Planctomycetes, Verrucomicrobia, Chloroflexi, Firmicutes, Bacteroidetes, candidate division WPS-1, candidate division WPS-2, Gemmatimonadetes, Armatimonadetes and Nitrospirae (ordered by decreasing mean relative abundance among all treatments). Unclassified sequences accounted for 6.49% to 10.62% among treatments. The seven most abundant phyla constituted at least 86.47% of all sequences inside each treatment, and were chosen for the graphical plot (Fig. 3A). Time and land use (NF × OE + YE) in combination influenced the relative abundance of some phyla, including Proteobacteria, Planctomycetes, and Chloroflexi. Verrucomicrobia only differed temporally, and Acidobacteria and Actinobacteria were different among time and seemed to have been impacted by *Eucalyptus* growth (NF and OE × YE). Firmicutes displayed no statistical difference among treatments. An interaction among factors was found for Acidobacteria.

Twenty-six classes were shared among all treatments. The ten most abundant classes constituted at least 81.05% of the sequences of each treatment (Fig. 3B). Gammaproteobacteria, Gp3, and Betaproteobacteria were influenced only by time. Alphaproteobacteria, Planctomycetia, and Spartobacteria were affected by time and land use (NF × OE + YE). Time and *Eucalyptus* growth period (NF + OE × YE) differentiated the relative abundance of Actinobacteria and Gp1. Land use alone impacted Ktedonobacteria. Gp2 displayed a difference in OE compared to the other areas. An interaction among factors was found for Gp1, Gp2, Gp3, and Spartobacteria.

According to the nMDS, *Eucalyptus* areas shared a more similar bacterial community distribution than with NF, despite their high variability (Fig. 4). NF areas showed a lower dispersion among samples, which indicated lower beta-diversity and higher stability compared to *Eucalyptus* areas. Whereas the NF community structure remained very similar from time 1 to 4, YE samples showed high variability and, at time 4, the difference in structure was more pronounced to OE than it was just after cutting. Two-way PERMANOVA test revealed that both

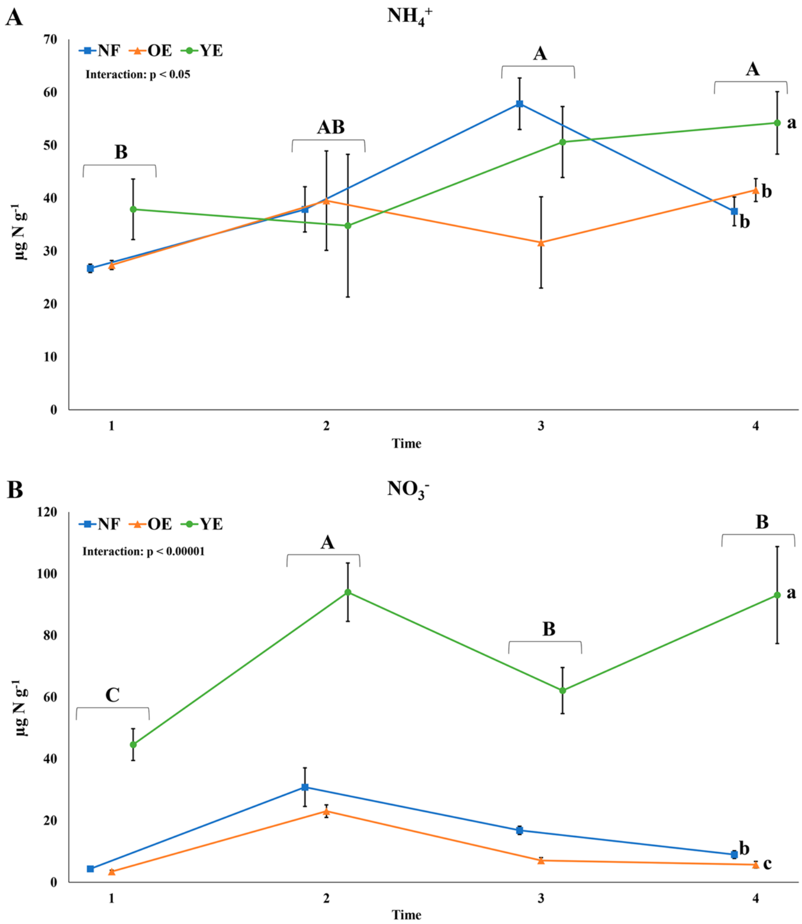

Figure 2. Inorganic N contents (**A**: NH_4^+; **B**: NO_3^-) found in the native forest (NF), old *Eucalyptus* (OE), and young *Eucalyptus* (YE) areas at times 1 (March), 2 (June), 3 (September), and 4 (December). Values represent means, and SEM is given as vertical error bars. Statistical differences are expressed as different upper-case letters for the time factor and as different lower-case letters for the treatment factor (two-way ANOVA followed by Tukey's test; $p < 0.05$).

Alpha diversity	NF.1	NF.4	OE.1	OE.4	YE.1	YE.4
OTU richness	1158 (143)b	1201 (139)b	1458 (131)a	1365 (129)a	1518 (225)a	1289 (66) a
Shannon index	4.93 (0.19)b	5.09 (0.14)b	5.5 (0.19)a	5.58 (0.15)a	5.61 (0.17)a	5.59 (0.09)a

Table 1. Bacterial alpha diversity based on the 16S rRNA gene sequencing from native forest (NF), old *Eucalyptus* (OE) and young *Eucalyptus* (YE) at time 1 (1) and time 4 (4). Values represent the mean of five replicates, with the standard deviation shown in brackets. Statistical differences were found in the treatment factor (two-way ANOVA followed by Tukey's test; $p < 0.05$) and are represented as different letters.

treatment and time factors induced statistical differences among communities, without interaction among the factors. Soil N_2O fluxes vector correlated with NF samples, while inorganic N contents correlated with YE.4 area.

A further analysis of the 49 most abundant OTUs (those with a relative abundance of at least 0.5%) using a blocked Indicator Species Analysis (ISA) was performed. These 49 OTUs represented 52% of the global relative abundance. The analysis revealed that 30 OTUs were impacted by land use (NF × OE + YE), with 20 significantly more abundant in NF areas and 10 in *Eucalyptus* areas. Regarding *Eucalyptus* growth phase effect (OE × YE), 23 OTUs were impacted, with 17 associated with the OE area and six with the YE area. The affected OTUs and their taxonomical affiliations are represented in Fig. 5A,B. The time effect (growth period) showed a clear pattern at the phylum level, with OE indicators belonging to Proteobacteria and Acidobacteria, while YE indicators belonged to Actinobacteria phylum and to Planctomycetes.

Regarding the Archaeal community analysis, the *Nitrososphaera* genus represented 96.7% up to 100% of the sequences in all treatments. Archaeal community showed a pattern like the bacterial community, with *Eucalyptus* areas having a more diverse and rich community than NF area (Supplementary Fig. 3).

To better understand the relationship of prokaryotic community members and our gas and soil monitored variables, Spearman correlations ($n = 30$) was performed among the 49 more abundant bacterial OTUs and

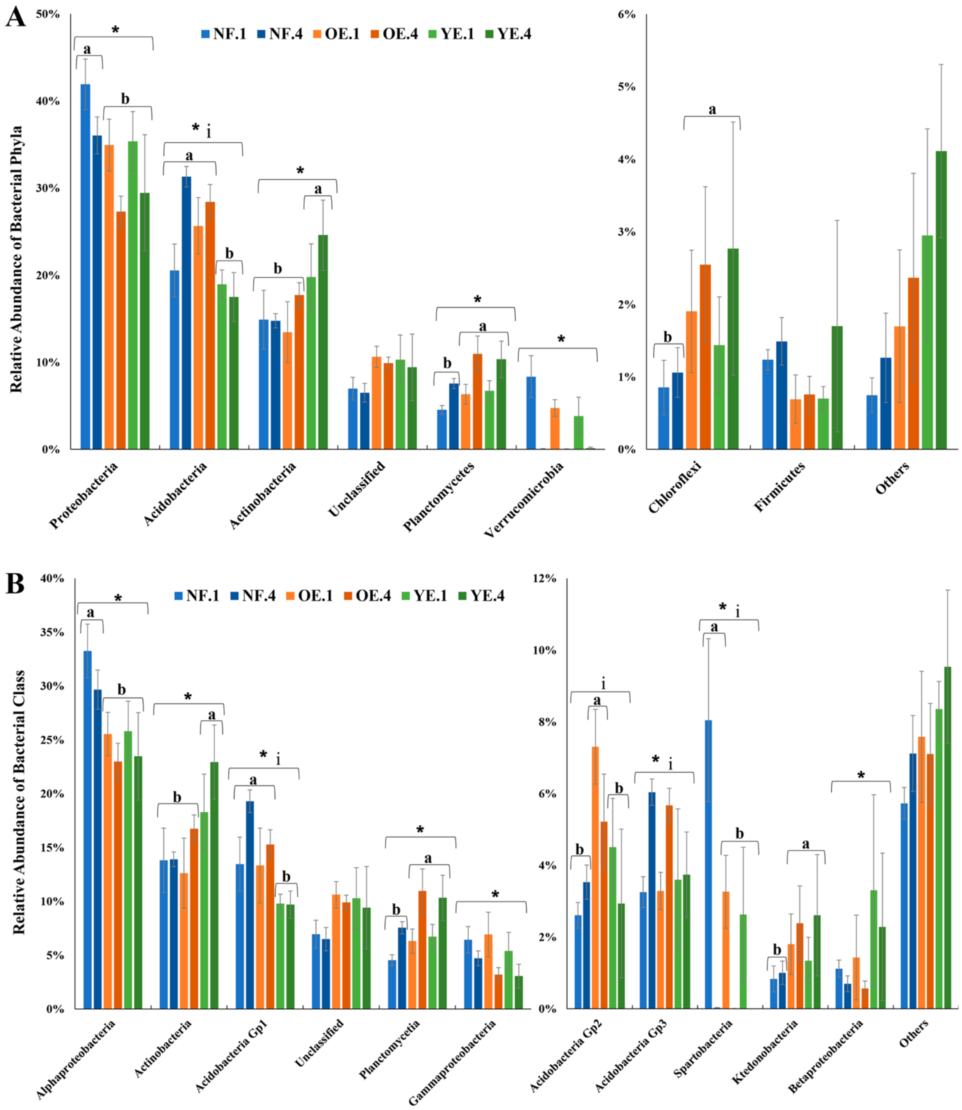

Figure 3. Mean relative abundance of bacterial phyla (**A**) and classes (**B**) in native forest (NF), old *Eucalyptus* (OE), and young *Eucalyptus* (YE) areas at time 1 (1) and time 4 (4). SD is denoted by the vertical error bars. Statistical differences (two-way ANOVA followed by Tukey's test; $p < 0.05$) among treatments are represented as different letters, differences among times 1 and 4 by asterisks, and interactions among factors by the letter i. Taxonomies are given based on the RDP database with a bootstrap value of 80%.

GHG fluxes or inorganic N contents (Table 2). No correlations among the OTUs and GHG were found. Multiple correlations between bacterial OTUs and soil NH_4^+ and NO_3^- contents were obtained. Among the positive correlations with both contents, one OTU was assigned as *Actinoallomurus* genus and one as Actinomycetales order. Three Spartobacteria OTUs negatively correlated with both mineral N forms. Members of the Proteobacteria phylum were all negatively correlated with NH_4^+, with one Gammaproteobacteria, four Rhizobiales, and one *Bradyrhizobium* OTU. A Bradyrhizobiaceae OTU was negatively correlated with NO_3^- content. Two negative and one positive correlations were observed between representatives of the Acidobacteria phylum for NH_4^+ content. A positive correlation among soil NH_4^+ and bacterial diversity was also found (Spearman correlation: NH_4^+ and Shannon index, $p < 0.001$, $r = 0.6$).

Functional profiles of microbial communities. RT-qPCR (RNA-based) and qPCR (DNA-based) approaches were used to evaluate the microbial community metabolic activity and potential. We were unable to quantify transcripts for the genes involved in CH_4 and N cycles, independent of the treatment or time of sample (detection limit was 10^2, data not shown). Replicates showed inconsistency in quantification and several non-specific reactions, demonstrated by dissociation curves and gel electrophoresis, despite the good quality of RNA extracts. As an alternative, traditional qPCR was used, which enabled the assessment of the metabolic potential of the samples (Fig. 6).

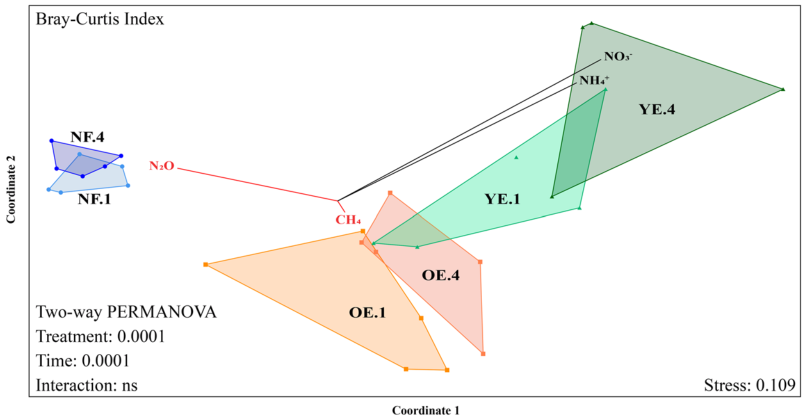

Figure 4. Non-metric multidimensional scaling (nMDS) ordination with Bray-Curtis dissimilarity index of OTU distribution in native forest (NF), old *Eucalyptus* (OE), and young *Eucalyptus* (YE) areas at time 1 (1) and time 4 (4). Red lines represent gas fluxes plotted as vectors. Black lines represent inorganic N. A two-way PERMANOVA test was performed using time and treatment as factors.

All qPCRs were specific, as determined by melting curve analysis and gel electrophoresis from the products. Run data are presented in Supplementary Table 3.

Gene quantification showed that the number of copies of 16 S rRNA gene were lower at time 4 than at time 1 (from approximately 10^{10} to 10^{9} copies; Fig. 6). Ratios of *mcr*A/16S (methanogenesis), *pmo*A/16S (methanotrophy), *nif*H/16S (nitrogen fixation), and *nir*S/16S and *nir*K/16S (denitrification) were also impacted by time. The ratios of *mcr*A/16S and *nif*H/16S decreased from time 1 to 4, while the ratios of *nir*S/16S and *nir*K/16S increased. *pmo*A/16S increased from time 1 to 4 for the *Eucalyptus* treatments, but showed a decrease for NF. The treatment factor affected *pmo*A/16S, AOA/16S (nitrification), *nir*K/16S, and *nos*Z/16S (denitrification). *pmoA/16S* and *nos*Z/16S ratios were different between *Eucalyptus* (YE + OE) and NF; AOA/16S had a difference between NF and OE and *nir*K/16S among NF and YE. No statistical differences among treatments or times for the AOB/16S ratio were detected.

To evaluate if there was a link between gene copy number and the other sampled variables, we tested the number of copies of 16S rRNA gene and gene/16S ratios for correlations with GHG and N contents. Only correlations with N contents were found (Table 3). 16S rRNA gene and *nif*H/16S ratio negatively correlated with N levels in soil, while *nir*K/16S positively correlated with N content levels and *mcr*A/16S ratio negatively correlated with the quantity of NH_4^+ in soil.

Discussion

Considering all sampling times, the studied soil behaved as a CH_4 sink and N_2O source, as previously described for *Eucalyptus* plantations areas[14–17] and tropical forest soils[19]. N_2O fluxes were considerable higher at time 4 (spring; December) in the OE and NF areas. This time point was collected after an extended period of precipitation (Supplementary Fig. 1), which seemed to explain the higher emissions. Time 1 (summer; March), which did not differ statistically from time 4, was during a period of abundant precipitation but not close to a precipitation episode, whereas times 2 and 3 (fall and winter; June and September) were collected during dry periods. CH_4 fluxes did not seem to be explained by collected environmental variables. Similar flux patterns for both gases[17] and for N_2O[14,39] have been observed in planted forests. Although not statistically different, the YE area presented a smaller variation in flux in the different sampling times than the other two well-established tree areas. In other studies involving tropical rain forests, logging differentiated the GHG fluxes among sites[15,40], probably due to an increase in soil bulk density and a decrease in air-filled spaces (YE displayed higher humidity than other areas in our study). This poorly aerated condition may favour heterotrophic and facultative anaerobic bacteria to produce different reduced derivatives of NO_3, as NO_2, NO and N_2O, not only N_2O[41].

The lack of statistical difference in terms of GHG dynamics among the studied areas could also be explained by the high variability within treatment. The different land use did not alter most of the soil physical-chemical characteristics (Supplementary Table 1), which can correlate with GHG flux[42]. The temporal differences of GHG flux are probably the effect of pluviometry, as these soils are poor in nutrients, experience frequent water deficit, are acidic and are high in Al^{+3}, which restricts microbial activity[43,44]. Increased humidity will increase microbial activity and shift the GHG dynamics.

We observed a near-zero net N_2O flux in the NF and OE area at times 2 and 3. Some chambers showed negative fluxes, which have often been reported in the literature, and which is often linked to low NO_3^- content and low O_2 concentrations. As the contribution to N_2O uptake, by reduction to N_2 through the N_2O reductase pathway is short under low supply of NO_3, we speculate that under YE, where the nitrate concentration in soil is high and the emissions of N_2O is also low, others factors are inhibiting the denitrification process or stimulating the N_2O uptake, such as the change ratio of NO_3 and N_2O in soil profile and changes in anoxic microsite (soil structure) or even abiotic reactions of N_2O[45–47] (Flechard *et al*., 2005; Chapuis-Lardy *et al*., 2007; Chalk and Smith, 2020). The nitrous oxide reductase gene quantified by qPCR (Fig. 6) is clear higher in YE than OE (but not different), inside of each season, what in part could explain lower emissions of N_2O, as cited above. Even without

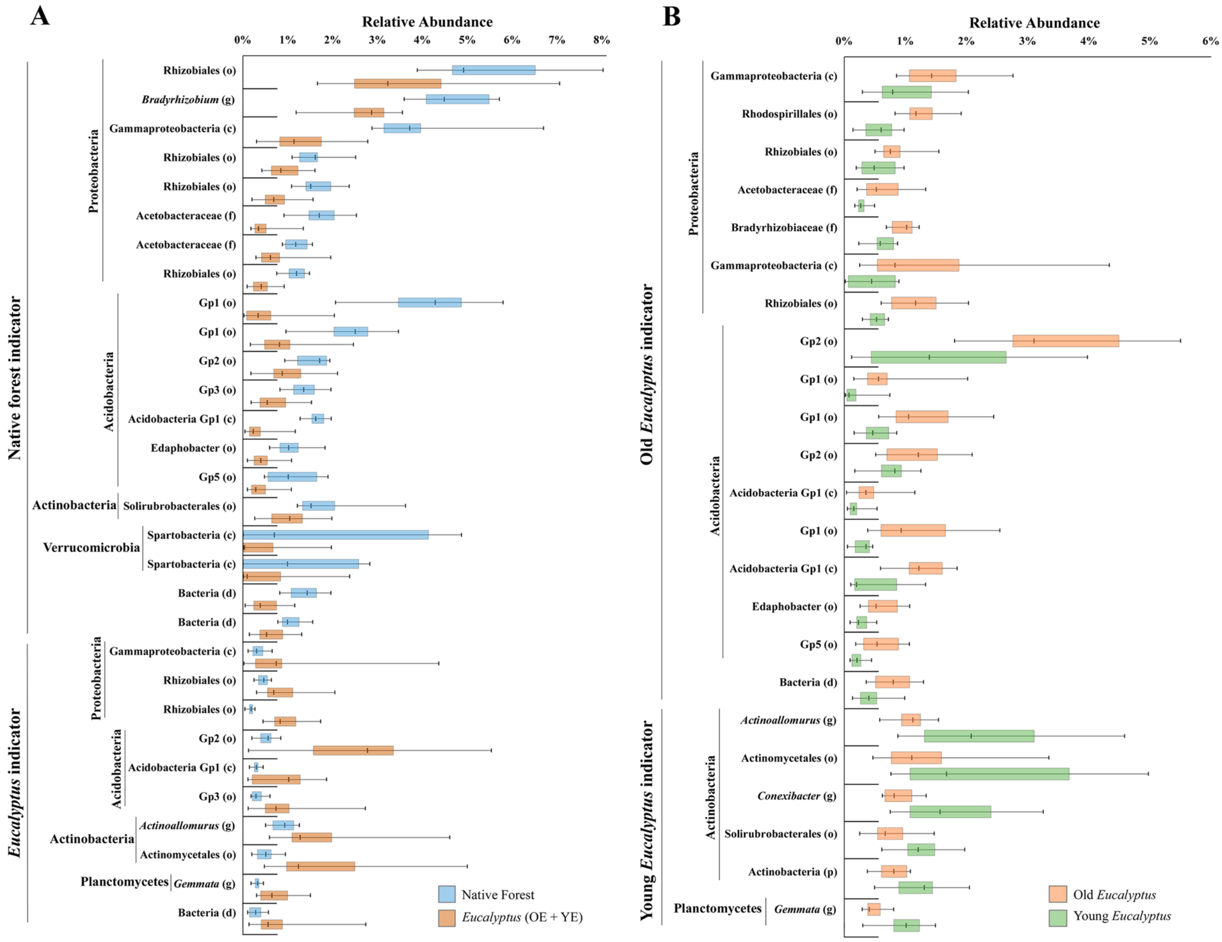

Figure 5. Disparity of relative abundance from the most abundant OTUs among *Eucalyptus* areas versus native (**A**), and old *Eucalyptus* versus young *Eucalyptus* (**B**). OTUs were submitted to a blocked Indicator Species Analysis (ISA). Only those that were significantly different are represented. The finest taxonomy is given (d – domain, p – phylum, c – class, o – order, f – family, g – genus).

Parameter	Phylum	Finest taxonomy	p	R
NH_4^+	Actinobacteria	Actinomycetales (o)	<0.0001	0.93
		Actinoallomurus (g)	<0.001	0.71
	Proteobacteria	Gammaproteobacteria (c)	<0.0001	−0.88
		Rhizobiales (o)	<0.0001	−0.75
			<0.001	−0.74
			<0.001	−0.70
			<0.01	−0.67
		Bradyrhizobium (g)	<0.001	−0.74
	Verrucomicrobia	Spartobacteria (c)	<0.0001	−0.87
			<0.0001	−0.81
	Acidobacteria	Gp1 (o)	<0.01	−0.69
		Acidobacteria Gp1 (c)	<0.05	−0.60
		Gp3 (o)	<0.01	0.63
NO_3^-	Proteobacteria	Bradyrhizobiaceae (f)	<0.01	−0.68
	Actinobacteria	*Actinoallomurus* (g)	<0.01	0.67
		Actinomycetales (o)	<0.01	0.64
	Verrucomicrobia	Spartobacteria (c)	<0.05	−0.61

Table 2. Spearman correlations (n = 30) among bacterial OTUs and inorganic N contents. The table contains only the correlations with $p < 0.05$ (Bonferroni corrected) and $r > |0.6|$ (correlation coefficient). No correlations among GHG fluxes and the bacterial OTUs were found (n = 30). The finest taxonomy is given (d – domain, p – phylum, c – class, o – order, f – family, g – genus).

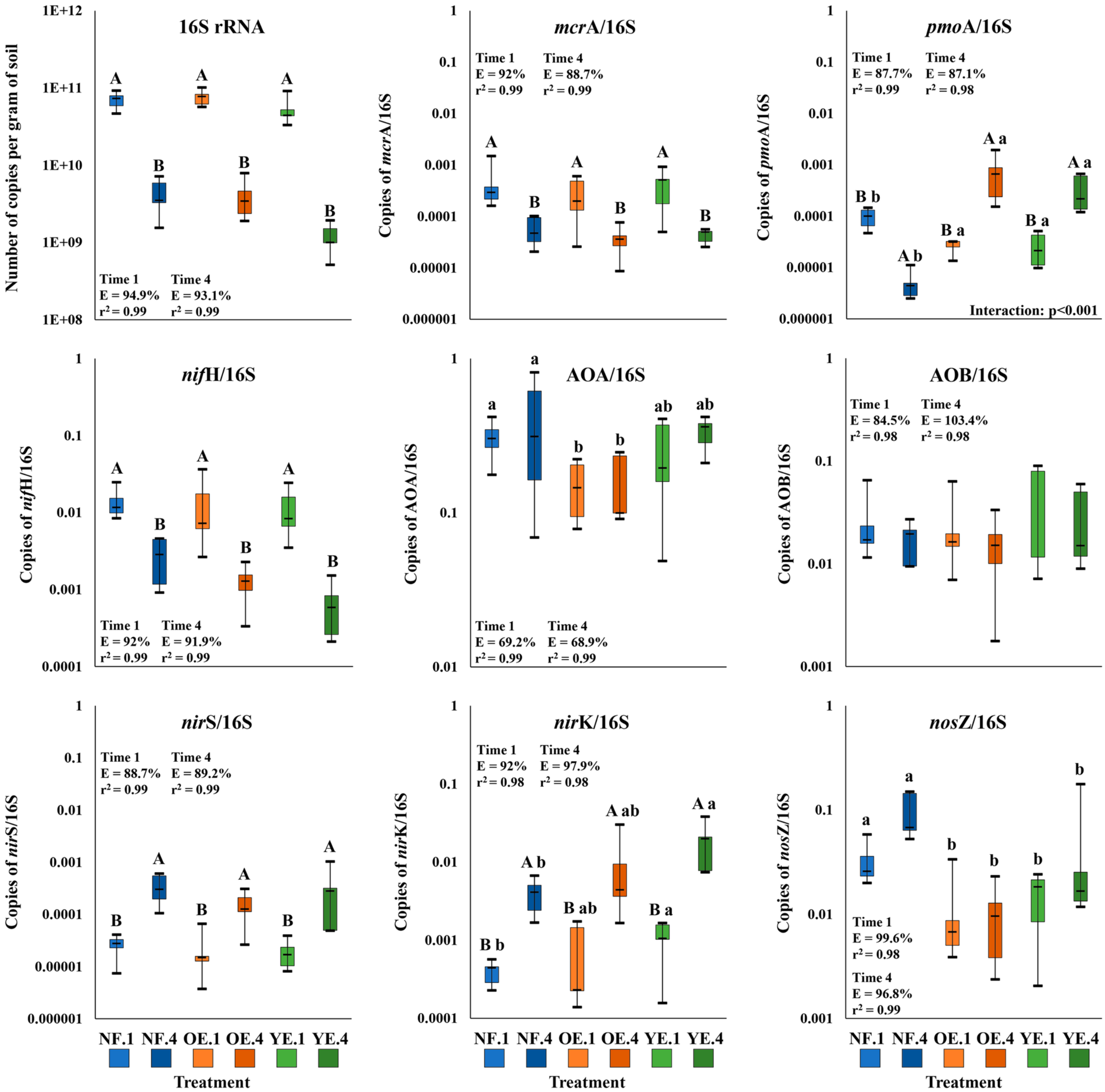

Figure 6. Boxplot graphs of 16S rRNA gene and gene/16S ratios quantified by qPCR in native forest (NF; blue), old *Eucalyptus* (OE; orange) and young *Eucalyptus* (YE; green) areas at time 1 (1; lighter shades) and time 4 (4; darker shades). Statistical differences are expressed as different upper-case letters for the time factor and as different lower-case letters for the treatment factor (two-way ANOVA followed by Tukey's test; $p < 0.05$). Abbreviations are: *mcr*A – methyl coenzyme M reductase subunit alpha, *pmo*A – particulate methane monooxygenase subunit alpha, *nif*H – nitrogenase, AOA – ammonia-oxidising archaea, AOB – ammonia-oxidizing bacteria, *nir*S – cytochrome cd_1-containing nitrite reductase, *nir*K – copper-containing nitrite reductase and *nos*Z – nitrous oxide reductase.

statistic difference, the *nirK* copies involved in nitrite reduction to NO should justify partially the low emissions of N_2O, and probably higher of NO. The regulation mechanisms of this process are still unclear, despite of some advances[46].

Higher inorganic N levels are expected in recently logged sites due to the decomposition of the organic matter of roots and tree residues. The NO_3^- levels in soil are especially enriched in logged soils[40,48]. The lack of appreciable root depth that enables contact with and consumption of NO_3^- might have contributed to the high levels throughout the sampling period. We found no correlations among GHG and inorganic N content in soils, despite the description of the correlation in other studies[16,17,49,50].

Higher bacterial richness and diversity were observed in *Eucalyptus* areas, indicating that land use change increased these indexes. Surprisingly, this trend was observed before deforestation events[51–53], suggesting that the alpha diversity of microbial communities increases as an adaptive response to soil disruption. We did not observe changes in alpha diversity after a 9-month period, which agrees with the theory that soil disturbance effects can

N content	16 s rRNA / gene/16S ratios	p	r
NH_4^+	16S rRNA	<0.0001	−0.78
	*mcr*A/16S	<0.05	−0.52
	*nif*H/16S	<0.0001	−0.74
	*nir*K/16S	<0.0001	0.75
NO_3^-	16S rRNA	<0.001	−0.68
	*nif*H/16S	<0.05	−0.51
	*nir*K/16S	<0.01	0.58

Table 3. Spearman correlations (n = 30) among N contents and copies of 16S rRNA or gene/16S ratios. The table contains only the correlations with $p < 0.05$ (Bonferroni corrected) and $r > |0.5|$ (correlation coefficient). No correlations among GHG fluxes and copies of 16S rRNA or gene/16S ratios were found (n = 30). Abbreviations are *mcr*A – methyl coenzyme M reductase subunit alpha, *nif*H – nitrogenase, and *nir*K – copper-containing nitrite reductase.

persist for a long period[52,54]. We also suggest another theory, in which, paradoxically, areas of *Eucalyptus* monoculture areas harbour a more diverse microbiome when compared to the nearby Atlantic forest, probably due to plant selection or higher primary productivity[55–57], since these areas have undergone *Eucalyptus* rotations since 1978.

Alpha diversity was previously described to be a negative indicator of land use effect, due to its high temporal variability[58]. However, presently the alpha diversity values were consistent, implicating alpha diversity as a good indicator to differentiate the *Eucalyptus* areas from NF. The land use effect over alpha diversity was also supported in another study[53]. It is important to highlight that higher alpha diversity does not necessarily imply more functional diversity in the ecosystem. In a recent study, although land use change seemed to increase 16S rRNA gene diversity, functional gene diversity was decreased in pastures compared to primary and secondary forests[59].

Phyla composition from all treatments resembled those found in a variety of soils, including Cerrado soils[60], *Eucalyptus* monoculture and in mixed plantations with *Acacia mangium*[56], grasslands[61], forests[51,53,62], agricultural soils[53,58], and even samples from Central Park in New York City[63]. Most phyla seem to temporally vary in abundance[53,58,64], as soil is a complex environment that seasonally shifts in many attributes[65,66]. However, the region of study did not vary greatly in terms of temperature during the year, and displayed very distinct patterns in terms of pluviometry, which may explain the slight variances in relative abundances and community structure over time.

A recent meta-analysis included 17 studies that addressed the conversion from forest to agriculture. The findings indicated that the abundances of Proteobacteria and Acidobacteria relative are higher in natural forest soils, while Actinobacteria, Chloroflexi, and Firmicutes showed higher abundance in agricultural soils[67]. Alpha diversity showed an average increase ratio of 1.17 ± 1 fold due to land use change. We observed that Proteobacteria and Chloroflexi followed this trend. However, for Acidobacteria and Actinobacteria, OE behaved just as NF, and no differences were observed for Firmicutes. The considerable differences observed with Verrucomicrobia at times 1 and 4 were due to the near-absence of Spartobacteria class sequences at time 4.

We detected differences in beta-diversity among treatments and between times 1 and 4. Yet, land use (*Eucalyptus* plantation) seemed to impact beta-diversity more than did time and planting renewal. Both land use and management have been associated with differences in beta-diversity[68,69], while land use alone affected beta-diversity in other studies, despite the time of sampling or land management[53,54,58]. Plant selection of the microbial community, fertilization history of *Eucalyptus* areas, soil disruption by harvesting, and differences in soil attributes could be linked to the variation in beta-diversity. It is also interesting that, after a 9-month period, YE samples were further to OE in the ordination, suggesting that it takes an even longer time for the YE microbial community to adapt to the OE structure.

Nitrogen content is correlated with many OTUs. Bradyrhizobiaceae is a family in the Rhizobiales order, which is recognized for its genera of nitrogen fixing bacteria (NFB)[70], including *Bradyrhizobium*. Rhizobiales members were negatively correlated with N content and we found that Rhizobiales representatives were enriched in NF and OE in comparison to YE (as also seen in ISA). This is probably due to lower level of mineral N in these areas, increasing the need for higher abundance of NFB species. *Actinoallomurus* was another bacterial genus that displayed correlation with inorganic N contents. However, all known representatives of *Actinoallomurus* lack mechanisms to use inorganic N[71]. Thus, its enrichment is more likely due an indirect factor, such as higher affinity with plants present in YE areas.

It is important to highlight that all correlations must be interpreted cautiously, as they are based on multiple comparisons with data from field experiments, where many conditions cannot be controlled, increasing the chance of spurious correlations.

Presently, RNA-based qPCR was unsuccessful, However, DNA based qPCR was successfully applied. Soil is frequently an oligotrophic environment, leading to a low level of metabolism of the microbial community. This leads to a higher abundance of DNA gene copies over RNA[72–74]. The soil we studied is acidic with high Al^{3+} levels, is nutrient-poor, and has a water deficit. All these factors inhibit microbial activity. Together, these factors can explain why specific microbial populations could be detected by qPCR but not by RT-qPCR.

We found no correlations among GHG fluxes and gene abundances, even though these correlations have been described[16,75]. Temporal differences in 16S rRNA gene abundances could be explained by N enrichment (as seen by the negative correlation among 16S rRNA gene and the inorganic N content). Decreases of microbial biomass due to N fertilization have been reported[76,77].

Methanotrophic metabolic potential differed by land use. Deforestation in Amazonian soils has been linked to decreases in methanotrophs[78] and methane mono-oxygenase genes in these soils[59,62,78]. Although other studies reported differences in the quantity of the *mcr*A gene following deforestation[62,78], we did not detect alterations in this gene caused by land use change.

We observed average AOA/AOB ratios from 8.3 to 19.9 in treatments. The findings support the description that archaea are the predominant ammonia-oxidizers in acidic soils[79]. It is interesting to note that our archaeal community was dominated by a single genus, *Nitrososphaera*, an AOA found abundantly in soils and some freshwater habitats[80,81].

We detected an increase in *nir*S and *nir*K/16S ratios and a decrease in *nif*H/16S ratio from time 1 to 4, which could indicate that the community is being restructured in response to higher levels of N in these soils. The *nir*K/16S ratio positively correlated with higher levels of both NH_4+ and NO_3^-, while *nif*H correlated negatively, consistent with this theory. Impacts on *nos*Z abundance by land use change were detected presently and previous studies[82–84].

In conclusion, although no considerable differences were found among treatments, the growth phase of the young trees changed the GHG dynamics of the *Eucalyptus* area. Yet, despite *Eucalyptus* plantations are anthropically established, they showed no difference from the nearby native forest in terms of GHG fluxes in our study. Secondly, *Eucalyptus* logging substantially increased the inorganic N content of soil, which was constant over the period of our study, but this phenomenon does not drive the N_2O emissions, probably by the harsh soil chemical conditions. On other hand, *Eucalyptus* areas displayed a richer and more diverse microbial community than the nearby Atlantic forest, which was a consistent indicator of this difference through the 9-month period studied. Land use was the main differentiating factor of the microbial community. Most taxa showed a temporal fluctuation in relative abundances, which could be shaped by the inorganic N content in the soils. Time also influenced the abundance of several genes in soils that were examined, some correlated with inorganic N contents,but it was not found correlation among assayed genes and GHG fluxes.

Planted forests in studied region have GHG emissions inhibited by the high acidity and high aluminum saturation in the soil. The decomposition of crop residues, stimulates nitrification in young eucalyptus plantations, but N_2O emissions remained low. Changes in the structures of the communities indicated by the quantification of the number of copies of the *nir*K and *nos*Z genes, seem to be related to the low N_2O emissions. Metanotrophy prevails over methanogenesis in both plantations and natural forests. More productive sites should be studied so that these findings can be generalized.

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The authors declare no competing interests.

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Integração Lavoura-Pecuária-Floresta no Brasil: uma estratégia de agricultura sustentável baseada nos conceitos da Green Economy Initiative

Crop-Livestock-Forestry Integration in Brazil: a sustainable agriculture strategy based on the concepts of Green Economy Initiative

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ARTIGO - VARIA

RESUMO

Este artigo tem como objetivo inserir a proposta de organização da agricultura baseada nos conceitos da Integração Lavoura-Pecuária-Floresta (ILPF) no âmbito das discussões relacionadas à necessidade de transformação do modelo produtivo vigente. Foram utilizadas as diretrizes e os conceitos relacionados com a Green Economy Initiative (GEI), uma iniciativa do Programa das Nações Unidas para o Meio Ambiente (Pnuma). Busca-se mostrar que a proposta ILPF está alinhada com os aspectos de agricultura sustentável proposta na GEI, e que a ILPF se coloca como uma importante estratégia de aumento da produção agropecuária de forma sustentável para o Brasil. A adoção da GEI é uma estratégia consistente para a implementação de políticas com a finalidade de promover o desenvolvimento sustentável. Dessa forma, a produção agrícola baseada no modelo ILPF alinha-se perfeitamente com as premissas da GEI no que tange à promoção e incentivos a modelos de agricultura de baixo carbono.

Palavras-chave: Agricultura Sustentável. Sistemas Agrossilvipastoris. Agricultura de Baixo Carbono.

ABSTRACT

This article proposes to transform the current production model through the organization of an agricultural system based on the concepts of crop-livestock-forestry integration (ICLF). We used the guidelines and concepts related to the Green Economy Initiative (GEI), a proposal of the United Nations Environment Program (UNEP). Within this framework, the agricultural sector is identified as an important sector due to its strong connection with economic, social and environmental dimensions. We intend to demonstrate that the ICLF proposal is in line with aspects of sustainable agriculture, as proposed by GEI, and that it is an important strategy to increase production in a sustainable manner in Brazil. The adoption of GEI is a consistent strategy for the implementation of policies to promote sustainable development.

Keywords: *Sustainable Agriculture. Agrosilvopastoral Systems. Low Carbon Agriculture.*

1 INTRODUÇÃO

No último século, os impactos ambientais decorrentes das ações humanas levaram a comunidade internacional a inserir na agenda das discussões sobre o futuro do planeta a percepção de que os recursos naturais são finitos. O aumento da população e do consumo está colocando exigências sem precedentes sobre a agricultura e os recursos naturais. Hoje, cerca de um bilhão de pessoas estão cronicamente desnutridas, enquanto os nossos sistemas agrícolas estão ao mesmo tempo degradando a terra, água, biodiversidade e clima em escala global (FOLEY *et al.*, 2011). Esse cenário leva a uma necessidade urgente de um novo paradigma que integre o desenvolvimento contínuo da sociedade e a manutenção do sistema Terra em um estado resiliente (STEFFEN *et al.*, 2015).

O crescimento econômico baseado na utilização intensiva dos fatores de produção ocasionou a alteração de, principalmente, duas das fronteiras planetárias: mudança do clima e integridade da biosfera. Essas fronteiras têm potencial para conduzir o Sistema Terra a um novo estado de equilíbrio (STEFFEN *et al.*, 2015). As fronteiras planetárias incluem processos sistêmicos que se manifestam em escala global e questões ambientais que se tornam problemas globais críticos quando eles são agregados a partir de escala regional ou local (CORNELL, 2012).

No centro dessa questão está a percepção de que esse modelo econômico dificilmente permitirá que as metas contidas na Agenda 2030 (ONU, 2015), bem como os novos Objetivos de Desenvolvimento Sustentável (ODS) (PNUD, 2015), sejam alcançadas.

Dessa forma, percebe-se como necessária uma mudança nos paradigmas relacionados à organização da atividade produtiva em escala global. Diante desse cenário, observa-se que o termo "Economia Verde" tem, recorrentemente, aparecido nas recentes rodadas de discussões sobre os desafios para a promoção do desenvolvimento econômico em base sustentáveis.

Em linhas gerais, o conceito de Economia Verde pode ser entendido como o estabelecimento de um sistema econômico que promova a elevação do bem-estar e a redução das desigualdades sociais ao longo do tempo, tendo como condição essencial a manutenção das condições ambientais vigentes (UNEP, 2011a).

De outra forma, a busca desses objetivos econômicos e sociais não deve implicar na exposição das futuras gerações a consideráveis riscos ambientais, assim como à escassez dos recursos naturais.

Ainda, a organização de um sistema econômico baseado nos preceitos da Economia Verde tem como pontos básicos: direcionar investimentos para setores que desenvolvam e/ou reforcem o capital natural (entendido aqui como sendo composto pela biodiversidade e pelos biomas); atividades que reduzam os riscos ambientais e ecológicos; e mão de obra intensiva, o que se configura como um importante instrumento para a geração de emprego e renda (UNEP, 2011a; UNEP, 2011b).

Considerando os setores prioritários que compõem a agenda da Economia Verde, no presente trabalho focaremos na dimensão da agricultura sustentável, considerada como componente do setor agrícola por meio de atividades de lavoura, pecuária e plantio de florestas. Mais especificamente, discutiremos como o sistema de Integração Lavoura-Pecuária-Floresta (ILPF) pode ser utilizado como estratégia de promoção do desenvolvimento sustentável.

Essa escolha deve-se à participação econômica que o setor agrícola tem em grande parte dos países menos desenvolvidos e em muitos países em desenvolvimento (FAO, 2011; BANCO MUNDIAL, 2011), além de empregar cerca de 1,3 bilhão de pessoas em todo o mundo (FAO, 2011; UNEP 2011a; CEPAL, 2011). Por outro lado, é senso comum que esse setor enfrenta nos últimos anos o desafio de aumentar constantemente a oferta de alimentos e, ao mesmo tempo, preservar os recursos ambientais disponíveis (GRAZIANO DA SILVA, 2010). Nesse sentido, ganham força os modelos de organização da estrutura produtiva agropecuária que estejam fundamentados no pilar: aumento da produção/produtividade e preservação ambiental (BALBINO *et al.* 2011; MARTHA JUNIOR et al, 2011).

Entre as iniciativas existentes, destacam-se no Brasil o Plano Setorial de Mitigação e de Adaptação às Mudanças Climáticas para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura – Plano ABC (BRASIL, 2012); Lei 12.805, de 29 de abril (BRASIL, 2013), que instituiu a Política Nacional de Integração Lavoura-Pecuária-Floresta; e a pretendida Contribuição Nacionalmente Determinada (intended Nationally Determined Contribution – iNDC, da sigla em inglês) (BRASIL, 2015).

REFERENCIAL TEÓRICO

2 GREEN ECONOMY INITIATIVE E A RELEVÂNCIA DO SETOR AGRÍCOLA

A dinâmica econômica dos países evidencia que alguns deles alcançaram altos níveis de desenvolvimento econômico e social. No entanto, esse resultado, na maioria dos casos, teve como contrapartida um elevado passivo ambiental: i) emissão em larga escala de gases de efeito estufa – GEE; ii) poluição atmosférica; iii) degradação dos recursos naturais, com destaque para a poluição dos recursos hídricos; iv) desmatamento; v) fragmentação dos ecossistemas; vi) erosão do solo; vii) alterações das propriedades físicas e químicas do solo; e, viii) extinção de espécies animais e vegetais (ABRAMOVAY, 2000; BALSAN 2006).

Outros países, embora ainda relativamente atrasados em termos econômicos e sociais, também apresentam resultados ambientais parecidos. Ou seja, o modelo de desenvolvimento amplamente adotado, baseado nos preceitos da industrialização moderna, intensificou os impactos das ações do homem nas escalas local, regional e global (FURTADO, 2000, 2003; GRAZIANO DA SILVA, 2010).

Diante dessas questões, iniciativas foram e continuam sendo tomadas no sentido de rediscutir esse padrão de desenvolvimento, em uma tentativa de incorporar pontos relacionados à preservação ambiental, à reversão do passivo ambiental já existente e à valorização de atividades que respeitem o meio ambiente.

O ponto-chave dessa discussão é a construção de um novo paradigma para o processo de desenvolvimento, fundamentado no equilíbrio entre tecnologia e ambiente, de maneira a preservar a qualidade de vida e o bem-estar da sociedade (DA VEIGA, 2008; FURTADO, 2003; GRAZIANO DA SILVA, 2010).

Essa nova perspectiva para o processo de desenvolvimento considera como premissa a habilidade e a capacidade da sociedade em satisfazer suas necessidades do presente sem comprometer as possibilidades das futuras gerações de atenderem as suas próprias necessidades (COMISSÃO MUNDIAL SOBRE MEIO AMBIENTE E DESENVOLVIMENTO, 1988; DA VEIGA, 2008; DINIZ E BERMANN, 2012).

Em linhas gerais, a proposta de adoção de um modelo de desenvolvimento sustentável fundamenta-se na tríade: geração de benefícios econômicos, sociais e ambientais (SACHS, 1986; DA VEIGA, 2008). Nesse sentido, de acordo com a Comissão Mundial sobre Meio Ambiente e Desenvolvimento (1988), os principais objetivos das políticas ambientais e desenvolvimentistas derivados do conceito de desenvolvimento sustentável, são: i) retomar o crescimento econômico como condição necessária para erradicar a pobreza; ii) inovar, permanentemente, os sistemas produtivos, tornando-os mais eficientes, democráticos e menos intensivos em matérias-primas e energia; iii) atender às necessidades humanas essenciais, como emprego, alimentação, energia, água e saneamento; iv) conservar as fontes de recursos naturais; v) valorizar o desenvolvimento tecnológico e administrar os riscos e vi) incluir o meio ambiente no processo decisório.

É nesse cenário de valorização e de reconhecimento da importância dos impactos ambientais da atividade produtiva, do aumento da preocupação com a escassez das reservas de recursos naturais e da crescente preocupação com o legado que esse atual padrão de desenvolvimento pode deixar, que propostas que tenham como pressupostos os preceitos da sustentabilidade passaram a ocupar posição de destaque. Nesse contexto político, ressalta-se a proposta lançada em 2008 pelo Programa das Nações Unidas para o Meio Ambiente (Pnuma) denominada Green Economy Initiative – GEI (UNEP, 2009a).

A GEI pode ser definida como uma proposta de reorganização do sistema econômico com o objetivo de aumentar o bem-estar humano e a equidade social e, ao mesmo tempo, reduzir os riscos ambientais e a degradação do capital natural (UNEP, 2009a; UNEP 2011a). Considerando essas diretrizes, a Economia Verde tem como características ser uma economia que incentiva atividades que promovam um melhor balanço do carbono no sistema, que utilizam de maneira eficiente os recursos disponíveis e que sejam socialmente inclusivas, na medida em que valorizam a promoção de renda, as características estruturais e as capacidades produtivas dos mais pobres (ALMEIDA, 2012; DINIZ e BERMANN, 2012; CECHIN e PACINI, 2012).

A novidade da proposta da Economia Verde é que esta defende políticas ambientais estratégicas integradas, sobretudo políticas de incentivo a inovações tecnológicas ambientais, visando conciliar crescimento econômico com qualidade ambiental e inclusão social (ALMEIDA, 2012). No entanto, para se alcançar de fato uma Economia Verde, é necessário que o impacto ambiental seja reduzido a uma taxa inferior à taxa de crescimento econômico, e isso requer mudanças rápidas e significativas na composição do Produto Interno Bruto – PIB (aumento na participação de serviços) e na eficiência no uso dos recursos naturais (CECHIN e PACINI, 2012).

Assim, a trajetória de desenvolvimento defendida pela GEI tem como premissas a manutenção, o aumento e, quando necessário, a reconstrução do capital natural, considerado, então, como um fator econômico fundamental para a geração desses benefícios sociais, econômicos e ambientais (SEROA DA MOTTA, 2011; SEROA DA MOTTA e DUBEUX, 2011). Esses aspectos são ainda mais relevantes para as pessoas que vivem ou dependem diretamente dos recursos naturais para viver (DINIZ e BERMANN, 2012).

Essa reconfiguração do sistema econômico implica no aumento da participação de atividades e produtos originados de práticas sustentáveis na pauta produtiva (UNEP, 2010c; DINIZ e BERMANN, 2012). A principal hipótese desse argumento é que a busca das metas de melhoria das condições sociais e do meio ambiente também pode proporcionar crescimento do nível de renda, crescimento econômico e melhoria do bem-estar (YOUNG, 2011).

Outro ponto importante é que, de acordo com as diretrizes e os preceitos da proposta GEI, investir nas atividades e nos setores promotores de mudanças estruturais voltadas para a produção de maneira sustentável pode mitigar as emissões de GEE e reduzir a volatilidade do preço das commodities (UNEP, 2009a, 2010a; ALMEIDA, 2012). Ainda, tem-se como premissa que os investimentos do setor público podem ajudar as pessoas e as comunidades mais vulneráveis a se adaptarem à mudança do clima (UNEP, 2011b; SEROA DA MOTTA e DUBEUX, 2011).

Para tanto, esses investimentos devem ser orientados para tornar mais eficiente a utilização de recursos naturais escassos ou ajudar a renovação e/ou restauração destes. A participação cooperativa do setor privado, em especial por meio de investimentos voltados para a promoção de atividades baseadas nos preceitos do desenvolvimento sustentável, é fundamental para a transformação proposta e o estabelecimento de um novo paradigma para o padrão de desenvolvimento (UNEP, 2010a; UNEP 2010b; SEROA DA MOTTA e DUBEUX, 2011). Dessa forma, fortalecer as interdependências entre o meio ambiente e as condições de bem-estar, entre a estabilidade econômica e social, considerando a promoção da rentabilidade e lucratividade dos investimentos privados, são os fundamentos da proposta de promoção do desenvolvimento econômico baseado na GEI.

Como estratégia de planejamento e como forma de possibilitar a transição para um modelo sustentável do ponto de vista econômico, social e ambiental, a proposta GEI identifica como setores-chave para o início do processo de transformação aqueles que promovam ou possibilitem o desenvolvimento e/ou a recuperação do capital natural, assim como aqueles setores que se baseiam em atividades que reduzam os riscos ambientais e ecológicos (SEROA DA MOTTA e DUBEUX, 2011; YOUNG, 2011).

Dessa forma, a implementação das ideias e dos preceitos da GEI perpassa pela valorização e pelo maciço investimento em setores como: i) energia renovável; ii) sistemas de transporte que apresentem baixas emissões de GEE; iii) construções que utilizam energia de maneira eficiente; iv) tecnologias limpas; v) gestão adequada dos recursos hídricos; vi) melhora da oferta de água potável; vii) agricultura sustentável; viii) gestão responsável dos recursos florestais e, ix) melhora no aproveitamento dos recursos pesqueiros (UNEP, 2011a).

Considerando esses setores, a agricultura assume papel diferenciado em função do seu atual cenário em escala global, em especial à solução da equação: aumentar a produção de alimentos e ao mesmo tempo promover a preservação dos recursos naturais, e, também, pela sua relação direta com vários aspectos sociais, econômicos e ambientais. Nesse contexto, vale ressaltar o caráter decisivo e direto da agricultura para o alcance de alguns dos Objetivos de Desenvolvimento Sustentável (ODS) como acabar com a fome, alcançar a segurança alimentar e melhoria da nutrição, promover a agricultura sustentável (ODS 2) e a tomar medidas urgentes para combater a mudança climática e seus impactos (ODS 13).

Reforçando essas características estruturais do setor agrícola e sua importância como atividade produtiva em escala global, de acordo com estatísticas da Organização das Nações Unidas para Alimentação e Agricultura (Food and Agriculture Organization – FAO), aproximadamente 2,6 bilhões de pessoas dependem de atividades relacionadas a sistemas de produção agrícola (FAOSTAT, 2011). Ainda de acordo com informações da FAO, o setor agrícola é o que mais absorve mão de obra em países menos desenvolvidos, colocando-se, nesses países, como o principal setor de ocupação. Outro ponto importante é que esse setor se coloca como o principal gerador de renda para os indivíduos mais pobres.

Tendo em conta esses aspectos, estatísticas do Banco Mundial mostram que o valor agregado da produção agrícola mundial como percentual do PIB gira em torno de 3%, considerando a produção agregada global. Todavia, essa participação apresenta uma correlação negativa com o estágio de desenvolvimento dos países: para o grupo dos países desenvolvidos, a participação média da agricultura é de cerca de 1,5% do PIB, já para os países menos desenvolvidos, esse número é de cerca de 30% (BANCO MUNDIAL, 2011).

Ainda, estimativas do Banco Mundial e do Pnuma indicam que uma variação positiva no PIB derivada de aumentos de produtividade do trabalho no setor agrícola em países em desenvolvimento possui, em média, uma possibilidade cerca de três vezes maior de aumentar a renda do quintil mais pobre da curva de distribuição de renda do que aumentos no PIB, de mesma magnitude, gerados por aumentos de produtividade do trabalho em setores não agrícolas (BANCO MUNDIAL, 2011; UNEP, 2011a).

Outra característica essencial do setor agrícola, que o coloca como um dos principais setores a serem considerados dentro de uma proposta de transformação na estrutura produtiva e no padrão de desenvolvimento, baseado nas diretrizes da GEI, é que esse setor, considerando o atual estágio produtivo e as técnicas empregadas, contribui sobremaneira para a elevação da degradação ambiental por meio da exaustão de recursos naturais e pelo aumento da emissão de GEE, principalmente gás metano (CH4) e óxido nitroso (N2O). Esses efeitos são observados tanto na produção de culturas agrícolas – na utilização de fertilizantes e no manejo das áreas agricultáveis – quanto na pecuária, por meio da utilização de áreas desmatadas e pela emissão desses gases pelo rebanho (VILELA *et al.*, 2008; MENDES e REIS, 2004).

O uso de práticas inadequadas e a utilização intensiva do modelo de produção agrícola baseada no monocultivo tendem a contribuir para a aceleração do processo de degradação das propriedades físicas (densidade, porosidade, estrutura e consistência), químicas (capacidade de troca catiônica, acidez e fertilidade) e biológicas (mesofauna e microrganismos) do solo, além de reduzir a produtividade das culturas, aumentar a ocorrência de plantas daninhas, pragas, doenças e aumentar a perda de solo por erosão (KLUTHCOUSKI *et al.*, 2003; MARTHA JR. *et al.*, 2007b).

Tendo em conta essas especificidades do setor agrícola, torna-se imperativa a criação/aplicação de políticas públicas e ações voltadas especificamente para esse setor no sentido de mitigar seus impactos negativos em termos de contribuição para a degradação do ambiente e, consequentemente, geração de passivos ambientais, mas que, por outro lado, consiga potencializar os efeitos positivos da agricultura em termos de produção sustentável de alimentos e renda, contribuindo assim para a redução da desigualdade social e da pobreza (GASQUES *et al.*, 2010).

O Caso Brasileiro

O Brasil, por meio da Casa Civil da Presidência da República, do Ministério da Agricultura, Pecuária e Abastecimento (Mapa) e da Empresa Brasileira de Pesquisa Agropecuária (Embrapa), vem demonstrando grande interesse na divulgação de práticas de manejo que proporcionem a mitigação das emissões de GEE e a ampliação de áreas de produção que utilizem tecnologias mais sustentáveis.

Após a 15ª Conferência das Partes da Convenção-Quadro das Nações Unidas sobre Mudança do Clima (COP-15), o Governo brasileiro indicou, de maneira voluntária, ações de mitigação da mudança do clima que o País pretendia adotar. O potencial da redução das emissões de gases de efeito estufa (GEE) resultantes dessas ações é de 36,1% – 38,9% em relação às emissões brasileiras projetadas até 2020, de acordo com a Lei 12.187/2009.

O art. 11 dessa Lei prevê a criação de Planos Setoriais de mitigação e de adaptação às mudanças climáticas visando à consolidação de uma economia de baixo consumo de carbono. Esses planos deveriam ser elaborados considerando as especificidades de cada setor, inclusive por meio do Mecanismo de Desenvolvimento Limpo – MDL e das Ações de Mitigação Nacionalmente Apropriadas – Namas.

O Plano Setorial da Agricultura é o Plano ABC que é baseado na ampliação da adoção de tecnologias, da seguinte forma: i) recuperação de 15 milhões de hectares de pastagens degradadas; ii) sistema de Integração Lavoura-Pecuária-Floresta e sistemas agroflorestais em 4 milhões de hectares; iii) Sistema Plantio Direto na palha em 8 milhões de hectares; iv) fixação biológica de nitrogênio (FBN) em 5,5 milhões de hectares de áreas de cultivo, em substituição ao uso de fertilizantes nitrogenados; v) plantio de florestas em 3 milhões de hectares e, vi) tratamento de 4,4 milhões de m3 de dejetos de animais.

Em 2015, o Brasil apresentou à Convenção-Quadro das Nações Unidas sobre Mudança do Clima a sua proposta de pretendida Contribuição Nacionalmente Determinada (iNDC), no contexto das negociações de um protocolo, outro instrumento jurídico ou resultado acordado com força legal sob a Convenção, de maneira a contribuir para a concretização do que veio a ser chamado de Acordo de Paris, pelas negociações da COP-21, em dezembro/2015.

Nessa ação, o Brasil apresentou as seguintes propostas adicionais de redução de emissões de gases de efeito estufa: aumentar a participação de bionergia sustentável na matriz energética; fortalecer o Código Florestal; promover o desmatamento ilegal zero até 2030; reflorestar 12 milhões de hectares; alcançar uma participação estimada de 45% de energias renováveis na composição da matriz energética até 2030; além de ações nos setores industrial e de transporte.

A iNDC também deu destaque ao setor agrícola, com objetivo de fortalecer o Plano de Agricultura de Baixa Emissão de Carbono (Plano ABC) como a principal estratégia para o desenvolvimento sustentável na agricultura, inclusive por meio da restauração adicional de 15 milhões de hectares de pastagens degradadas e pelo incremento de 5 milhões de hectares de sistemas de Integração Lavoura-Pecuária-Floresta, ambos até 2030.

Essa inclusão adicional de áreas com ILPF reforça a importância do sistema na busca pela intensificação sustentável da produção agrícola e mostra a relevância dessa tecnologia para o Governo brasileiro.

Observações sobre o Plano ABC

O Plano ABC encontra-se em acordo com os termos do Pnuma uma vez que possui forte atuação nas questões sobre mudança do clima, gestão de ecossistemas e biodiversidade, uso eficiente de recursos, consumo e produção sustentáveis, além de apresentar diretrizes para a governança ambiental contribuindo, assim, para a troca de informações e experiências entre os setores público, privado e acadêmico.

Além disso, apresenta como diretriz o uso de tecnologias para aumentar a produtividade agropecuária e reduzir custos de produção, melhorando o nível de renda e promovendo a diminuição de emissão de GEE por meio de práticas agrícolas sustentáveis, mudanças adaptativas no processo produtivo e transferência de tecnologias. O Plano ABC apresenta estratégias diferenciadas que estimulam a diversidade da produção, a autonomia tecnológica e a produção ecologicamente sustentável, visando garantir não apenas a viabilidade da agricultura, mas, sobretudo, a segurança alimentar do País (BRASIL, 2012).

Desde a implementação do Plano ABC, em 2012, a expansão tanto em área quanto em número de contratos da adoção e/ou uso de tecnologias para mitigar emissões de GEE tem aumentado notavelmente em cada ano-safra. Entretanto, esses números estão aquém do compromisso voluntário brasileiro assumido na COP-15. Nesse sentido, é preciso aprofundar as ações previstas no Plano ABC associadas à adoção de tecnologias sustentáveis para que as metas sejam alcançadas (ASSAD, 2013).

De 2011/12 a 2014/15, de acordo com dados do Observatório ABC (2016), o número total de contratos foi de pouco mais de 43 mil, sendo a região Sudeste responsável por grande parte (cerca de 16 mil contratos), seguida pelo Centro-Oeste, Sul, Nordeste e Norte. Do total de contratos, quase 9 mil estão distribuídos em programas de plantio direto, ILPF, fixação biológica de nitrogênio, recuperação de áreas degradadas, florestas plantadas e manejo de dejetos.

Segundo Assad (2013), das tecnologias previstas no programa, desde a implementação do Plano ABC, 41% dos recursos financiados foram para recuperação de pastagens degradadas; 7% foram para ILPF; 22% para Sistema de Plantio Direto; 14% para florestas plantadas; e 16% para outros. A explicação para a baixa adesão aos sistemas ILPF pode ser devido, entre outros fatores, à sua alta complexidade de implementação no campo.

No entanto, por ser uma das tecnologias com maior potencial de redução de emissão de GEE, entende-se que sua adesão deve ser maximizada. De acordo com as estimativas do Plano ABC, a ILPF possui um potencial de mitigação de 5 Mg CO2e ha-1, muito a frente do Sistema Plantio Direto (2,25 Mg CO2e ha-1) e da fixação biológica de nitrogênio (1,8 Mg CO2e ha-1) e só atrás da recuperação de pastagens degradadas (6,2 Mg CO2e ha-1). Entretanto, apesar desses números constarem em uma política pública nacional, eles ainda carecem de mais estudos, principalmente devido à enorme gama de sistemas de produção e características de solos, climas e manejos presentes no País. Dados específicos para cada situação representativa devem ser desenvolvidos para termos uma maior precisão do real potencial de mitigação de cada tecnologia.

O público-alvo do Programa é de cerca de 5 milhões de propriedades agrícolas, com pelo menos 1,8 milhão de agricultores familiares. Entretanto, o Plano ABC parece não ser competitivo para o agricultor familiar. Desde a concepção do Programa ABC (a linha de crédito concedida pelos bancos para implantação das tecnologias do Plano ABC), havia uma tendência a estimular que agricultores considerados não familiares adotassem práticas que já vinham sendo estimuladas na agricultura familiar, por meio do Pronaf, que possui taxa de juros mais atrativa que o programa ABC.

3 O SISTEMA INTEGRAÇÃO LAVOURA-PECUÁRIA-FLORESTA NO BRASIL

Para atender a futuras necessidades de segurança alimentar e de sustentabilidade do mundo, a produção de alimentos deve crescer substancialmente, enquanto, ao mesmo tempo, a pegada ambiental da agricultura deve diminuir acentuadamente (FOLEY *et al.*, 2011). Aliar aumentos constantes de produção/produtividade com preservação e recuperação ambiental, promovendo uma intensificação sustentável da produção, é o atual desafio do setor agrícola (SMITH, 2015).

A crescente demanda por alimentos de qualidade, o aprofundamento das discussões referentes aos impactos ambientais da agricultura e um mercado consumidor cada vez mais consciente são aspectos que caracterizam e desafiam a atividade agropecuária contemporânea.

Para atender ao aumento da demanda por alimentos, os produtores necessitam aumentar a área plantada, aumentar a produtividade ou implementar uma estratégia que combine essas duas alternativas. Entretanto, no contexto atual, em virtude de uma crescente valorização das práticas sustentáveis, há nítida preferência pela expansão da produção por meio de ganhos continuados em produtividade, baseados na intensificação do uso da terra em áreas já ocupadas. Essas questões fomentam a busca por um novo paradigma de sustentabilidade para a agricultura (SACHS, 1986; VILELA *et al.*, 2008; UNEP 2009a, 2011a).

É nesse contexto que se encontra a proposta de organização do sistema produtivo baseado no modelo de ILPF. Esse sistema tem como princípio básico a produção sustentável por meio da integração de atividades agrícolas, pecuárias e florestais, realizadas em uma mesma área, em cultivo consorciado, em sucessão ou rotacionado, buscando efeitos sinérgicos entre os componentes do agroecossistema, contemplando a adequação ambiental, a valorização do homem e a viabilidade econômica (BALBINO *et al.*; 2011; MACEDO 2009; NAIR, 1991).

A principal premissa da ILPF é a de ser um sistema de produção agrícola sustentável ao longo do tempo (PORFÍRIO-DA-SILVA, 2007; KLUTHCOUSKI *et al.*, 2003; MARTHA JR. *et al.*, 2007b).

Os sistemas de ILPF possuem como uma de suas características principais a possibilidade de recuperação de áreas degradadas por meio da intensificação do uso da terra, potencializando os efeitos complementares e/ou sinergéticos existentes entre as diversas espécies vegetais e a criação de animais, proporcionando, de forma sustentável, uma maior produção por área.

Esses sistemas otimizam o uso do solo, com a produção de grãos em áreas de pastagens, e melhoram a produtividade das pastagens em decorrência de sua renovação pelo aproveitamento da adubação residual da lavoura, possibilitando maior ciclagem de nutrientes e o incremento da matéria orgânica do solo (TRECENTI *et al.*, 2008; VILELA *et al.*, 2008; MARTHA JR. e VILELA, 2009).

Ademais, os sistemas ILPF se apresentam como sistemas em busca da sustentabilidade, pois preconizam: i) a utilização dos princípios do manejo e conservação do solo e da água; ii) o respeito à capacidade de uso da terra e ao zoneamento climático agrícola; iii) o manejo integrado de pragas, doenças e plantas daninhas; iv) a otimização na utilização dos recursos de produção; v) o Sistema de Plantio Direto (SPD); e, como característica central, vi) o sinergismo entre lavoura, pecuária e floresta (KLUTHCOUSKI *et al.*, 2003; PORFÍRIO-DA-SILVA, 2007; PORFÍRIO-DA-SILVA, 2010).

Muitos estudos apontam sobre os benefícios de sistemas integrados, como a ILPF: aumento da fertilidade do solo, devido ao acúmulo de matéria orgânica; melhoria da ciclagem de nutrientes (FLORES *et al.*, 2008; CARVALHO *et al.*, 2010); redução de pragas, doenças e ervas daninhas, diminuindo assim os custos de produção, aumentando os resultados econômicos e ambientais – causados pela rotação de culturas – (LAZZAROTTO *et al.*, 2009; MARTHA JR. *et al.*, 2011) e redução do risco ambiental pelo uso reduzido de insumos agroquímicos (VILELA *et al.*, 2008).

De acordo com Castro *et al.* (2008), a adoção de sistemas agroflorestais – agrosilvipastoris e sistemas silvipastoris – com culturas anuais, florestas e pastagens, reduzem os efeitos negativos causados pelas altas temperaturas do clima tropical sobre os animais e melhora a utilização dos recursos naturais, com o consequente aumento de produtividade e redução do custo de produção.

Esse novo paradigma de organização da estrutura produtiva agropecuária coloca-se como um instrumento-chave para a manutenção do Brasil como um dos principais atores no cenário mundial da produção agrícola e ao mesmo tempo permite reverter o avançado processo de degradação ambiental das áreas cultivadas, em especial, nas áreas de pastagens do Cerrado brasileiro (MARTHA JR. *et al.*, 2007a, 2007b).

Ademais, a degradação de pastagens gera, em adição às dificuldades econômicas, problemas ambientais, e pode também suscitar, com o tempo, impactos sociais indesejáveis como o aprofundamento da pobreza e da concentração de renda em áreas rurais (MARTHA JR. *et al.*, 2007a).

Esses trabalhos apontam que os sistemas ILPF possibilitam aumento da eficiência produtiva, incremento em conservação e qualidade do solo, aumento e diversificação da renda para o produtor, conservação de água, aumento do rendimento animal pelo conforto térmico, mitigação das emissões dos gases de efeito estufa, potencial de adaptação aos efeitos da mudança do clima, recuperação de áreas degradadas por meio da intensificação do uso da terra, potencializando os efeitos complementares ou sinergéticos existentes entre as diversas espécies vegetais e a criação de animais, proporcionando, de forma sustentável, uma maior produção por área (SCHROEDER, 1993; KLUTHCOUSKI *et al.*, 2003, 2006; PORFÍRIO-DA-SILVA, 2007; TRECENTI e HASS, 2008; LAZZAROTTO *et al.*, 2009).

DISCUSSÃO

4 PRÓXIMOS PASSOS E O QUE SE ESPERA

De forma geral, os trabalhos que procuram avaliar os impactos econômicos dos sistemas ILPF apresentam como objeto de análise os aspectos individuais do produtor e da produção, ou seja, são voltados para características e problemas encontrados dentro da propriedade, não enfatizando em profundidade questões relacionadas à interação desta com o meio no qual está inserida.

Refletindo esse viés de análise e de acordo com Martha Jr. *et al.* (2010), tem-se que o foco dos estudos econômicos sobre sistemas ILPF tem sido: i) avaliar as possibilidades de redução dos custos unitários de produção, em função das interações entre as culturas; ii) avaliar o aspecto de minimização dos riscos e vulnerabilidades dada a característica de diversificação da produção proporcionada pelo sistema; iii) avaliar a variação da rentabilidade nas diferentes combinações de sistemas de produção integrada e, por fim, iv) potencialidades relacionadas ao aumento de produtividade por unidade de área. Dessa forma, dentro de uma perspectiva privada e individual, os benefícios econômicos do sistema ILPF se concentrariam na possibilidade de aumentar a oferta com custos de produção unitários menores.

Todavia, novos campos de pesquisa vêm ganhando espaço nessa discussão, indicando que os benefícios socioeconômicos e ambientais advindos do sistema integrado vão além da perspectiva individual, e que uma análise mais ampla desse sistema, que procure avaliar suas interações com o meio no qual ele está inserido, é necessária.

Nesse sentido, pode-se destacar as iniciativas de pesquisa que analisam as possíveis externalidades socioeconômicas e ambientais positivas da tecnologia ILPF como a possibilidade de geração de trabalho e renda no campo; a potencialidade de redução do avanço da fronteira agrícola – efeito poupa-terra; o potencial de mitigação de emissão de GEE e do aumento no estoque de carbono do solo; o potencial de adaptação do sistema produtivo a climas futuros, mais quentes e secos, com maior intensidade e frequência de eventos extremos como El niños, La niñas e veranicos; a maior eficiência no uso de insumos – agroquímicos e fertilizantes – e o potencial para a redução de perdas de água e de solo.

Destaca-se, também, o potencial de redução de emissão de metano pelo processo de fermentação entérica de animais ruminantes em pastejo, devido à maior qualidade dos pastos e os prováveis ganhos em termos de quantidade e de qualidade de forragem em comparação à pecuária tradicional (KLUTHCOUSKI *et al.*, 2003, 2006; MARTHA JR., 2010).

Entretanto, essa perspectiva de análise mais ampla, focada nos potenciais efeitos do sistema integrado sobre as características da produção, sobre as condições de vida do produtor, assim como sobre as externalidades socioeconômicas e ambientais dos modelos ILPF, ainda carece de aprofundamento e precisa incorporar aspectos mais gerais e, em certo sentido, anteriores à implementação e difusão dessa tecnologia.

Para tanto, é necessário desenvolver abordagens interdisciplinares, flexíveis, que considerem diferentes escalas territoriais e que possibilitem identificar e avaliar os potenciais efeitos positivos, em termos socioeconômicos e ambientais, já identificados, do sistema integrado em relação a modelos produtivos baseados em monoculturas, além de possibilitar a identificação de novos efeitos como, por exemplo, a possibilidade de exploração econômica de serviços ambientais. Um ponto importante é que esses métodos permitiriam avaliar em que medida essa proposta de organização da atividade produtiva baseada na integração de sistemas pode representar uma estratégia de desenvolvimento local.

Esse último aspecto é central, pois uma mudança estrutural na organização da produção agropecuária, como a proposta ILPF, requer um amplo aparato econômico, social e institucional na medida em que esse sistema produtivo permite mobilizar várias atividades econômicas simultaneamente, requerendo um elevado nível de conhecimento por parte do produtor. Ademais, a adoção de um sistema integrado implica na utilização de tecnologias de ponta, permitindo uma maior agregação de valor da produção, além de possibilitar uma maior integração setorial. Isso induziria a um processo de desenvolvimento local baseado em um processo de crescimento econômico elevado, contínuo, e orientado para a diminuição das disparidades socioeconômicas.

5 CONSIDERAÇÕES FINAIS

A adoção da GEI coloca-se como uma estratégia consistente para a implementação de políticas com a finalidade de promover o desenvolvimento sustentável. A GEI reconhece que a finalidade da adoção de uma agenda voltada para o estabelecimento de uma trajetória de desenvolvimento em bases sustentáveis é a promoção do bem-estar social tendo em conta a perspectiva de que os recursos naturais são finitos, o que inclui, necessariamente, incorporar à agenda político

-econômica medidas para mitigar os efeitos e as causas negativas da mudança do clima, da falta de energia e da degradação ambiental.

Contudo, é importante ter em conta que a GEI não deve ser interpretada como uma estratégia voltada, exclusivamente, para a eliminação dos problemas ambientais associados às atividades produtivas. Ao contrário, ela deve ser interpretada como uma alternativa que tem como fim a promoção do desenvolvimento sustentável, com o incentivo ao bem-estar e voltada para o combate à pobreza. E essa é uma temática central, pois observa-se, atualmente, o afloramento de diversos conflitos que apresentam como fundamento questões como renda, emprego, desigualdade de renda e acesso a recursos como água e terra.

Considerando a proposta GEI, assim como os setores por ela identificados como os mais relevantes para a implementação do processo de mudança estrutural necessário, tem-se o setor agrícola como elemento-chave dessa transformação. A solução da complexa equação de aumentar a oferta de alimentos respeitando as restrições impostas pelos fatores ambientais coloca-se como um dos principais desafios para a sociedade. Nesse sentido, muito se tem investido e pesquisado com o propósito de encontrar alternativas sustentáveis para a produção de alimentos.

O sistema ILPF pode ser considerado como uma dessas alternativas. Em que pese o fato dessa proposta de reestruturação da atividade produtiva agropecuária ainda requerer maiores estudos, suas potencialidades em termos econômicos, sociais e ambientais o credencia como uma possibilidade de superação do paradigma de intensificação do uso dos fatores de produção baseado na utilização predatória dos recursos naturais. Além disso, a proposta ILPF tem como premissa a geração de renda e a manutenção do homem no campo. Aspectos fundamentais para a construção de estratégias de superação da condição de pobreza das pessoas que são oriundas da área rural.

Dessa forma, a estratégia de organização da produção agrícola baseada no modelo ILPF alinha-se perfeitamente com as premissas da GEI no que tange à promoção e incentivos a modelos de agricultura sustentável. Ademais, considerando os resultados iniciais, esse sistema pode fortalecer a posição de liderança do Brasil em diversos segmentos produtivos relacionados com a produção agropecuária, além de possibilitar o estabelecimento de um novo paradigma para a organização do sistema de produção agrícola.

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International climate change negotiation: the role of Brazil

Negociação internacional da mudança do clima: o papel do Brasil

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ARTICLE- VARIA

ABSTRACT

The increase of greenhouse gases in the atmosphere raises the average temperature of the planet, triggering problems that threaten the survival of humans. Protecting the global climate from the effects of climate change is an essential condition for sustaining life. For this reason, governments, scientists, and society are joining forces to propose better solutions that could well-rounded environmentally, social and economic development relationships. International climate change negotiations involve many countries in establishing strategies to mitigate the problem. Therefore, understanding international negotiation processes and how ratified agreements impact a country is of fundamental importance. The purpose of this paper is to systematize information about how climate negotiations have progressed, detailing key moments and results, analyzing the role that Brazil played in the course of these negotiations and the country's future perspectives.

Keywords: Intergovernmental Panel on Climate Change. United Nations Framework Convention on Climate Change. Conference of the Parties. Sustainable Development. Low Carbon Agriculture.

RESUMO

O aumento dos gases de efeito estufa na atmosfera eleva a temperatura média do planeta, desencadeando problemas que ameaçam a sobrevivência do ser humano. A proteção do clima global frente aos efeitos das mudanças climáticas é uma condição essencial para a sustentação da vida. Por essa razão, governos, cientistas e a sociedade estão unindo forças para propor melhores soluções que possam agregar relações de desenvolvimento ambiental, social e econômico. As negociações internacionais sobre a mudança do clima envolvem muitos países no estabelecimento de estratégias para a mitigação do problema. Portanto, entender os processos internacionais de negociação e de que maneira os acordos ratificados impactam um país são de importância fundamental. O objetivo deste artigo é sistematizar informações sobre como as negociações têm procedido, detalhando momentos chave e os resultados, analisando o papel que o Brasil desempenhou no decorrer dessas negociações e as perspectivas futuras do País.

Palavras-Chave: Painel Intergovernamental em Mudança do Clima. Convenção-Quadro das Nações Unidas sobre Mudança do Clima. Conferência das Partes. Desenvolvimento Sustentável. Agricultura de Baixo Carbono.

1 INTRODUCTION

In 1988, the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC), an intergovernmental body of the United Nations with the purpose of scientifically evaluating the possible socioeconomic and environmental impacts of climate change and formulating realistic strategies to deal with the problem (MIGUEZ, 2002). Their reports are essential to recognizing the effect of greenhouse gases (GHG) on the climate system. The first IPCC assessment report, AR1, was published in 1990 and featured work on two items: (a) evaluation of how developing countries could increase their participation and cooperation with IPCC work and (b) elements for implementing future work on international cooperation within the theme (IPCC, 1990).

The Second World Climate Conference (WCC), held in Geneva in 1990, was the starting point for discussions on the establishment of the United Nations Framework Convention on Climate Change

(UNFCC) (hereinafter referred to as the Convention), a treaty between almost every country in the world setting the principles, norms, roles and cooperation between the parties for decision-making on climate change. The Intergovernmental Negotiating Committee for the Convention was established in the same year at the United Nations General Assembly, and the participating countries signed the document at the United Nations Conference on Environment and Development (Rio 92) in 1992 (MENDES, 2014). Brazil was the first country to sign the agreement and had a significant presence in international environmental articulations and debates.

The Convention that was implemented in 1994 convenes the participating countries once a year at the Annual Conference of the Parties (COP), which features discussions, debates, results, agreements, and decision-making on the challenges of economic development, environmental maintenance and social problems in the face of climate change (CENCI, 2020).

The Convention follows the principle of multilateralism, which is contained in the UN Charter, and considers that each signatory country is a party to the agreement (hence the term "Conference of the Parties") and that any decision taken must be consensual, not determined by a simple majority of votes. Moreover, decisions are part of a global agreement of interest to all Parties. In the language of negotiation: "nothing is decided until everything is decided" (UNFCCC, 1992).

For its time, considering the lack of full knowledge about the processes and impacts of climate change, the text of the Convention brought significant advances to the discussion of the environment. The Convention recognized, amongst other points, that (UNFCCC, 1992):

- Earth's climate change and its adverse effects are a common concern of humanity;
- The largest share of global, historical and current emissions of greenhouse gases originates in developed countries;
- Per capita emissions from developing countries are still relatively low, and the share of global emissions from developing countries will grow so that they can meet their social and development needs.

Moreover, the ultimate objective was to "achieve stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992, p4). The text further warned that such a level should be achieved within a sufficient period to enable ecosystems to adapt naturally to climate change, ensure that food production is not threatened, and enable economic development to proceed sustainably.

The Convention imposed a set of targets for GHG emission reductions for some countries, mainly the developed ones, listed in the Convention Annex I. The Convention did not impose initial emission reduction targets for developing and least developed countries (UNFCCC, 1992), because the developed countries accounted for most of the emissions, most of the concentration of gases in the atmosphere, and the rise in the average temperature of the planet. Further, Annex I listed countries were required to promote policies and measures for the reduction of emissions to reach the emission level of the year 1990, a commitment that has not been achieved.

The Convention still contains two fundamental principles for the consolidation of international negotiation and sustainable development, especially in developing countries (UNFCCC, 1992):

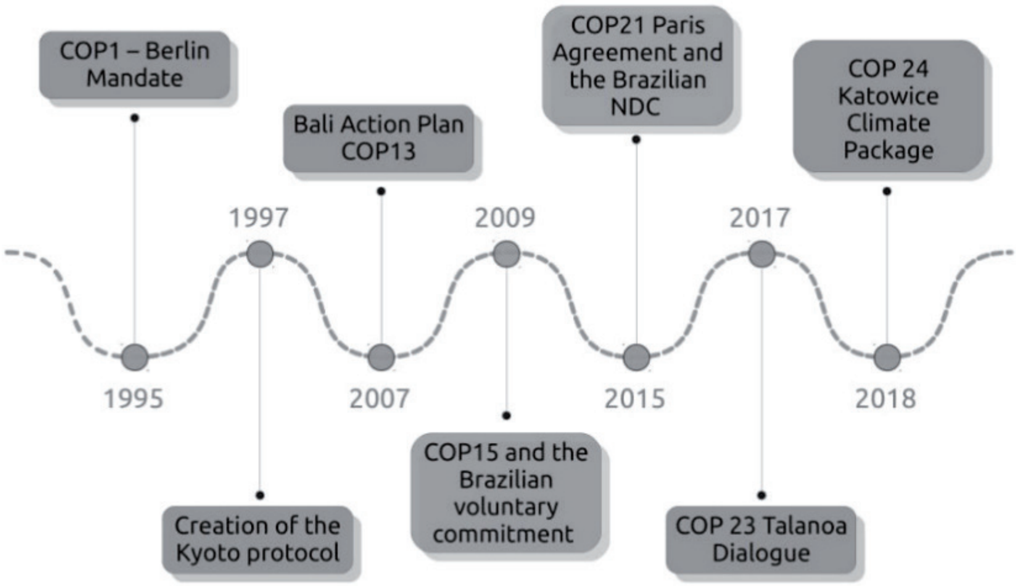
- Precautionary Principle: Lack of full scientific certainty should not be used as a reason for countries to postpone measures to predict, prevent, or minimize the causes of climate change and mitigate its adverse effects.
- Principle of Common but Differentiated Responsibilities: Parties shall protect the climate system for the benefit of present and future generations based on equity and following their common but differentiated responsibilities and respective capabilities. In this regard,

developed country Parties should take the lead in addressing climate change and the adverse impacts of climate change.

The Convention, through the Principle of Common but Differentiated Responsibilities, proposed a series of commitments common to all signatory Parties, such as:

- Preparation of a National Communication, containing the inventory of anthropogenic GHG emissions by gas and economic sector;
- Promotion of mitigation and adaptation programs;
- Development of technologies for emission reduction and prevention;
- Protection of carbon sinks, such as forests and oceans;
- Consideration of climate change in social, economic and environmental policies;
- Promotion of scientific research on climate change;
- Promotion of education, training and awareness actions.

A plethora of decisions and documents have been produced throughout the more than 20 years of negotiation. This paper will explore seven crucial moments that occurred during this extensive process of negotiations and future perspectives of Brazil's role in international negotiations. In chronological order (Figure 1) we will present and discuss the main issues of the first COP and the Brazilian Proposal;



the creation of the Kyoto Protocol; the Bali Action Plan; COP15 and Brazil's voluntary commitment; COP21, the Paris Agreement and Brazil's Nationally Determined Contribution; the Talanoa Dialogue and finally COP24 and the Katowice Climate Package.

Figure 1 | Chronological order of the international negotiations events for climate change.
Source: elaborated by the authors

2 MATERIAL AND METHODS

To conduct this research the method of literature review was used. First, fifteen key terms were defined for our topic: Climate change; International negotiations; Greenhouse gases; Intergovernmental Panel on Climate Change; United Nations Framework Convention on Climate Change; Conference of the

Parties; Environmental maintenance; Challenges of economic development; Kyoto Protocol; Paris Agreement; Brazil's Nationally Determined Contribution; Talanoa Dialogue; Katowice Climate Package; Bali Action Plan and Low Carbon Agriculture Plan of National policy on climate change.

Second, a systematic search was conducted using library catalogs, abstracts and reviews, citation indexes, bibliographies, websites and national and international journals. We restrict the search to Portuguese and English, focusing on literature between 1990 and 2018. The web-based search was proceeded using only seven websites: Google Scholar, Science Direct, Springerlink, Scielo, ERIC, Science.gov, and ScienceResearch.

For each website, we include items embracing thesis, scientific papers, books, book chapters, reviews, reports, and government documents. All documents were identified in three categories: i) broader documents, that is, documents that match one key term, but the scope is not related to climate theme or is not related to Brazil; ii) related documents, that is, documents that match key term and the theme embrace climate and Brazil; iii) narrower documents, that is, documents that exactly about International climate change negotiations involving Brazil. Finally, a list of 187 key references was obtained and 94 evaluated. As exclusion criteria, we exclude documents that are focusing mainly on the effects of climate on biophysical systems; documents that not included negotiations strategies, or are not clear; documents that not mention sustainable Brazil programs.

3 INTERNATIONAL NEGOTIATION ON CLIMATE CHANGE

3.1 COP1 AND THE BRAZILIAN PROPOSAL

The first COP was held in Berlin in 1995, after the actual implementation of the Convention in 1994. At that first meeting, it was already possible to identify that there existed an increase in GHG emissions and that the initial goal of emission reductions proposed for developed countries would be insufficient. The proposed solution was "jointly implemented activities", presented in the document called the "Berlin Mandate" (Ad Hoc Group on the Berlin Mandate - AGBM).

At this COP, Brazil played an important role in presenting elements for a protocol in response to the Berlin Mandate, known as the "Brazilian Proposal". This Proposal was a very innovative approach, and the document presented two elements to support discussion regarding the future negotiation process (UNFCCC, 1997): (a) the Proposal of objective criteria to establish the individual responsibility of Annex I countries in relation to the causes of the greenhouse effect; and (b) the idea of a Clean Development Fund.

This proposal assumed that the responsibility of each country should not be taken solely concerning its GHG emissions or its contribution to increasing the concentration of GHG in the atmosphere. Thus, as the higher concentrations of GHG in the atmosphere increase the planet's temperature, the responsibility of each country must also be related to its contribution to the increase of global temperature. This difference in parameters implies that Annex I countries have made an even more significant contribution to the problem, as shown in Figure 2.

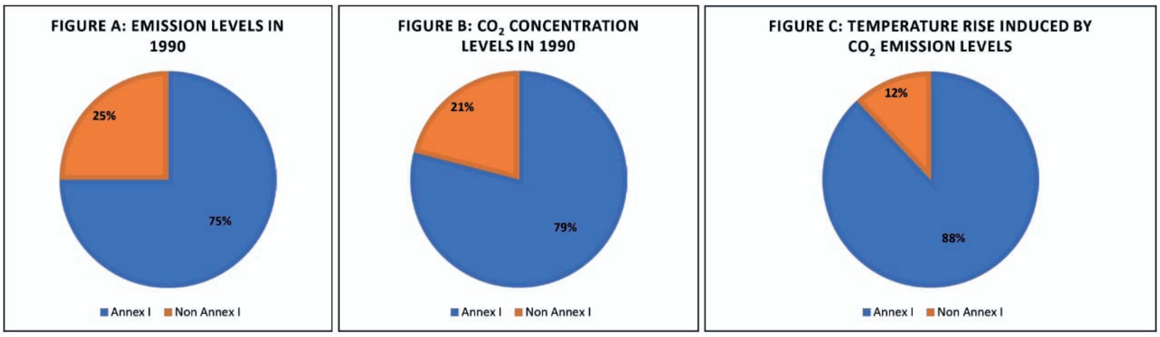


Figure 2: Relative contribution allocated to each Party according to the First Report of the IPCC (1990).
Source: adapted from FRONDIZI (2009).

3.2 CREATION OF THE KYOTO PROTOCOL

The Brazilian proposal, in the first COP, was not entirely accepted by the developed countries (BRAZIL, 2010), but it provided influential subsidies for international negotiations and was a precursor to the COP3 decision (in 1997) with the signing of the Kyoto Protocol, which conferring real regard to the human influence on climate (OPPENHEIMER et al., 2007). At the moment, Brazil start to emerge as a climate mitigation-wise country.

The Kyoto Protocol was the first legally binding agreement to reduce GHG emissions and created three important mechanisms for industrialized countries to meet their reduction targets; which are Emissions trading, Joint implementation and the Clean Development Mechanism (CDM) (MAAMOUN, 2019; UNFCCC, 1998).

However, for the Kyoto Protocol to enter into force, two requirements were necessary: (a) at least 55 Convention countries would have to ratify the Protocol, and (b) the inclusion of Annex I countries representing at least 55% of total CO2 emissions in 1990 (UNFCCC, 1998).

These requirements somehow embraced a twofold way and gave the US and Russia veto power, polarizing these countries again after the cold war, a kind of climate war. This is because if one of them did not ratify the agreement, the value of 55% of emissions would not be reached. The US did not accede to the agreement but made its participation conditional to any Convention protocol if commitments to limit and reduce GHG emissions were also made by developing countries in the same period. This a priori political US position seems to be intended to safeguard a privileged position in the global scenario, however, it may have been the key to the effectiveness of the protocol (MAAMOUN, 2019; MOSS et al., 2008).

An intense negotiation period followed until the US announced, in March 2001, that they would not ratify the Protocol. With that, the only way forward was to ensure Russia's presence in the agreement, which was finally granted on November 4, 2004.

Since the ratification of the Kyoto Protocol in 2004, there has been a significant change in the negotiation process resulting in "two tracks": the Convention (Ad Hoc Working Group on Long-term Cooperative Action - AWG-LCA - ad hoc group for long-term dialogues for the implementation of the Convention) and the Kyoto Protocol (Ad Hoc Working Group on Further Committees for Annex I Parties under the Kyoto Protocol - AWG-KP - ad hoc group for establishing the Kyoto Protocol). Thus, the COP came to host a new modality of meeting: the COP/MOP, where the Conference of the Parties serves as the basis for the meeting of the Kyoto Protocol.

Maamoun (2019) assessed emissions data from countries committed to the Kyoto protocol and found that the protocol was a successful first step. The author noted that the protocol prevented a worse emission level from occurring even though leading countries in GHG emissions, such as the US, did not participate in the agreement.

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3.3 BALI ACTION PLAN

During the COP13 (2007) in Bali (Indonesia), the Bali Action Plan (BAP) was created to guide negotiations until COP15, when a new legally binding agreement was expected. The BAP was composed of negotiating areas, the main ones being: expanded international and national action on mitigation, expanded action on adaptation and expanded action on technology transfer and development (UNFCCC, 2008).

The expanded mitigation action negotiation area was subdivided into six areas: (i) mitigation in Annex I countries; (ii) mitigation in non-Annex I countries; (iii) reduce emissions from deforestation and forest degradation and maintain soil carbon stocks through forest management; (iv) market; (v) economic measures and (vi) social measures.

Reducing emissions from deforestation and forest degradation has the acronym REDD while reducing emissions from deforestation and forest degradation, maintaining soil carbon stocks through forest management has the acronym REDD+. This area deserves attention, as it refers to a mechanism that allows compensation to those who maintain forests without deforestation, avoiding greenhouse gas emissions, plus conservation activities, sustainable forest management, and increased stocks in developing countries (ARTS; INGRAM; BROCKHAUS, 2019).

The BAP proposed to intensify mitigation measures under three premises (UNFCCC, 2008):

- Measurable, reported and verified (MRV) commitments or mitigation measures for each country, including quantified emission limitation and reduction targets, from all Annex I Parties, ensuring comparability between them and taking into account differences in national circumstances;
- Country-appropriate mitigation measures for non-Annex I Parties, in the context of sustainable development, with appropriate technological, financial and capacity support, to enable MRV requirements to be met;
- Approaches to cross-sectoral cooperation and sector-specific measures to improve implementation of Article 4, paragraph 1 (c) of the Convention, which is primarily measures to promote and cooperate with development including technology transfer and commitments that control, reduce or prevent anthropogenic GHG emissions.

Developing countries do not have emission reduction targets. However, the BAP demanded that the implementation of the Convention were extended with nationally appropriate mitigation actions, leading to a substantial deviation of emissions from non-Annex I countries from the trend path. These actions were to be supported by Annex I countries in terms of financing, technology transfer, and capacity building.

Thus, Brazil has the following examples of mitigation actions (BRAZIL, 2010):

- Deforestation: further reduction of deforestation focusing on the Amazon and Cerrado;
- Energy: energy efficiency, increased use of biofuels, an increased supply of energy by hydropower, alternative sources of energy;
- Agriculture: recovery of degraded pastures, crop-livestock integration, no-tillage system, biological nitrogen fixation;
- Industry: increased reforestation area for coal production for the steel industry.

Brazil’s participation increased the significant effort to reduce emissions already made in the country in order to achieve a substantial slowdown in its emissions growth. According to the Brazilian view of the time, mitigation actions should not be a means of offsetting emissions from the Annex I countries, because it was an agreement under the Convention where there are no mandatory targets for developing countries, but a framework that guides developing countries in terms of mitigating climate change.

Concerning broadened action on adaptation, the BAP takes into account international cooperation for the urgent implementation of adaptation measures to the adverse effects of climate change in developing and least developed countries. Also, for these countries, it provides for risk management and mitigation strategies, disaster reduction strategies, economic diversification to increase resilience and synergies between activities and processes as a way of supporting adaptation in a coherent and integrated manner (UNFCCC, 2008).

With respect to expanded action in technology transfer and development, the BAP aims to remove obstacles and provide financial resources, accelerate the diffusion and expansion of technology deployment as well as promoting cooperation between research and development (R&D) for current, new and innovative technologies (UNFCCC, 2008).

3.4 COP15 AND THE BRAZILIAN VOLUNTARY COMMITMENT

The Copenhagen Conference in 2009 (COP15) generated high expectations from the Parties, the world press and society. A new, broadly and legally binding agreement was expected to bring a “solution” to the problem of climate change. Under pressure from all sides, the COP presidency considered necessary to present a proposal. That was the moment the Copenhagen Accord was created.

The Copenhagen Accord presented legal and procedural problems that hindered its operation. It was prepared by 29 countries and had the direct participation of several Heads of State. Several parties formally rejected it based on various procedural irregularities denounced during the Conference. The main problem was the lack of consensus, which would be enough to make the Accord non-operational. The COP observed the rejection of the Accord expressed by some parties, becoming a document without legal value. Consequently, it is not part of the official architecture of the Convention and has been repeatedly challenged by the Parties that have rejected it (DIMITROV, 2010).

However, although the general outcome of COP15 was not as expected, for Brazil it was significant, especially for the agricultural sector. During COP15, Brazil made a voluntary commitment to reduce emissions, playing a crucial role in the negotiations and motivating other developing countries to send voluntary commitments as well. The Brazilian commitment foresees a reduction of 36.1% to 38.9% of projected emissions by 2020, thus avoiding the emission of about 1 billion tons of CO2 equivalent (tCO2e), which represents the most significant reduction effort on the planet (BRAZIL, 2010).

In late January 2010, Brazil submitted to the Convention Secretariat two reports ratifying mitigation actions appropriate to the national context that had been proposed in Copenhagen. It also expressed, with due caution, its accession to the Copenhagen Accord. The proposals presented in Copenhagen were internalized by Law 12.187/09, which instituted the National Policy on Climate Change.

In 2010, Sectoral Plans were created to achieve this voluntary commitment, among them the ABC (Low Carbon Agriculture) Plan. According to Rodrigues and Galvão (2018), the National Policy on Climate Change established institutions that would be responsible for the governance of an essentially environmental policy with direct connections to the performance of the Brazilian economy, as demanded by the Brazilian climate change policy.

3.5 COP21, THE PARIS AGREEMENT AND THE BRAZILIAN NDC

Following the unmet expectations at COP15 and the hard work of regaining confidence in the multilateral process of the United Nations Framework Convention on Climate Change and its signatory countries, COP21, which took place in Paris, had the mission to finally reach a legally binding global agreement that could meet the objective requirements of the Convention (MILKOREIT, 2019).

Lower expectations from the press and civil society facilitated the process, and the outcome of the Conference was the Paris Agreement, which was opened for ratification in April 2016. The Parties to the Agreement reflected the original content of the Convention, seeking to achieve the goals guided by the principles, justice and common but differentiated responsibilities, and their respective capacities, according to their different national circumstances.

The Agreement was marked by recognizing the need to respond effectively to the threats of climate change, based on substantial scientific knowledge, and the need to identify which countries could be most affected by climate change and also the measures taken by them. Priority was placed on ensuring food security and eradicating hunger, defending and protecting food production systems from the negative impacts of climate change, as well as recognizing the importance of conserving and strengthening anticipated greenhouse gas sinks and reservoirs (SHARMA; PAYAL, 2019). It was recognized that the adoption of sustainable lifestyles and sustainable consumption and production patterns will play an essential role in combating climate change, with developed countries taking the lead (UNFCCC, 2015).

By strengthening the implementation of the Convention, including its objective, this Agreement aims to strengthen the global response to the threat of climate change in the context of sustainable development and poverty eradication efforts, including (UNFCCC, 2015):

I. To maintain the overall average temperature increase below 2°C above pre-industrial levels and to make efforts to limit this temperature increase to 1.5°C in relation to pre-industrial levels, recognizing that this would reduce the risks and impacts of climate change;

II. To increase the capacity to adapt to the negative impacts of climate change and promote resilience to climate change and low GHG emissions in a way that does not threaten food production; and

III. To make financial flows compatible with a path towards low GHG emissions and resilient to climate change.

The adoption by consensus that the increase in global average temperature should not exceed 2°C was an essential complement to the central objective of the Convention. The limitations of using annual GHG emissions inventories and applying different metrics for gas equivalence were also identified. It has been shown that, for mitigation target-based policy monitoring, the Global Temperature Change Potential (GTP) metric is more appropriate than the Global Warming Potential (GWP) metric currently most commonly used in inventory and mitigation policy analysis (MENDES, 2014).

In the IPCC's first assessment report, the GWP is proposed as a method for comparing the potential climate impact of different non-CO2 GHGs as a CO2 equivalent unit. However, the use of GWP does not explain the magnitude of climate change, and scientists have proposed GTP as an alternative measure to GWP to assess its potential impact on increasing planetary surface temperature (KUMARI et al., 2019).

Article 3 of the Agreement brings a new dimension to the action strategies of countries regarding the mitigation of GHG emissions, with measures more appropriate to the reality of each Party. However, it was recognized that countries of Annex I have greater participation in the status quo of the GHG emissions problem, and the difficulties that non-Annex I countries will encounter in achieving these reductions (UNFCCC, 2015, p. 22).

In this way, we return to the main objective of the Convention, which seeks to limit the rise in the average temperature of the planet in the short term through the immediate reduction of emissions from developed countries, and in the short to medium-long term for developing countries. Commitments to reduce emissions by country or by block of countries (such as the European Union) must be notified to the Convention through "Nationally Determined Contributions" (NDC).

Brazil was the first country to ratify the Paris Agreement, presenting its NDC to reduce emissions. The delivery of this document before COP21 was intended to demonstrate Brazil's goodwill with international negotiations and the signing of a legally binding agreement, in line with the Convention's guidelines and principles. The initial document used the term "intended" (iNDC) because, at the time, it still depended on the ratification, acceptance or approval of the Paris Agreement, and could thus be adjusted.

In its iNDC, Brazil proposed actions to mitigate GHG emissions and actions for adaptation to the effects of climate change, as well as outlining ways to implement these actions in the country and other developing countries through South-South cooperation based on solidarity and shared priorities for sustainable development. In expanding cooperation initiatives to other developing countries, the area of resilient and low-carbon agriculture plays a prominent role (BRAZIL, 2015).

Regarding mitigation, Brazil committed to reducing GHG emissions by 37% below 2005 levels by 2025, in addition to a subsequent indicative contribution to reduce GHG emissions by 43% below 2005 levels by 2030. The reference year 2005 uses the emissions as calculated in the inventory in Brazil's second communication to the UNFCCC, which was the official document lodged with the United Nations when the iNDC was announced on September 2015 (BRAZIL, 2015).

This reduction of emissions may occur throughout the national territory for the whole economy, including CO2, CH4, N2O, perfluorocarbons, hydrofluorocarbons, and SF6. The metric adopted was the Global Warming Potential in 100 years (GWP-100) using IPCC AR5 values.

Among the mitigation actions presented by Brazil, the following stand out (BRAZIL, 2015):

I. Increase the share of sustainable bioenergy in the Brazilian energy matrix to approximately 18% by 2030, expanding biofuel consumption, increasing ethanol supply, including increases in the share of advanced biofuels (second generation), and enlarging the share of biodiesel in the blend of diesel;

II. In the forest sector and in terms of land-use change, strengthen compliance with the Forest Code at the federal, state and municipal levels; strengthen policies and measures aimed at achieving zero illegal deforestation in the Brazilian Amazon by 2030 and offset GHG emissions from legal vegetation suppression by 2030; restore and reforest 12 million hectares of forest by 2030 for multiple uses; expand sustainable native forest management systems through georeferencing and traceability systems applicable to native forest management to discourage illegal and unsustainable practices;

III. In the energy sector, achieve an estimated 45% share of renewable energy in the energy matrix by 2030, including: expanding the use of renewable sources to between 28% to 33% by 2030; expand domestic use of non-fossil energy sources by increasing the share of renewable energy (in addition to hydropower) in electricity supply to at least 23% by 2030, including wind, biomass and solar energy increases; achieve 10% efficiency gains in the electricity sector by 2030;

IV. In the agricultural sector, strengthen the strategy for sustainable intensification in agriculture, including restoring an additional 15 million hectares of degraded pasture by 2030 and increasing by 5 million hectares the area with integrated crop-livestock-forest systems (ICLF) by 2030.

This new commitment, in addition to the one proposed by Brazil at COP15, largely reinforces the consolidation of low carbon agriculture and, in particular, the recovery of degraded pastures and ICLF, as a real way to achieve sustainable intensification of agricultural production. These technologies contribute to the mitigation of greenhouse gas emissions, increase productivity and income, increase social benefits to producers and consolidate sustainable development.

3.6 TALANOA DIALOGUE

The Paris Agreement will only come into force in 2020. Thus, during the COP 23 held in Germany in 2017, the Talanoa Dialogue was created with the aims to encourage UNFCCC signatory countries to strengthen their commitments to curb global warming during the period before 2020 (LESNIEWSKA; SIEGELE, 2018). The Talanoa Dialogue consists of an international platform where all countries can share their actions to combat climate change and thus exchange experiences.

Talanoa is a word used to reflect an inclusive, participatory, and transparent dialogue process in Fiji and other Pacific islands. Talanoa's goal is to share stories, build empathy, and make wise decisions for the collective good. The Talanoa process involves the sharing of ideas, skills, and experiences through narrative (UNFCCC, 2018).

In Brazil, this inclusive dialogue process began on August 2, 2018, at an event called Talanoa Dialogue - Brazil, coordinated by the Ministry of the Environment and the Ministry of Foreign Relations, with support from the World Bank. This event took place in Rio de Janeiro and was attended by more than 30 representatives from different sectors (government, the private sector, academia, civil society, and rural settlement communities). Throughout the year 2018, several Talanoas occurred in Brazil, organized by different sectors of society.

3.7 KATOWICE CLIMATE PACKAGE

With the creation of the Paris Agreement at COP 21, the next step was to create a way to implement the Agreement. Thus, during the Conference of the Parties (COP24) in Katowice, Poland (2018), the parties adopted a package of guidelines for implementing the Paris Agreement, called the Katowice Climate Package. The main objective of the Package is to operationalize the climate change regime contained in the Paris Agreement.

The Katowice package includes (UNFCCC, 2019):

- The transparency mechanism, which details how to measure national efforts to operationalize the transparency framework jointly and the definition of how countries will provide information about their NDCs with their respective mitigation and adaptation actions;
- Guidelines related to the process of establishing new funding targets from 2025, based on the current goal of mobilizing $100 billion per year from 2020 to support developing countries, as well as guidelines to assess progress in the development and transfer of technology;
- Rules on how to update each country's goals in five-year cycles, among other items.

Furthermore, the Climate Package emphasizes the urgent need to increase the mobilization of climate finance. On the other hand, issues such as the use of cooperative approaches and sustainable development mechanism, as set out in Article 6 of the Paris Agreement, are still pending. The use of such a mechanism would allow countries to meet some of their national mitigation targets through the use of so-called "market mechanisms". The idea of these market mechanisms is to provide flexible instruments to reduce the costs of mitigation actions, for example, through the use of carbon markets.

Thus, the outcome document of COP24 underscores the importance of strengthening countries responsibility in replenishing the impact of programs of the Global Environment Facility. It also requests that the Global Environment Facility ensures that its policies and procedures relating to the consideration and review of funding proposals are duly and efficiently followed up. Further, the document looks forward to the planned delivery of reductions in GHG emissions in the seventh replacement period, which is double than foreseen for the sixth replacement period.

For some critics, from a climate point of view, Katowice failed (OBSERVATÓRIO DO CLIMA, 2019). For them, the Package failed to adequately capture the sense of urgency communicated by science about action against climate chaos. Also, it left in the hands of the individual countries any decision on how to use this information. For Patricia Espinosa, the Executive Secretary of the UNFCCC, Katowice was a success: “The result of Katowice is a breakthrough that all governments can be proud of! It strengthens the Paris Accord and opens the door to implementing climate action around the world!” (UNITED NATIONS CLIMATE CHANGE, 2019).

4 FUTURE PERSPECTIVES OF BRAZIL IN CLIMATE NEGOTIATIONS

The world went through the industrial race and countries like England, France and Germany came out ahead. In a second moment, we had a technological race, for example, the space race and advances in computing. Since the 1990s, there has been an increase in environmental concern, which is linked to sustainable production. This fact paved the way for environmental protagonism in the world. However, there is no environmental power yet. There is still no country that is promoting sustainable development by aligning environmental preservation, that’s because big challenges must be faced and cooperation between the countries is essential.

Some authors argue for the possibility of economic development and environmental preservation through strategic decision-making among government agencies, industry players, and non-governmental organizations following the Sustainable Development Goals developed by the ONU (OPOKU, 2019). However, other authors raise the issue that sustainable development prioritizes economic development and will inevitably cause damage to environmental preservation.

These authors argue that the path to environmental preservation would be an economic downturn through an awareness of society concerning the high consumption, aiming at the search for social equity and human well-being (SANDBERG; KLOCKARS; WILÉN, 2019). However, from this discussion, questions emerge that still have no answer. Will current or future technology be able to increase productivity and preserve the environment to optimal limits? Nevertheless, would not a greater awareness of society and a quest for social equality be an essential pillar of sustainable development? Thus, a possible solution would be in the middle path, which is a balance between the social, economic, and environmental aspects.

A descriptive analysis conducted by Sforna (2019) shows that most developing countries demonstrates a willingness to actively contribute to climate change mitigation in cooperation with developed countries. However, external support requirements in the form of technology transfer, training, and financial support are paramount for these countries. At the same time, the author shows that the demand for climate finance from developing countries is higher than the current supply from developed countries and that trying to fill this gap is one of the critical challenges to controlling GHG emissions and thus reducing the catastrophic effects of climate change.

Brazil, however, is a country that has a higher potential to assume the role of great green power on the planet, especially when it comes to agriculture and biodiversity. Regarding agriculture development, environmental, and biodiversity protection, some countries, especially Brazil, have the opportunity to be future agri-environmental world potency. This opportunity is significant, as countries like Brazil will no longer achieve the technological status of developed countries. Thus, there is an opportunity for Brazil's agri-environment role in the world, but this will make future negotiations much more complicated and force the government to act intelligently.

In the last 45 years, Brazil has consolidated itself as a significant agricultural power. Grain production grew more than fivefold, while the planted area increased by only 60%. However, the most significant boost has occurred since 1990, partly due to the growth in exports, which have become the driving force of recent growth in Brazilian agribusiness. The country is currently the leading exporter of orange juice, coffee, pulp and paper, chicken meat, soy complex, and the second largest exporter of sugar and corn (USDA, 2017).

The total area of land occupied and in use in Brazil is approximately 30%, while Permanent Preservation Areas (indigenous lands and protected areas) and areas of native vegetation on private properties, separated according to environmental legislation—such as Legal Reserve - represent almost 50% of the Brazilian territory. If added to the native vegetation in unregistered lands, this percentage reaches 66%. Crops and planted forests occupy only 9% of the territory; planted pastures 13%; and native ones 8% (MIRANDA, 2017). On the other hand, from January 2019, with the new Brazilian government of Jair Bolsonaro, satellite data from Brazil's National Institute for Space Research (INPE) show a significant increase in Amazon deforestation and an expansion of the exploratory agricultural frontier (KAMIMURA; SAUER, 2019). This increase in deforestation is related to the President's aggressive discourse and policies for economic development by promoting agriculture and mining on protected lands (ESCOBAR, 2019). Not surprisingly, the current government denies that humans have a direct impact on climate change and elects a foreign minister who believes global warming is an "invention of Marxist ideology" (FERRANTE; FEARNSIDE, 2019).

The president's policies loosen legislation and weaken institutions that help fight deforestation, as well as the participation of civil society and NGOs concerned with environmental preservation (RODRIGUES et al., 2019). A clear example is the flexibility of the forest code by President Bolsonaro and the Minister of Agriculture, Tereza Cristina Dias, which includes a longer deadline for ruralists to restore natural vegetation in illegally deforested areas (FERRANTE & Fearnside, 2019).

Besides, the new minister Ricardo Salles, very close to the ruralists and condemned for altering an environmental plan to benefit the companies (PEREIRA; VIOLA, 2019), extinguished the Secretariat of Climate Change and Forests, early in the government. This fact has impacted Brazil's relationship with project donor countries, such as Norway and Germany, and has shaken international relations and the execution of important projects and partnerships, such as the Amazon Fund. These political decisions drastically affect Brazil's role in the fight against deforestation and environmental preservation, which are fundamental for reducing greenhouse gas emissions.

No other country in the world, not even the major agribusiness players, has the same conditions as Brazil to advance sustainable food production in the coming decades, and the governments must understand this position. The old idea of agricultural expansion through advancement in forested areas must be abandoned in favor of more integrated agriculture. Countries like China are already preparing to dominate the world agri-environment scenario in a clear vision of true patriotism, which implies protecting their people and dialoguing with the rest of the world for political empowerment (GUAN, 2019; LIU et al., 2015).

Meanwhile, Brazil, which has agri-environmental technology and a biodiverse landscape to assume this scenario, is still assuming a light idea of patriotism and betting on the old bankrupt commodity model. The danger of this nationalism so defended by the current Brazilian government, as well as other countries in the world, is worrying as it leads to separation, war, and conflict, while the practical solution to the challenges of climate change lies in cooperation between countries. No country can solve climate change issues on its own. Extreme nationalism, therefore, limits humanity's ability to deal with the current and future challenges the planet will face (HARARI, 2018).

Brazil has a structure of science and innovation that has recently produced an unprecedented revolution in the rural zone, as well as farmers that are creative, enterprising and sensitive in incorporating new technologies into production. Pasture area which functions below its productive capacity still occurs, which represents room for growth in production and productivity, without opening new productive areas (EMBRAPA, 2018).

Thus, it is clear that Brazil's significant competitive advantage in the international scenario for the next decade is sustainable development, combining efficient agricultural production and preservation of natural environments. Since 2009, Brazil has taken on a massive role in this agenda, when it made voluntary commitments to reduce GHG emissions and adapt to climate change. Brazil's position in the negotiation motivated other developing countries to submit voluntary commitments.

The proposals presented in Copenhagen were internalized in the National Policy on Climate Change. In 2010, in order to achieve this commitment Sector Plans were created, including the Low Carbon Agriculture Plan (ABC Plan, from the acronym in Portuguese). In addition to Copenhagen, in 2015, Brazil submitted to the UNFCCC its intended Nationally Determined Contribution (iNDC), in the context of negotiations on a protocol, other legal instruments, or outcomes legally agreed upon under the Convention, applicable to all Parties.

This new commitment, made in addition to the one proposed by Brazil at COP15, reinforces the consolidation of low carbon agriculture and, in particular, the recovery of degraded pastures and ICLF as a real way to achieve the sustainable intensification of agricultural production. These technologies, beyond their ability to contribute to the mitigation of GHG emissions, may have the potential to increase productivity, income, and social benefits to farmers and consolidate sustainable rural development (RODRIGUES et al., 2019).

5 CONCLUSIONS

Following the ratification of the Kyoto Protocol, in 2009, Brazil made a voluntary commitment to reduce GHG emissions and, with the Paris Agreement in 2016, a new commitment to further reduce GHG emissions in some sectors. It is noteworthy that both the voluntary commitment made at COP15 and the commitment made at COP21 through the NDCs are not actions linked to the commitment of Annex I countries to the Kyoto Protocol. All actions reported in this paper have demonstrated not only Brazil's commitment to contribute to the negotiations under the Convention, but also its interest in making the country's economy a world reference, based on the sustainable use of its natural resources and optimization processes involving all sectors of the economy.

Since the founding of the UNFCCC during Rio 92, Brazil has shown immense leadership in international negotiations and gained respect from all parties. All this effort has shown Brazil's commitment and prominent role in promoting actions to reduce global warming and the development of a more sustainable economy.

However, this scenario is already change dramatically with the new policies and decision-making of the current government, which took office in 2019. Current political leaders deny the anthropic impacts on global climate change and weaken institutions that promote environmental preservation and oversee the deforestation.

While most emissions are the responsibility of developed countries, the countries that will be most affected by the catastrophic consequences of climate change are developing and underdeveloped countries. So as long as the current government does not leverage the actions proposed by the climate change mitigation agenda, the country's economic development is doomed to failure.

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Future challenges, given population growth, the effects of climate change, technological advances, and inequality in income distribution and concentration, significantly increase the importance of international negotiation and effective mechanisms for regulating the planet's climate. For this to happen, it is necessary to establish a new economic model, giving up the extreme nationalism advocated by the current Brazilian government.

Therefore, Brazil's consolidation as the world's first green energy (in agriculture and environmental preservation) must be worked on as a country, not as a government agenda.

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The actions of the Brazilian agricultural sector in the context of climate change negotiations

As ações do setor agropecuário brasileiro no contexto das negociações sobre mudança do clima

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ABSTRACT

Brazil has always maintained a prominent position in negotiations within the United Nations Framework Convention on Climate Change, playing a major role in setting increasingly ambitious goals and encouraging consensus among Parties. With the purpose of reducing GHG emissions from the agricultural sector and disseminating and financing good agricultural practices, Brazil developed a platform of sustainable technologies and public policies, as the Low Carbon Agriculture Plan (the "ABC Plan"). This article reviews the main milestones of Brazil's role in the international negotiation on climate change, how these factors affected the Brazilian agricultural sector between 2009 and 2018 and the authors' personal view on this context. The objective is to provide an overview of Brazil's actions regarding the agricultural sector which contribute to the voluntary commitment assumed by the Brazilian government at COPs 15 and 21 and to provide a critical analysis of how these actions are being implemented. The main results show that low carbon agriculture has been consolidated as the main Brazilian strategy for sustainable rural development, but it is vital for our country to continue with these actions.

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Keywords: Greenhouse Gases; Mitigation; Adaptation; Public Polices.

RESUMO

O Brasil sempre manteve uma posição de destaque nas negociações da Convenção-Quadro das Nações Unidas sobre Mudança do Clima, desempenhando um papel importante no estabelecimento de metas cada vez mais ambiciosas e no incentivo ao consenso entre as Partes. Com o objetivo de reduzir as emissões de Gases de Efeito Estufa (GEE) do setor agrícola e disseminar e financiar boas práticas agrícolas, o Brasil desenvolveu uma plataforma de tecnologias e políticas públicas sustentáveis, como o Plano de Agricultura de Baixo Carbono (o "Plano ABC"). O presente artigo faz uma revisão dos principais marcos da atuação do Brasil no âmbito da negociação internacional sobre mudança do clima, como esses fatores afetaram o setor agrícola brasileiro, entre 2009 e 2018, e a visão pessoal dos autores sobre esse contexto. O objetivo é fornecer uma visão geral das ações do Brasil em relação ao setor agrícola, que contribuem para o compromisso voluntário assumido pelo governo brasileiro nas COPs 15 e 21 e para fornecer uma análise crítica de como essas ações estão sendo implementadas. Os principais resultados mostram que a agricultura de baixo carbono se consolidou como a principal estratégia brasileira para o desenvolvimento rural sustentável, porém é vital que o país continue com essas ações.

Palavras-chave: Gases de Efeito Estufa; Adaptação; Políticas Públicas.

1 INTRODUCTION

Issues related to climate change are gaining increasing prominence and attention in the agenda of governments and society at large. The Brazilian government has always maintained a prominent position in negotiations within the United Nations Framework Convention on Climate Change, playing a major role in setting increasingly ambitious goals and encouraging consensus among Parties. An example of this prominence can be seen in the suggestion of a Clean Development Fund, which later gave rise to the Clean Development Mechanism, which is one of the mechanisms of flexibilization of the Kyoto Protocol.

This protagonism is reflected in the stance the Brazilian government has towards its own agricultural sector. According to FAO and OECD (2015), Brazil will become the world's leading exporter of agricultural goods in 2024, thus consolidating advances made by the sector in recent years. In view of this growth forecast and the climate commitments made by Brazil, the development of more sustainable agriculture is of fundamental importance.

The agricultural sector is both a major contributor to global climate change, and one of the sectors most affected by the adverse effects of climate change (TILMAN et al. 2001; FOLEY et al. 2005; FOLEY, et al., 2011; GODFRAY and GARNETT, 2014; KUYPER and STRUIK, 2014; IPCC, 2014; ROCKSTRÖM et al., 2017; SMITH and GREGORY, 2013).

Agriculture is the strongest sector of the Brazilian economy, contributing 25% of GDP. On the other hand, it exerts strong pressure for land use and emits large amounts of greenhouse gases (around 32% of Brazil's total emissions, according to OBSERVATÓRIO DO CLIMA, 2018).

Despite this seemingly incompatible relationship, increasing agricultural production is necessary to meet the challenge of the UN Sustainable Development Goals of eradicating hunger and securing food for a growing world population expected to reach 9–10 billion by 2050. This population may require an increase in global food production of between 60 and 110% (Foley et al. 2005; Foley, et al., 2011; IAASTD, 2008; Tilman et al. 2011; Pardey et al. 2014) at a time when the consequences of climate change are affecting agricultural producers around the world. As described by Smith and Gregory (2013) and Foley et al. (2011), whilst ensuring food security, there is an urgent need to reduce the impact of food production on the climate (Smith et al., 2008), and to improve the resilience of food production to future environmental changes (SMITH et al., 2013a; SMITH 2015; FOLEY et al., 2011).

Despite the critical role the sector plays in current and future emissions, in many countries action to reduce emissions related to agriculture has lagged behind other sectors (Richards, et al., 2018). Brazil and others countries however, has undertaken strong measures to reduce emissions from the agricultural sector and land use change.

France, like Brazil, has been working on the theme, such as the proposed 4:1000 Initiative. Based on strong scientific foundations and concrete field actions, this initiative aims to show that food security and combating climate change are complementary and that agriculture can bring solutions (4p1000, 2019).

According to Richards, et al. (2018), for countries with high agricultural emissions, the challenge is to increase the ambition of mitigation targets for the agricultural sector over time. Mitigation options currently available are based on improved efficiency and better agricultural practices such as improved nutrition and ruminant health management (Gerber et al., 2013), the more efficient use of nitrogen fertilizers (Gerber et al., 2016), and the implementation of Integrated Livestock Crop and Forest systems (ICLF) and the no-tillage system, which not only reduce GHG emissions, but can also contribute to soil carbon storage.

The objective of this article is to provide an overview of Brazil's actions regarding the agricultural sector which contribute to the voluntary commitment assumed by the Brazilian government at COPs 15 and 21 and to provide a critical analysis of how these actions are being implemented.

2 THE BRAZILIAN VOLUNTARY COMMITMENT AND THE ABC PLAN

During COP15, Brazil submitted a voluntary commitment to reduce GHG emissions. Brazil's position in the negotiation motivated other developing countries to also submit voluntary commitments. The Brazilian Nationally Appropriate Mitigation Actions (NAMAs), foresaw a reduction of 36.1% to 38.9% of projected emissions for 2020, thus avoiding the emission of about 1 billion tons of CO2 equivalent (tCO2e) (Brazil, 2010). This was the largest effort to reduce emissions on the planet.

The proposals presented in Copenhagen were internalized through Law 12,187/2009, which instituted the National Policy on Climate Change. In 2010, in order to reach this voluntary commitment, Sector Plans were created, including the Low Carbon Agriculture Plan (ABC Plan, from the acronym in Portuguese).

2.1 THE ABC PLAN

With the purpose of reducing GHG emissions from the agricultural sector and disseminating and financing good agricultural practices, the Federal Government launched the ABC Plan in 2012.

The nationwide ABC Plan has a period of validity from 2010 to 2020. Revisions and updates were planned at regular intervals, not exceeding two years, in order to adapt the plan to the demands of society, the arrival of new technologies and to incorporate new actions and goals if necessary. The Plan is composed of seven programs, six of them related to mitigation technologies, and one program related to climate adaptation (BRASIL, 2012):

- Program 1: Recovery of Degraded Pastures;
- Program 2: Integration of Crop-Livestock-Forest (ICLF) and Agroforestry Systems;
- Program 3: No-tillage System;
- Program 4: Nitrogen Biological Fixation (NBF);
- Program 5: Planted Forests;
- Program 6: Animal Waste Treatment;
- Program 7: Adapting to Climate Change.

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The GHG emission reduction potential of the Plan is estimated at approximately 150 million Mg CO_2e, not counting the potential for CO_2 sequestration by forest plantations. Each program proposes the adoption of a series of actions, such as strengthening technical assistance, training and information, technology transfer strategies (TT), field days, lectures, seminars, workshops, the implementation of Technological Reference Units, publicity campaigns and public calls for the contracting of technical assistance and rural extension services (BRASIL, 2012).

To reach the objectives set forth in the ABC Plan, in the period between 2011 and 2020, it was estimated that resources of the order of R$ 197 billion would be needed, financed through budgetary sources or agricultural credit lines.

According to data on agricultural credit from the MAPA (2019), from 2010 to January 2010, over 34 thousand contracts were executed, with a disbursement of more than R$ 17 billion, totaling an average of around R$ 504 thousand per contract. The total available for the credit line in this period was R$ 27.67 billion. The number of capacity building events related to the low carbon emission technologies outlined in the Plan carried out between 2011 to 2017 was 40,484, occurring in the 940 Demonstration Units that the Plan has implemented throughout the country.

Data related to the area with these technologies implemented, as well as their respective mitigation potentials, are presented in Table 1.

Table 1 | Adapted from: Adoption and mitigation of greenhouse gases by the technologies of the Sectoral Plan for Mitigation and Adaptation to Climate Change (ABC Plan).

	Commit (until 2020)		*Achievement*		
	Expansion Area	Mitigation Potential (million Mg CO_2 eq)	Period	Expansion Area	Mitigation Potential (million Mg CO_2 eq)
DEGRADED PASTURES RECOVERY	15.0 million ha	83 to 104	2010 to 2018	4.46 million ha, representing 30% of goal achievement	16.9, representing 18% of target set
INTEGRATED CROP-LIVESTOCK-FOREST	4.0 million ha	18 to 22	2010 to 2016	5.83 million ha, representing 146% of goal achievement	22.11, representing 111% of goal achieved
NO-TILLAGE SYSTEM	8.0 million ha	16 to 20	2010 to 2016	9.97 million ha, representing 125% of goal achievement	18.25, representing 101% of goal achieved
BIOLOGICAL NOTROGEN FIXATION	5.5 million ha	10	2010 to 2016	9.97 million ha, representing 181% of goal achievement	18.25, representing 182% of goal achieved
PLANTED FORESTS	3.0 million ha	8 to 10	2010 to 2018	1.10 million ha, representing 37% of goal achievement	2.01 million Mg CO_2 eq
ANIMAL WASTE TREATMENT	4.40 million ha	6.9	2013 to 2018	1.70 million m^3, representing 39% of goal achievement	2.67, representing 39% of goal achieved
TOTAL OF ALL TECHNOLOGIES	35.5 million ha	132.9 to 162.9	2010 to 2018	27.65 million ha, representing 77% of goal achieved	100.21, representing 68% of goal achieved

Source: MAPA, 2018.

According to Table 1, the technologies implemented over the largest area were ICLF systems, biological nitrogen fixation and the no-tillage system. These technologies were also responsible for the largest emissions reductions. This is due to the fact that the cultivation of many crops in Brazil, mainly soybeans, can already be done with biological nitrogen fixation and in a no-tillage system. In addition, with regard to ILCF technology, its success is largely due to the private sector alliance with the productive sector.

Gil et al. (2015) present an overview of integrated land-use systems in Mato Grosso and investigate the determinants of their adoption. In this paper cultural aspects play a major role in farmer decisions to adopt integrated systems, credit provision has not been relevant for adoption, and a broader dissemination of integrated systems may occur as land transitions continue. In addition, farm size, cultural preferences and know-how are major determinants for this technology adoption. The credit offered by the government has had limited influence on integrated systems adoption.

In addition, accordingly to Gil et al. (2016), from the farmer perspective, there is evidently a high degree of uncertainty regarding the synergy effects of integrated systems as well as their economic performance. Adopters of integrated crop-livestock systems are better educated and have greater access to technical assistance than specialized producers.

On the other hand, the areas in which recovery of degraded pastures, planted forests and manure management had been implemented, were far below the proposed goals. However, the area with recovered pasture was probably underestimated. The recovery of degraded pasture is not exactly a technology. Pasture degradation can be defined as the gradual loss of vigor, productivity and natural capacity for recovery to sustain the production and quality of feed and to withstand detrimental effects from insects, diseases and weeds (MACEDO AND ZIMMER, 1993).

Degraded pastures can be recovered with different technologies, including almost all other technologies proposed in the ABC Plan, except for the waste management technology. Thus, the real area of degraded pastures that have been recovered is certainly much larger than the area presented by MAPA.

This low adherence may be associated with aversion to inherent risk among producers in relation to liabilities, lack of skilled labor and bureaucracy linked to ABC credit (Latawiec et al., 2017). This includes ownership requirements, alternative land use implications, and emission reporting (SILVA, et al., 2018).

According to Carauta et al. (2018), specific credit conditions might speed up the diffusion of low-carbon agricultural systems. This study suggests that with ABC credit the adoption of integrated systems more than doubled, reaching an agent land-use share of 27% in Mato Grosso State. Credit from the ABC program has not been regarded as a crucial determinant of the adoption of integrated systems in Mato Grosso. In fact, only a small share of current integrated systems adopters has used the ABC credit lines so far (GIL et al. 2015; OBSERVATÓRIO ABC 2015).

The results reached by Carauta et al. (2018), suggest that ABC credit substantially increased the integrated system area in Mato Grosso and thereby highlight the importance of understanding farmer adoption decisions and responses to changes in financing conditions, especially in situations with high rates of interest and inflation which Brazil currently faces. Transaction and learning costs associated with adopting new agricultural practices and on-farm technologies influence farmer land-use decisions. Such barriers, economic benefits of innovation and externally provided economic incentives (i.e., ABC credit) altogether constitute the factors determining the actual diffusion of agricultural innovations (LEE, 2005).

In order to improve the functioning of the ABC Plan, some obstacles need to be overcome, such as technical training, bureaucracy to access the ABC Program, as well as the improvement of its rules and the speed of project implementation (ABC OBSERVATORY, 2013; PINTO et al., 2015). Problems with the dissemination of the Program and the lack of interest from higher schools in research and extension were also reported in another study (SCHEMBERGUE et al., 2017). For Barbanti et al. (2015), the main reasons for the low performance are the lack of technical assistance, rural extension and regularization of rural properties.

According to Martins et al. (2018), the potential to mitigate GHG emissions by the Brazilian agricultural sector is more than ten times the target set by the ABC Plan. Between 2012 and 2023, it may be possible to reach 1.8 billion tCO2 eq, incorporating the avoided emissions and carbon stored in the soil, through the adoption of just two technologies of the ABC Plan (pasture recovery and integration of crop-livestock-forest) in 52 million hectares of degraded pasture.

3 THE BRAZILIAN NDC

In 2015, Brazil submitted to the UNFCCC its intended Nationally Determined Contribution (iNDC), in the context of negotiations on a protocol, other legal instrument or outcome legally agreed upon under the Convention, applicable to all Parties.

In its iNDC, Brazil proposed actions to mitigate GHG emissions and adaptation actions to the effects of climate change, as well as ways to implement these actions in Brazil and in other developing countries, through South-South cooperation, based on solidarity and common priorities for sustainable development, with cooperation in the area of resilient and low carbon agriculture playing a prominent role.

Regarding mitigation, Brazil committed to reduce GHG emissions by 37% below 2005 levels by 2025, in addition to a subsequent indicative contribution to reduce GHG emissions by 43% below 2005 levels by 2030. The reference year 2005 uses the emissions as calculated in the inventory in Brazil's Second National Communication to the UNFCCC, which was the official document lodged with the United Nations when the iNDC was announced in September 2015 (BRAZIL, 2015).

Within the NDC actions, we will highlight those related to the agricultural sector, including the strengthening of the strategy for the sustainable intensification of agriculture, including, by 2030, the restoration of an additional 15 million hectares of degraded pasture and increasing, by 5 million hectares, the area with productive systems using crop-livestock-forest integration (ICLF) (BRASIL, 2015).

This new commitment, made in addition to the one proposed by Brazil at COP15, reinforces the consolidation of low carbon agriculture and, in particular, the recovery of degraded pastures and ICLF as a real way to achieve the sustainable intensification of agricultural production. These technologies contribute to the mitigation of GHG emissions, increase productivity and income, improve social benefits to producers and consolidate sustainable development.

According to Silva et al. (2018), among the actions of the NDC, emissions related to deforestation control and changes in land use are among the most important. As such, agricultural intensification is a key component in the fulfillment of this new commitment, potentially allowing the country to undertake long-term mitigation commitments that are aligned with a national development strategy to increase sustainable agricultural production (SILVA et al., 2018).

Integrated Crop-Livestock-Forest is a sustainable production strategy that is consolidating in Brazil as an important option for the agricultural sector. According to data from the ICLF Network Association, the area with this technology adopted is 11.5 million hectares, twice the NDC target. According to this Association, among the main obstacles identified to the further adoption of ICLF are: the need to improve knowledge among researchers as well as the training of consultants; the need for interaction to build capacity to work with ICLF systems; insufficient institutional integration with the involvement of agents from funding institutions, government managers (MAPA, MMA, MDA), public and private technology transfer agents and others; and the lack of communication and marketing actions.

Given the low adherence to the recovery of degraded pasture, much needs to be done in order for the NDC agreed target to be met. Credit lines with lower interest rates and greater disclosure of this technology may help increase technology adherence.

4 CONCLUSIONS

After the ratification of the Kyoto Protocol, Brazil assumed, in 2009, a voluntary commitment to reduce GHG emissions and with the Paris Agreement in 2016, made another commitment to further reduce GHG emissions in some sectors. All this effort shows Brazil's commitment and important role in promoting actions aimed at reducing global warming and developing a more sustainable economy.

Results show that the ABC Plan has already mitigated between 100.21 and 154.38 million Mg CO2 eq. in the period from 2010 to 2018, indicating that the voluntary targets for reducing GHG emissions, agreed at COP15, are already being met. The data presented further demonstrate the country's potential to implement its Nationally Determined Contribution under the Paris Climate Agreement for the period 2020-2030, reinforcing the need for continuity in efforts to promote low carbon agricultural technologies and in capacity building for the adoption of practices that increase resilience and improve sector productivity.

The implementation of low carbon emission technologies that promote the sustainable intensification of Brazilian agriculture will be essential for the achievement of commitments and contributions assumed by Brazil, not only because of their strong potential for mitigation, but also for their potential to increase the resilience of agricultural productivity in the face of a changing climate.

Also, in this context, the dissemination of these technologies in rural areas may contribute to reducing pressure for deforestation. The increase in productivity derived from integrated systems implies that they require less space to produce the same amount of food and can be implemented in areas of degraded pasture, reducing the need for agricultural expansion. It is also worth noting that these technologies, besides promoting an increase and diversification of production, enhance carbon stocks and soil fertility and also contribute to the maintenance of water resources, with a consequent reduction in the need for water in crop production.

The actions reported here demonstrate not only the commitment Brazil has to contribute to the negotiations within the framework of the Climate Change Convention, but also the interest in making the agricultural sector of this country a world reference, based on the sustainable use of natural resources and optimization processes involving all stages of agricultural production.

However, all this effort made by Brazil over the last decades, may be with the days numbered. The president, Jair Bolsonaro, is turning his environmental policies toward a milder and more permissive regime. Through the legislation that weakens the institutional and legal framework that helps fight deforestation and other environmental offenses, as well as reforms that substantially weaken the participation of civil society, including pro-environment groups, in policymaking and in oversight of policy implementation.

While it is difficult to predict the long-term effect of these regulatory changes on emissions, it can be predicted that much of these effects have the potential to increase illegal deforestation and other environmental violations. Given the important role of NDC's Land Use and Forests sector and the enormous global importance of its forests for environmental services, biodiversity and carbon sequestration, the Brazilian government urgently needs to strengthen mitigation actions in this sector - rather than weaken it. The current government has also not implemented any new policy to halt emissions growth in other sectors. Bolsonaro's environmental agenda is at odds with the urgent need for climate action that Brazil had been presenting in previous governments.

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Overcoming barriers to low carbon agriculture and forest restoration in Brazil: The *Rural Sustentável* project

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ABSTRACT

The *Rural Sustentável* project aims to decrease greenhouse gas emissions, reduce poverty, and promote sustainable rural development in the Brazilian Amazon and Atlantic Forest biomes: by restoring deforested and degraded land, and by facilitating and promoting the uptake of low carbon agricultural technologies. The project offers farmers a) access to information, through demonstration units and field days; b) access to technical assistance, through in-person and online training and capacity-building; c) access to rural credit, through collaborative farmer-technician partnerships, and d) financial incentives, in the form of results based financing to successful farmer-technician teams. The project is still in its implementation stage, but the innovative design and theory of change of this project offer insights into possible mechanisms for promoting forest restoration on private lands in the tropics.

1. Main text

1.1. Background

Agricultural production is the principal source (32%) of greenhouse gas emissions in Brazil. Agricultural expansion is a driver of deforestation and land use change, which comprise the third biggest source (28%) of emissions. Supported by the United Nations Framework Convention on Climate Change (UNFCCC) and by Food and Agriculture Organization of the United Nations (FAO), agricultural production in Brazil is projected to increase in coming decades. This increase will support the national economy, and meet growing international food demand driven by global scale population increases and changing dietary preferences. Brazil has voluntarily committed to achieving this increase in agricultural productivity in a sustainable manner. At the same time, the livelihoods of many small- and medium-sized farmers in Brazil are vulnerable to variations in environmental and economic conditions, and many farmers are limited in their capacity to adopt more sustainable on-farm practices that might help to alleviate climate and livelihood challenges. Decision-makers in Brazil – including government ministries, donor agencies, NGOs, and banks – are thus seeking ways to simultaneously reduce agricultural and land use change emissions, and to secure the livelihoods and wellbeing of rural producers.

As part of a national strategy to reduce greenhouse gas emissions, Brazil launched its Low Carbon Agriculture Plan (*Plano Agricultura Baixo Carbono*, ABC Plan) in 2010. At the core of the ABC Plan is a new line of low-interest rural credit (the ABC Program) that is specifically intended to fund the implementation of low carbon agricultural practices, or 'technologies', that are likely to contribute to climate change mitigation and adaptation, either by reducing greenhouse gas emissions and/or by sequestering carbon.

In the Brazilian context, low carbon agricultural practices include many forest-centric activities, including restoration of

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degraded forest areas, developing commercial plantation forests, managing natural forests, and developing integrated crop-livestock-forestry systems. The ABC Plan also promotes other, non-forest technologies that include restoration of degraded pasture, biological nitrogen fixation, no-till farming, and manure management.

More than R$13.2 billion has been lent to rural producers in 28,500 loans through the ABC Program since its inception (MAPA, 2016). However, the amount loaned in 2015–16 (R$ 2 billion) was 45% less than in 2014–15 (R$ 3.6 billion). This slow-down in uptake of the ABC Program may be due to a) an increase in ABC credit interest rates (from an average 5–5.5% to an average 8–8.5%) over the same time period, and/or b) the availability of other credit lines that don't focus on low carbon agricultural technologies but which offer lower interest rates. As a consequence, the current rates of adoption of low carbon agricultural practices mean that Brazil is projected to fall short of its declared targets for Nationally Appropriate Mitigation Actions by 2020.

A number of additional factors are thought to hinder higher participation rates in the ABC Plan and to constrain uptake of the ABC Program, including: 1) Insufficient knowledge among many farmers about the ABC Plan and Program; 2) Insufficient technical capacity among many farmers that would enable them to implement low carbon technologies, and insufficient technical support from public or private agencies to help train these producers in more sustainable production methods; 3) Insufficient training and knowledge about low carbon agricultural technologies among staff and managers in commercial banks that can approve ABC Program loans; 4) Barriers to access credit – for example, a) applying for credit involves a substantial administrative process, and b) a prerequisite for farmers wishing to access the ABC Program is registration in the Rural Environmental Registry (*Cadastro Ambiental Rural*, CAR), a national database of rural property boundaries; yet until recently many farmers were not registered in the CAR; and 5) Insufficient incentives for farmers to invest the time and energy needed, and to assume the risks that a change of agricultural practices may incur (IPAM, 2012). Many of these constraints apply particularly to small- and medium-sized farmers, who often have limited access to financial and technical resources.

2. The *Rural Sustentável* project

The *Rural Sustentável* project aims to decrease greenhouse gas emissions, reduce poverty, and promote sustainable rural development: by restoring deforested and degraded land, and by facilitating and promoting the uptake of low carbon agricultural technologies (Projeto Rural Sustentável, 2016). The project promotes four low carbon agricultural technologies, all of which can involve the restoration or management of forests: integrated crop-livestock-forestry systems; development of commercial plantation forests; sustainable management of native forests; and restoration of degraded forest and/or pasture. With respect to this last technology: forest restoration entails the protection and active restoration of forests that have been degraded through anthropogenic activity; pasture restoration entails the improvement of pasture quality (Vilar & Carvalheiro, 2016).

The project targets small- and medium-sized farmers in 70 municipalities in seven Brazilian states: three in the Amazon biome (Pará, Mato Grosso, and Rondônia), and four in the Atlantic Forest biome (Bahia, Minas Gerais, Paraná, and Rio Grande do Sul). The project is funded through the International Climate Fund and the UK's Department for Environment and Rural Affairs (Defra), and is being implemented by the Inter-American Development Bank (IDB).

The *Rural Sustentável* project began in 2013 and is still midway through implementation. As such, it is too early to report concrete results of the project. Rather, this paper outlines the project's theories of change, and how its approach could promote forest restoration and management on private lands in Brazil.

2.1. Theories of change

The *Rural Sustentável* project promotes low carbon agriculture, including forest restoration and management, through a set of complementary mechanisms that address key barriers thought to constrain participation in the ABC Plan and uptake of ABC Program credit loans. The project facilitates access to information, technical assistance, rural credit, and financial incentives, respectively addressing insufficient knowledge, technical capacity, credit access, and motivation.

The *Rural Sustentável* project is an interesting and innovative case because its design a) explicitly addresses identified barriers to the uptake of low carbon agricultural technologies, and b) incorporates a suite of strategies to mitigate these barriers. Many conservation and development projects have variously experimented with information, capacity-building, and cash incentives as potential agents of change in rural people's land and natural resource use behavior, and researchers have tried to understand the relative importance of these different approaches in effecting change. But the *Rural Sustentável* project creates conditions under which these different mechanistic approaches can interact and complement each other. If information, technical assistance, rural credit, and financial incentives are each necessary but individually insufficient to nudge rural producers into behavioral changes that promote forest restoration, then a project package that includes all four in a cohesive manner may have more success than disparate interventions that promote just one or two of these approaches.

2.2. Information

The *Rural Sustentável* project has, via a public call, identified a number of farms across the seven project states to act as 'Demonstration Units' (DUs). Such farms had already implemented one or more of the four low carbon agricultural technologies that the project promotes, independently of the project. The project then organizes 'field days' at the DUs, inviting interested farmers to observe and learn first-hand from their peers about the process and benefits of implementing these technologies. The objective of this project component is to spread information about the opportunities associated with the ABC Plan and Program. The project aims to establish a total of 350 DUs across the seven states, which will host approximately 2600 field days.

2.3. Technical assistance

The *Rural Sustentável* project incorporates several mechanisms for delivering technical training to farmers and rural extension agents. Individuals can access training opportunities during field days, through online courses, and via information disseminated on the project's website. In all cases, the objective of this project component is to facilitate the transfer of knowledge about the implementation of low carbon agricultural technologies and land management practices.

2.4. Access to credit

The core component of the *Rural Sustentável* project is to encourage farmer-extension agent teams to jointly develop and submit proposals that, if funded, would allow them to implement one or more low carbon agricultural technologies on the farmer's property. The project leverages the differing but complementary knowledge of farmers and rural extension agents and capitalizes on their respective strengths, by facilitating collaboration between the two parties.

A central emphasis is that farmer-extension agent proposals should be eligible for a loan from the ABC Program. In this sense, the project aims to leverage its core funding by facilitating access to, and uptake of, the underutilized ABC Program funding. Farms that successfully implement a proposal are referred to as 'Multiplication Units' (MUs). The project aims to establish ten times more MUs than DUs – approximately 3500 MUs across the seven states.

2.5. Incentives: Results based financing

The final component of the *Rural Sustentável* project is to provide financial incentives to motivate farmers to adopt and implement low carbon agricultural practices. Even with sufficient knowledge, technical capacity, and credit, farmers may be reluctant to assume the risk of adopting unfamiliar new practices. The project offers results-based payments to farmer-extension agent teams whose proposals are approved and successfully implemented. Since the cash transfers are contingent upon success, the project's theory of change is that they will generate motivation among both parties to pursue their collaboration until completion.

3. The *Rural Sustentável* project mechanisms promote forest restoration and management

All four of the low carbon agricultural technologies promoted by the *Rural Sustentável* project can involve the restoration or management of forests. The project is therefore likely to contribute to forest restoration and management efforts among small- and medium-sized farmers on private lands in Brazil's Amazon and Atlantic Forest biomes. Such restoration and management may generate both private and public benefits.

First, forest restoration may deliver livelihood benefits to farmers. On-farm trees and forests may provide access to natural resources such as food, firewood, and timber. They may also restore or maintain ecosystem services, such as watershed protection and soil retention. Farmers that maintain forest cover on their properties may have more diversified livelihoods, which may be more resilient. For example, integrated crop-livestock-forestry systems represent a diversified production strategy that may make farmers less vulnerable to economic and environmental shocks, including climate variability and change (Lasco, Delfino, Catacutan, Simelton, & Wilson, 2014).

Second, forest restoration may also help farmers to become compliant with Brazil's Forest Code. This national environmental legislation requires all rural property owners in Brazil to maintain a prescribed proportion of their land as forest, as well as to maintain riverine forests. Many farmers in Brazil are non-compliant with the Forest Code, maintaining less than the required area of forest on their properties. While the Forest Code has historically not been strictly enforced, a recent and widespread effort to register all rural properties in the CAR may make monitoring and enforcement of the Forest Code more feasible and more likely. Farmers who become compliant with the Forest Code through forest restoration activities may be better protected from risks and liabilities, such as fines, associated with non-compliance.

Finally, forest restoration at scale could help Brazil to achieve climate change mitigation and adaptation objectives: Brazil is a signatory to the Bonn challenge, and has adopted a target of approximately 20 million hectares of reforestation. Forest restoration and planting commercial forests on degraded lands also offers significant potential for carbon sequestration. Managing native forest areas may reduce deforestation. And integrated crop-livestock-forestry systems may be more resilient to climate shocks, and variations in market prices.

4. Outcomes

Brazil's agricultural research corporation, *Embrapa*, is leading research on a number of important outcomes, including: the impacts of the project on the livelihoods of rural producers, and on ecosystem services; the greenhouse gas emissions reductions attributable to the project; and the number of hectares of forests conserved and restored as a consequence of the project. Future publications will report on these metrics. In addition, spatial analyses may reveal: a) whether variations in the adoption of low carbon technologies can reveal differences in the specific barriers to ABC Program credit uptake in different regions, and b) whether policy diffusion (e.g. between neighboring farms) can lead to landscape-level change.

Some uncertainty remains about the scale of the impacts that the project will achieve. The project's geographic scope, covering 70 municipalities in seven states across two biomes, means that there is potential for widespread change. But restoring forests on private lands at scale may be challenging, since a large number of individual farmers need to participate. The project's success thus depends on convincing farmers that it is both possible and desirable to change their on-farm practices. It remains to be seen whether the combination of information, technical assistance, credit, and results-based payments are sufficient to motivate a significant number of individual farmers to adopt low carbon agricultural technologies. If it is, this project may generate important lessons about how best to combine governance interventions to achieve both environmental and socio-economic development goals.

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