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Could bovine livestock intensification in Pantanal be neutral regarding enteric methane emissions?

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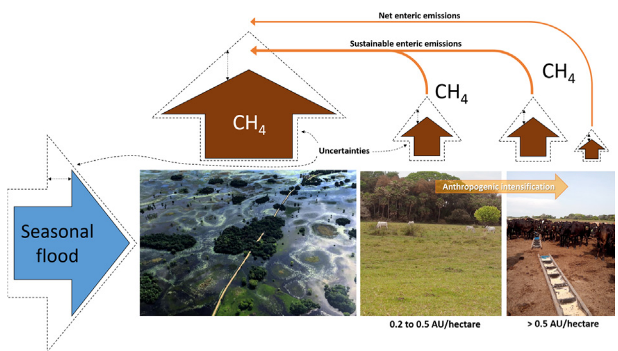
HIGHLIGHTS

- Bovine enteric CH_4 is a major segment of Brazilian greenhouse gases emissions.
- We compared enteric emissions with farm landscape CH_4 emissions in Pantanal.
- Landscape-integrated CH_4 emissions largely exceeds bovine enteric emissions.
- Traditional system can be CH_4 neutral whereas intensification leads to net emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Bovine livestock is a major anthropogenic greenhouse gas source via enteric methane. Brazilian bovine livestock is also responsible for emissions from land-use changes. In contrast, enteric emissions from extensive cattle systems in wetlands might have been overestimated. We provide scientific evidences that the human footprint of bovine products delivered by the Pantanal can be much lower. To assess this, a historical cloud-free imagery of the Landsat-5, spanning 26 years, were processed for mapping spatiotemporal landscapes in a Pantanal farm under cattle intensification studies. Eight landscape categories were identified according to spatiotemporal dynamics of interannual floods. The spatiotemporal map allowed in the field the adoption of stratified random samplings of chamber gas fluxes. The combination of stratified sampled landscapes with Monte Carlo simulations of measured methane emissions in wet and dry soils permitted to integrate landscapes emissions at annual basis with biased uncertainties. Assuming enteric emissions obtained for the Pantanal region, our results suggest that the landscapes methane emissions are 10- to 23-fold superior than the enteric emissions of traditional bovine systems. While enteric emissions seem negligible with respect to net farmland emissions, cattle livestock provide important environmental services like carbon recycling through non-competing herbivory. Moreover, cattle might be making use of a biomass that would undergo decomposition during the flooding phase. Our analysis thus indicate that enteric emissions from traditional bovine systems in flooding farmlands could be considered neutral. By contrast, intensification to improve the stocking rate should be accounted as net anthropogenic emissions. A case study of intensification allowed an increase of 48% in the stocking rate, which is associated with net anthropogenic emissions from 534 bovine animals or about 27 to 63 Mg of enteric CH_4 per year. In short, the

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competition between traditional and distinct levels of cattle intensification will result from a trade-off between public policies and strategic market niches (organic, sustainable) for the optimal landscape management of the Pantanal.

1. Introduction

Tropical wetlands are major sources of atmospheric methane (CH_4). By the end of this century, they may account for up to 53.2% of global CH_4 emissions from natural sources (Zhang et al., 2017). The Pantanal is one of the largest wetlands in South America, where the main economic activity is bovine farming. The contribution of Brazilian cattle to anthropogenic greenhouse gas emissions has gained attention in the last decades, particularly due to deforestation and enteric emissions. By 2010, the Brazilian agricultural sector accounted for 35% of CO_2-eq. emissions by human activities, of which 56.4% comprise enteric methane emissions from beef cattle (MCTI, 2014). A closer look at cattle systems in the Pantanal suggests, however, that enteric emissions might be negligible compared to background emissions of flooding and wetlands landscapes.

By 2016, Corumbá, in Pantanal, ranked as the second municipality in number of cattle, with 1.82 million bovine animals or 0.8% of the cattle population in Brazil (IBGE, 2017). In general, Brazilian bovine enteric emissions may vary around 115 and 150 g CH_4 per day (Esteves et al., 2010; IBGE, 2012; MCTI, 2014). From PECUS Project, Oliveira et al. (2016) have measured daily enteric emissions ranging from 141 and 323 g CH_4 for well-adapted Nellore in the Pantanal. Considering the latter emission range, the annual enteric emissions of the bovine livestock in Corumbá should lie in between 94 and 214 Gg CH_4.

A typical extensive farm in Pantanal, of approximately 10,000 ha and about 2000 bovine animals (0.2 animal unit per hectare or 5 ha per animal unit), should produce annually around 103 to 236 Mg of enteric CH_4. Assuming that ~50% of the farmland is flooded, and the CH_4 emission factors by diffusion and bubbling between 24 and 592 mg $CH_4.m^{-2}\cdot d^{-1}$ (Bastviken et al., 2010), the farm landscapes emissions are then in the range of 440 to 10,800 Mg CH_4 per year. As a result, enteric CH_4 emissions of traditional bovine systems in Pantanal is expectedly much lower and may indeed represent a negligible fraction of both magnitude and variability of landscapes CH_4 emissions due to seasonal, annual and interannual flood pulses (Junk et al., 1989).

A still open question is how would be the carbon (C) cycle on wetlands and floodplains of Pantanal's farms without bovine animals. From historic standing points, the livestock introduced >200 years ago (Abreu et al., 2010) can replace ecological services of herbivory by the extinct megafauna that usually grazed this vast biomass-productive region (Galetti, 2004). In addition, Bergier and Salis (2011) argued that in the lacking of bovine animals, much of the atmospheric C sequestered via ecosystem's Net Primary Production (NPP) would naturally return to the atmosphere as pyrogenic and/or biogenic gases derived respectively from fires and decomposition of organic matter via fermentation and respiration in wetlands and flooding lands. Livestock retain a small C pool whereas recycle a significant fraction of NPP that, instead, would be naturally combusted by usual savanna landscape fires, with CO_2 and pyrogenic CH_4 emissions, biologically respired as CO_2 or reduced via methanogens in anoxic wetlands and flooding lands.

Consequently, correct lenses over traditional bovine systems in Pantanal would better reveal its ecosystem functionalities, services and global warming effect. In that wisdom, traditional cattle in the Pantanal likely make use of an 'ecosystem surplus' (Bergier and Salis, 2011). In other words, it may appropriate a large fraction of ecosystem respiration (R, including fermentation) (Bergier and Salis, 2011) or a small fraction of the Net Ecosystem Production (NEP = NPP - R) in a sustainable way (Haberl et al., 2007; Takahashi et al., 2010). The concept of ecosystem surplus in wetlands is related to the partial Human Appropriation of R (Bergier and Salis, 2011) or NEP (Haberl et al., 2007) for the provision of food, fiber, leather, bioenergy and financial resources to people, concomitantly with the maintenance of environmental services in land spare or land share farming designs (Power, 2010).

Brazilian beef production in nonflooded lands adopts land sparing of the Brazilian Forest Code (Brazil, 2012) to save ecosystem services and biodiversity. Land use that adopt high-yield grazing management, semi-intensive, silvopasture and feedlot-finishing boost food production alongside lowering greenhouse gases emissions (Balmford et al., 2018). Nevertheless, the flooding and the avulsive nature of flat landscape rivers in Pantanal (Assine et al., 2018) make it very difficult to follow land spare commitments (Silva et al., 2016). Analogously, natural methane emissions by anaerobic decomposition of annually flooded biomass also make these farmlands very particular in terms of anthropogenic greenhouse gases emissions.

Cattle in Pantanal clearly distinguish from cattle in a system deprived of seasonal floods and marked by drastic land-use changes (normally a tropical forest converted to exotic pasture), particularly those in the Cerrado and in the highlands of the Amazonia (Lapola et al., 2014; Buller et al., 2015). On the other hand, such distinction might be somewhat lessened whenever some level of intensification is introduced to Pantanal farmlands as a strategy to guarantee sustainable revenues and market competitiveness (Oliveira et al., 2014; Bailey et al., 2015; Abreu et al., 2018).

In summary, this work aims to verify 1) whether a traditional beef farm system in the Pantanal could be considered neutral with respect to enteric methane emissions and 2) if intensification would incrementally offset any confirmed neutrality. The study is founded on the combination of a multivariate statistics (Principal Component Analysis), available for GIS image analysis of historical remote sensing data (e.g. Almeida et al., 2015), with a Monte Carlo approach to the probability distribution functions of field data (e.g. Ramirez et al., 2008) for considering spatiotemporal uncertainties of the methane emissions from flooding farmland landscapes. Results and discussions can be very useful for the optimal landscape management of the Pantanal wetlands by establishing a new understanding about the competition between traditional and distinct levels of intensification (cattle stocking rate and land use), which is ultimately mediated by public policies and market niches (e.g. organic, sustainable) trade-offs.

2. Material and methods

2.1. Study area

The study area is the Fazenda (Farm) São Bento, in "Estrada Parque", State road MS-228 (Fig. 1). The farm area is limited to the north by the Rio (River) Abobral and to the south by the Rio Miranda. The farmland comprises almost ten thousand hectares, of which 4.96 thousand hectares are of native grasslands, 2.38 thousand hectare of native grasslands were converted to cultivated brachiaria (*Urochloa humidicola* or *Brachiaria humidicola* (Rendle) Schweick), and 1.86 thousand hectares gather natural reserves ("Reserva Legal", RL).

Mean annual rainfall from January 2013 to September 2018 ranged from 917 mm in drier years to 1440 mm in wetter years. Rio Miranda stage level from January 2015 to September 2018 showed well-marked monomodal annual pulse ranging from 0.87 to 3.86 m. The mean rainfall, river stage seasonality and the river stage monthly

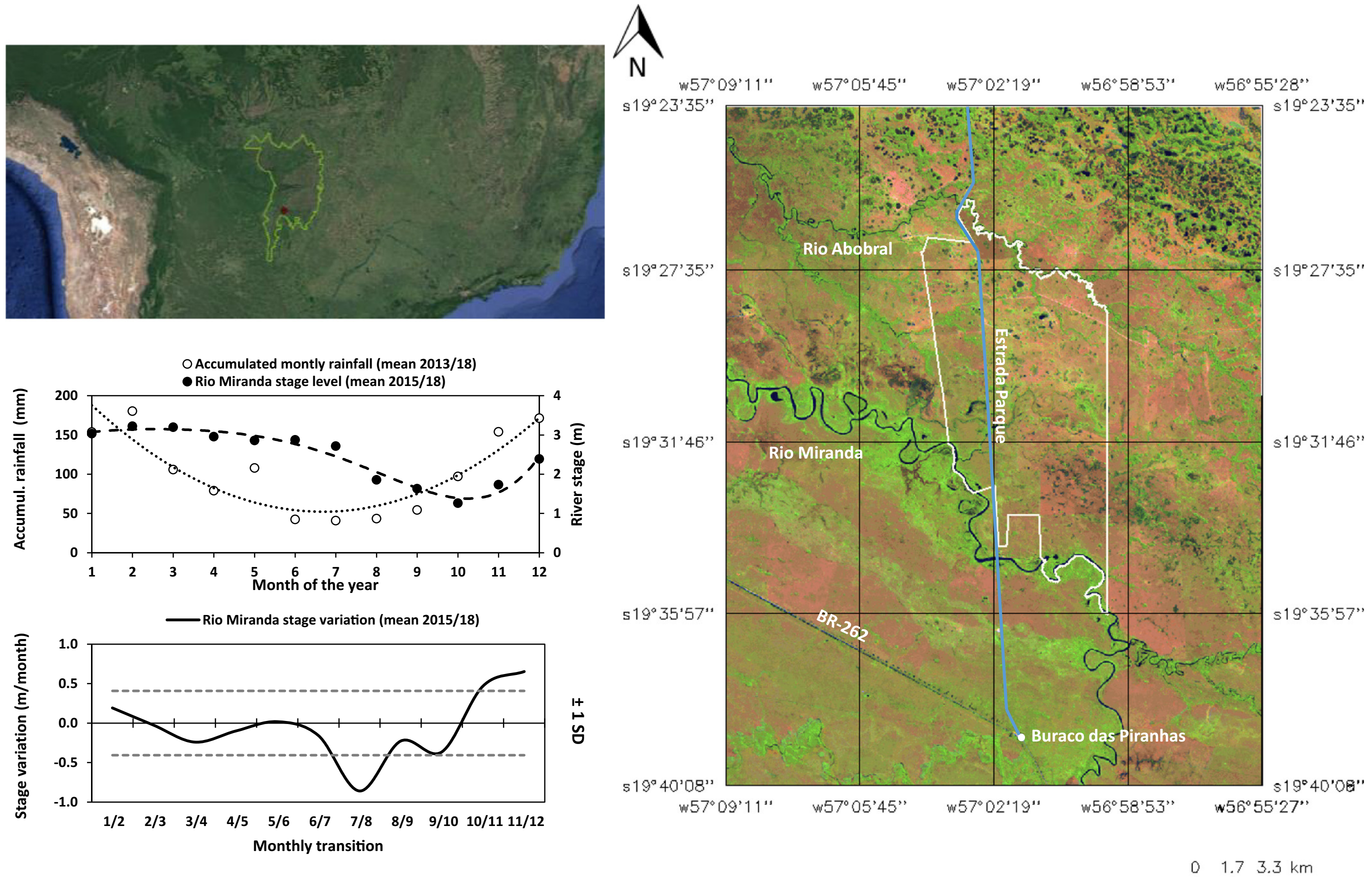

Fig. 1. Location of Fazenda São Bento in Pantanal, "Estrada Parque" (road MS-228, in blue) from "Buraco das Piranhas" (State Environmental Police Office) in BR-262, municipality of Corumbá, Mato Grosso do Sul (R5G4B3 composition from Thematic Mapper sensor of Landsat-5, orbit 226, point 74, August 2011). Also shown rainfall, monthly maximum level, and inter-monthly variation (which is most of the time within ±1 SD over the four consecutive years) of the Rio Miranda. Hydrological data source: on-site monitoring provided by Célio Silva Junior and Marcelo Dias, administration team of Fazenda São Bento. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

variation (±1 standard deviation or SD, dashed lines) of the Miranda River are shown in Fig. 1.

2.2. Remote sensing historical imagery

2.2.1. Selecting and preprocessing digital images

The study relies on multivariate and multitemporal analyses of historical orbital images obtained between 1985 and 2011 by the NASA Landsat-5 satellite. The imagery were processed in SPRING (Geographic Information Processing System) developed by the National Institute for Space Research, INPE (http://www.dpi.inpe.br/spring).

Twenty-six cloud-free dates/scenes (Table 1) from orbit and point 226/74 of the Landsat-5 Thematic Mapper (30 m spatial resolution with 8-bit or 256 levels of radiometric resolution) were selected. Scenes of the spectral bands 3 (0.63–0.69 μm), 4 (0.76–0.90 μm) and 5 (1.55–1.75 μm) were obtained in the online catalog of the Image Generation Division of INPE (www.dgi.inpe.br). Image data between June and September (Table 1) were selected to ensure cloud-free scenes and to avoid spurious data in statistics by Principal Component Analysis. Besides, images from the rainy/flood (austral summer) period were also avoided in order to remove excessive bias from open water in temporal information variability at the first components of each set of spectral band analyzed.

Table 1
Dates of cloud-free TM/Landsat-5226/74 imagery selected for spatiotemporal mapping.

Months	Years
June (n = 3)	1992 1995 2001
July (n = 6)	1988 1991 1994 1997 2004 2010
August (n = 13)	1896 1987 1990 1993 1996 1998 1999 2000 2005 2006 2008 2009 2011
September (n = 4)	1985 1989 2003 2007

The cartographic projection was UTM, Datum WGS 84 and Zone 21. All scenes were geometrically corrected, assuming a second polynomial order and an error < 0.5 pixel, with a georeferenced Landsat-5 image of May 2006 available by Global Land Survey (GLS-Landsat, www.dgi.inpe.br/CDSR/).

Optical sensors are susceptible to radiometric distortions due to differences in atmospheric conditions, solar illumination, soil moisture, and others (Hall et al., 1991). To minimize these effects and to improve comparisons of statistical moments among orbital scenes obtained at the same orbit/point over several dates, it is recommended to rectify or radiometric normalize the dataset. Radiometric correction was done in SPRING by the method of standardization of means and variances (Santos et al., 2010). The purpose of this method is to match the mean and variance between two images (adjustment image and reference image) by a linear transformation. The spectral bands 3, 4 and 5 of the August 2011 image (most recent date of the database) were selected as the reference image. After radiometric rectification, each scene band layer was cropped with a vectorial polygon representing the perimeter of Fazenda São Bento (Fig. 1), restraining for statistical analyses the most relevant historical information.

Statistical exploration of the satellite images consisted of Principal Component Analysis for each spectral band over time. The analysis involved the rotation and translation in a multidimensional space of the attributes in a coordinate system of the probability density function, producing new variables known by principal components that are linear combinations of the original data (several dates in the same spectral band over the same area). In the new Cartesian coordinate system (or rotational orthogonal components), it was selected only the first principal component (PC1), which corresponds to the greatest amount of useful spatiotemporal spectral information (Banon, 1992; Meneses and Almeida, 2012). Hence, PC1 images of bands 3, 4 and 5, aggregating (eigenvalues) respectively 95.29%, 37.08% and 53.15% of the temporal variability, were used for the next step of farm landscape mapping. The main benefit of this technique is that it is easily implemented in the SPRING GIS to produce spatiotemporal maps associated to flooding farms like the Pantanal wetlands. However, farmlands often disturbed by forest fires, deforestation, intense cloud cover, among others natural or man-induced changes, could prevent the successful use of the technique. Therefore, historical imagery must be carefully compiled to avoid spurious non-flood related data.

An object-oriented algorithm, named segmentation in SPRING, was used to fragment sets of pixels or polygons of homogeneous units (Vasconcelos and Novo, 2004). “Region Growth” was the chosen algorithm to label pixels by associating each of them to a given polygon. Two parameters are set to empirically define the best degree of segmentation (size of polygons) for optimizing mapping results. The “similarity” parameter is based on Euclidean distances between the average values of gray levels of each region, while the “area” parameter represents the minimum number of pixels for polygons (Almeida Filho and Shimabukuro, 2002; Dlugosz et al., 2009). After performing several tests, the “similarity” was set to 8 and the “area” to 9 and the segmentation result is shown in Fig. 2.

Geotagged photograph images taken in the field allowed distinguishing major landscapes and validating the landscape mapping procedure. Fifteen polygons were sampled as training classifier in supervised classification via Bhattacharya method with an acceptance threshold of 99.9% (Cruz et al., 2009).

2.2.2. Emission factors for enteric methane and spatiotemporal landscapes

Oliveira et al. (2016) have measured daily enteric emissions ranging from 141 and 323 g CH_4 for well-adapted Nellore in Pantanal. We used that range for comparing enteric emissions with background landscape emissions.

Estimates of CH_4 (and CO_2 as a proxy of plant/microbial respiration) emissions were carried out in October 2016, March 2017, and April 2017. The fieldwork design was based on stratified random sampling guided by the types of spatiotemporal landscapes identified on the produced map. Water sealing soil rings were installed in dry and wet areas to measure gaseous fluxes with an Ultra-Portable Gas Analyzer (Los Gatos Research, UPGA-LGR) connected to a static chamber through closed air tight tubing (Mosier, 1989). Fig. 3 illustrates dry and wet landscapes sampled in the farm and their typical gas chamber flux plots. In general, drier soils behave as small CH_4 sink while wet areas tend to exhibit positive changes in partial pressures of methane during the chamber deployment. Chamber flux measurements were all acquired during daylight and those with $R^2 > 0.9$ over about 10 min of chamber deployment were selected ($n = 50$).

The lower (LC) and upper (UC) confidence intervals of the mean emission factors for dry and wet landscape soils were estimated by Monte Carlo simulation (bootstrap samples with 9999 iterations) of the probability distribution function for samples obtained in wet soils ($n = 18$) and in dry soils ($n = 32$) (Fig. 4). The range of emission factors for open water was not measured. Emission factors for open water in the region, available in Alvalá and Kirchhoff (2000), were then used in the calculations.

The main reason for adopting the Monte Carlo simulation is to define the uncertainty (biased) ranges of methane emissions that allow combining them with the uncertainties obtained by the spatiotemporal classification map. By this approach, it is possible to consider overall uncertainties of the system but not its exact, precise functioning at a certain period of time.

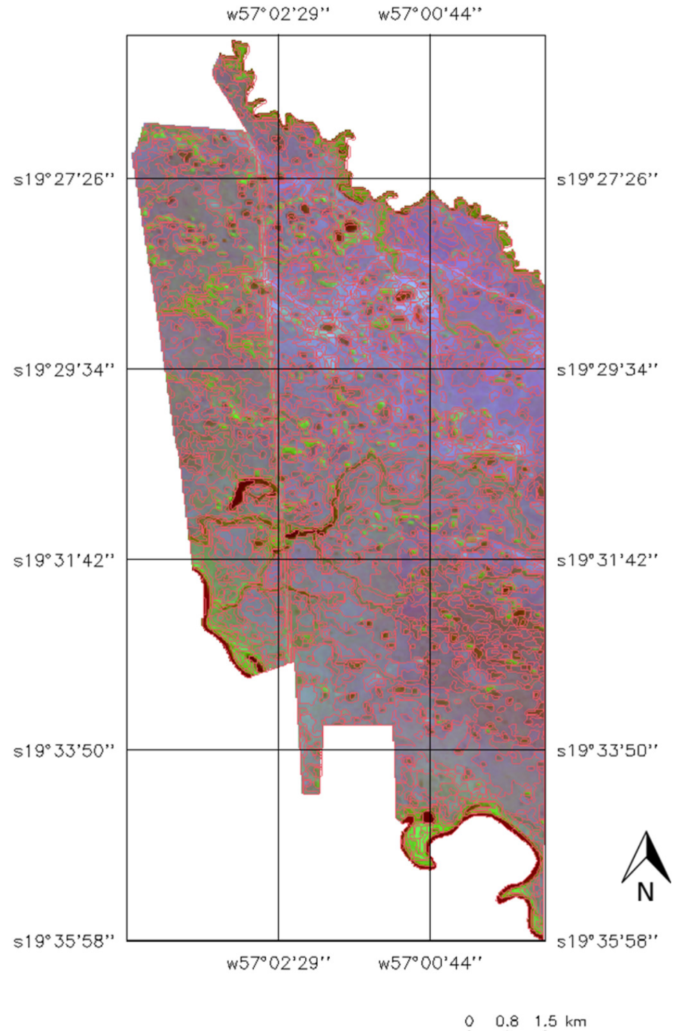

Fig. 2. RGB composition image (PC1 (band 3) - Red; PC1 (band 4) - Green; PC1 (band 5) - Blue) and segments (polygons in red) obtained by parametrizing similarity 8 and area 9 of Fazenda São Bento. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

3.1. Landscape characterization in Fazenda São Bento

The notion of landscape is controversial and authors often define it in a conflicting way (Britto and Ferreira, 2011). The concept of landscape used in the present study is a heterogeneous mosaic formed by interactive units, in which heterogeneity exists for at least a factor according to an observer and over a certain scale of observation (Metzger, 2001). This concept is embedded in a geographical approach, from a human perspective and how human acts in the territory according to wishes, needs and plans of occupation. This approach allows an analysis on a broad spatiotemporal scale, in which the interactive set of landscapes in the present study is composed of units of land use and occupation of a farmland. The interacting units are defined by the abiotic background (hydrogeomorphological dynamics, local topography and soil-vegetation types), by natural disturbances (e.g. floods, fire and droughts) and by anthropic interventions (like native vegetation suppression for villages, grain or pasture cultivation, roads, etc.).

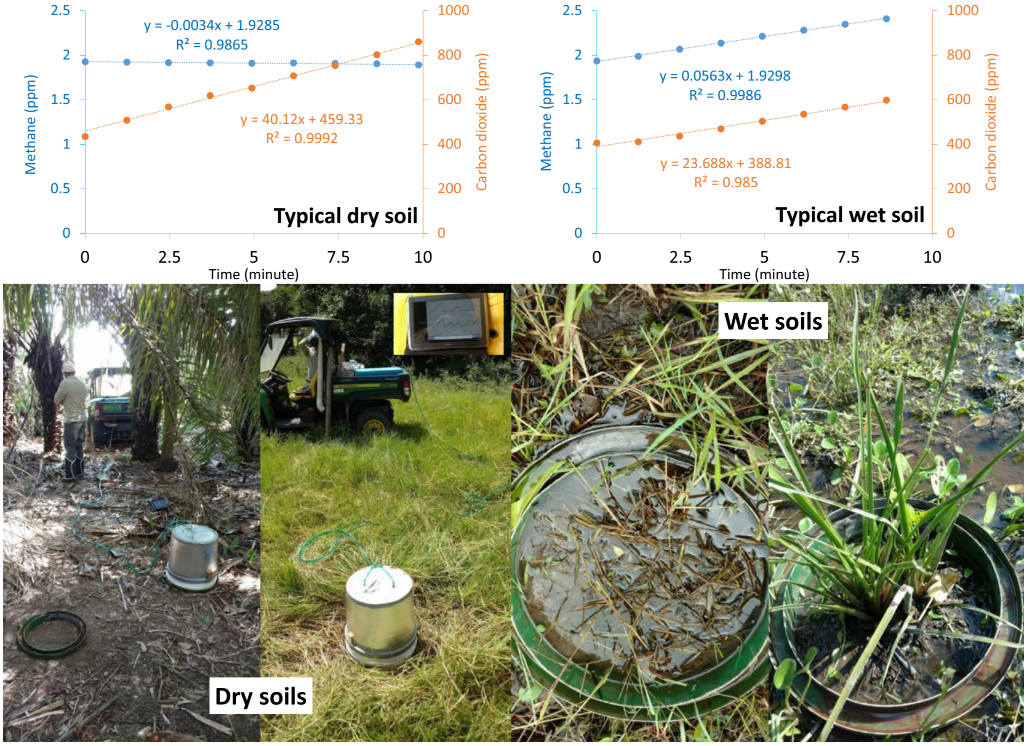

Fig. 3. Gaseous fluxes measured in dry and wet soils of Fazenda São Bento.

Fig. 5 presents the spatiotemporal mapping of landscapes available in Fazenda São Bento. The mapping was successfully achieved by field validation and supervised classification following object-oriented segmentation of the first principal components of multitemporal and multispectral imagery obtained from Landsat-5 satellite. The imagery mapping allowed discriminating eight categories with the following relative area (in %):

- Non-flooding woody forests: patchy or riparian arboreal-shrub in elevated topography (9.9%);
- Less flooding grasslands: portions of herbaceous vegetation little influenced by floods (24%);
- Flooding grasslands: portions of herbaceous vegetation heavily influenced by floods (32.2%);
- Wetlands: lower humid portions with herbaceous vegetation in swamps or marshes (6.5%);
- Fluvial floodplains: herbaceous vegetation directly influenced by riverine floods (16.2%);
- Aquatic macrophytes: portions of shallow water colonized by aquatic vegetation (6.3%);
- Open waters: flowing or standing waters distributed over floodplains and grasslands (1.4%); and
- Roads: farmland accesses, including "Estrada Parque" road MS-228 (3.4%).

Wetlands, aquatic macrophytes and open waters are topographically lower in the terrain and totalize 14.2% of the farmland. Wetlands are particularly concentrated in the southeast region, influenced by the floods of Rio Miranda (Fig. 5). Aquatic macrophytes make up a mosaic of floating and emerging species (Pott and Pott, 2000). On the other

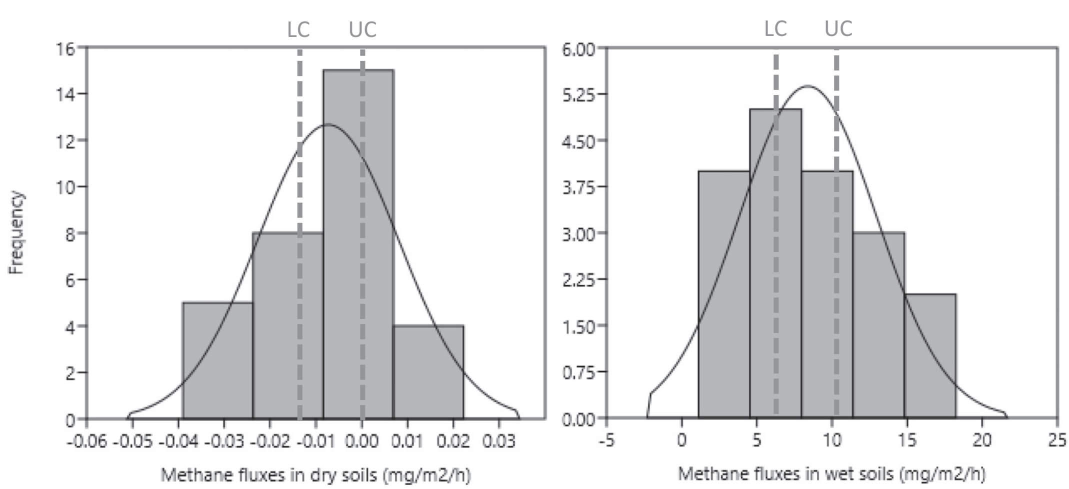

Fig. 4. Monte Carlo estimation of lower (LC) and upper (UC) confidence intervals of the mean methane emission factors obtained for dry and wet landscape soils.

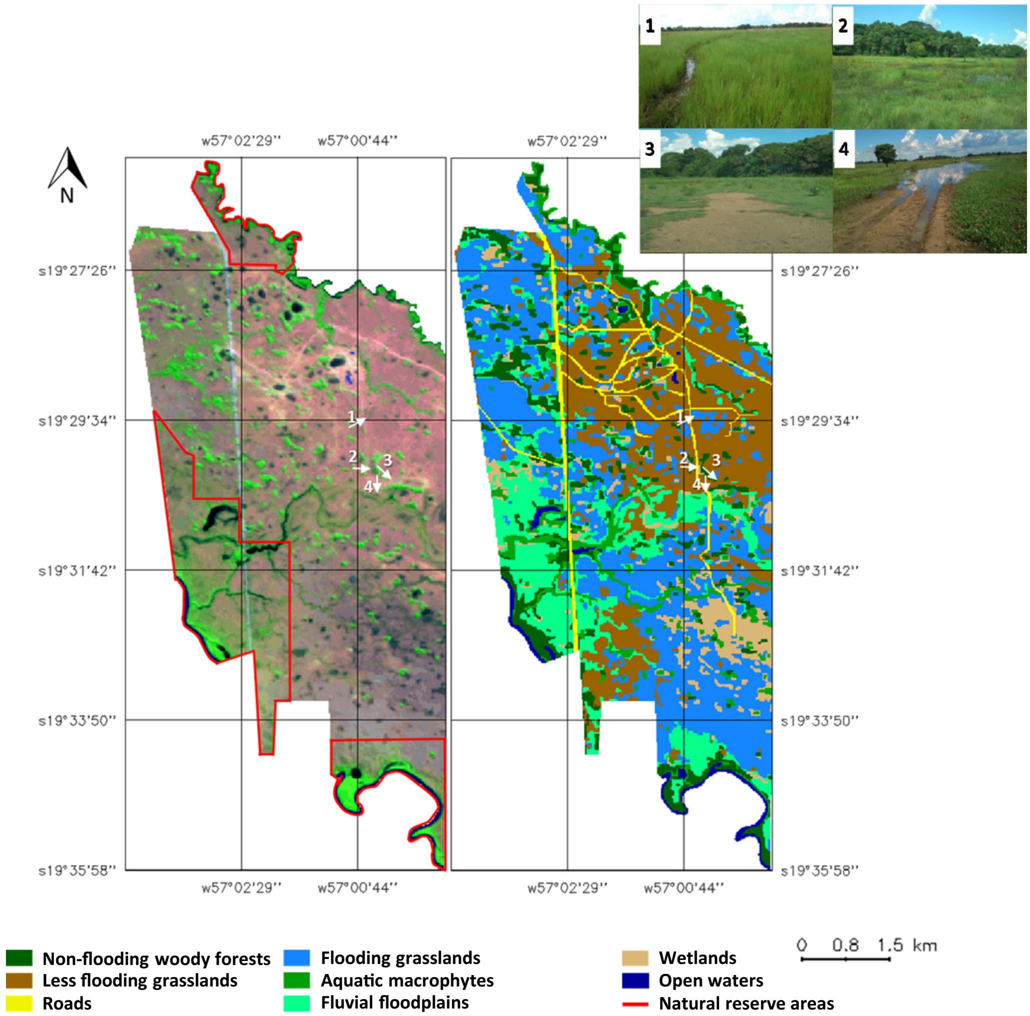

Fig. 5. Color composition PC1-5R/PC1-4G/PC1-3B (left) used for mapping spatiotemporal landscapes (right) according to interannual floods between 1985 and 2011. The red polygons in color composition image delineate natural reserve areas, called Reserva Legal in the Brazilian Forest Code (Brazil, 2012), and comprising 1843 ha or 20% of the farm area. Numbers 1 to 4 and their respective arrows (sight direction) indicate places where geotagging pictures (upper right corner) were taken for mapping validation. 1) Flooding grasslands (first plane) and non-flooding woody riparian forests (second plane). 2) Wetlands and non-flooding woody patchy forests. 3) Less flooding grasslands and non-flooding woody riparian forests. 4) Roads and fluvial floodplains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

hand, open waters aggregate running and standing water bodies lacking aquatic macrophytes.

The highest landscape in the terrain and the most representative are woody forests and less flooding grasslands. The landscape of patchy woody forests are distributed as 'islands' scattered throughout the farm. Riparian woody forests in cords are distributed alongside the rivers Miranda and Abobral and other several creeks locally known as "corixos".

Flooding grasslands are the most widespread landscape with the prevalence of species of native grasses like *Axonopus purpusii* (Mez) Chase (mimoso), *Reimarochloa brasiliensis* (Spreng.) Hitchc.) (mimosinho), *Setaria geniculata* (Lam.) P.Beauv. (red mimoso), *Axonopus argentinus* Parodi (fine grass), *Paspalum plicatulum* (felpudo), as well as *Andropogon hypogynus* Hack. (red grass) and *Andopogon bicornis* L. (rabo-de-burro). These grasses are seasonally flooded in the fluvial floodplains, filled with water by "corixos" of Miranda and Abobral rivers and by the rivers themselves as the flood reaches its acme (Abreu et al., 2001).

3.2. Defining traditional and intensified beef systems in Pantanal

In the late austral summer, livestock are moved to more elevated grazing areas due to the rising water. At Fazenda São Bento, native grasses of low nutritional value were replaced by cultivated grasses in some part of these elevated areas. *Brachiaria humidicola* has adapted successfully to the region and has improved farm productivity, especially to cattle categories more sensitive to periods of food restriction during extreme droughts after flooding (Abreu et al., 2000). Ensuring a positive trade-off between economic benefits and environmental conservation, cultivated pastures can sustain an average yield per hectare 2.25 times higher than traditional farming systems based solely on native grasses (Moraes and Sampaio, 2010).

The main advantage of the exotic *Brachiaria humidicola* in Pantanal farms is that it enhances productivity with curtailed risk of large-scale environmental impacts; the African forage tends to be restricted to topographically elevated areas, thus minimizing its competition with native grasses in areas more susceptible to enduring flood (Bao et al., 2014; Pott and Silva, 2015). Moreover, exotic forage is usually introduced in areas of native grasslands instead of native woody forests that provides other essential environmental services of water cycling, carbon storage and refugee for biodiversity (D'Odorico et al., 2010).

The 10th article of the Brazilian Forest Code (Brazil, 2012) states that in wetlands and floodplains of the Pantanal, the sustainable exploration of natural resources is permitted by considering technical recommendations of official research centers, and new suppression of native vegetation for land use is conditioned to the authorization of the state environmental agency based on scientific recommendations. For the specific case of Fazenda São Bento, the greatest interest is the substitution of native grasses for cultivated pasture in less flooding grasslands landscape, which represent 24% of the farmland area. During non-exceptional flood or dry periods, it is possible to accommodate more cattle if grazing is amended to cope with these critical periods (Abreu et al., 2000).

The number of animal unit (AU) per hectare, or simply the stocking rate, is a key indicator of economic land use efficiency in bovine systems (Balmford et al., 2018). As a response to flood dynamics, the stocking rate undergoes continuous adjustments according to pasture availability. In traditional bovine systems based on native grasslands, stocking rate vary seasonally from forage abundance (0.5 AU/ha) to scarcity (0.2 AU/ha) (Santos et al., 2003). By contrast, cultivated pasture can provide a rather constant feed supply, which can potentially increase the stocking rate up to 0.8 AU/ha (Comastri Filho, 1997).

During the falling water, in the dry season, cattle can be progressively redistributed over the farm area, using topographic higher grazing sites with cultivated pasture and lower grazing sites with native grasses. Both grazing sites represent about 72.4% of the farm area. Intensification by cultivated pasture with new technologies such as fixed-time artificial insemination, early weaning calves (in ~100 days), genetic selection and creep feeding increases pregnancy and cattle productivity (Nogueira et al., 2011, 2013, 2015; Oliveira et al., 2014). Therefore, intensification technologies enhance bovine systems, whereas its degree of sustainability will depend upon their levels of ecosystem impacts, particularly due to land-use changes and net enteric emissions (see further below).

Cattle systems in spatiotemporal flood dynamics have affinity with land sharing practices (Acton, 2014). However, major farm systems in Brazil adopt land sparing approaches (Permanent Preservation Areas or APP and Legal Reserve or RL). To adequate to the Brazilian Forest Code (Brazil, 2012), it was agreed the term Area of Restricted Use (AUR) for land sharing approaches conditioned by state government agencies. Land sharing usually involves less intensive systems in a patchy land with used areas in the midst of preserved areas, rather than splitting productive from preservation areas (Power, 2010). On the other hand, land sparing is supposed to be more effective for biodiversity conservation than land sharing (Phalan et al., 2011). This is because some species have evolved to occupy a particular ecological niche and this approach benefits the most specialized species (Acton, 2014). However, for the complex Pantanal landscapes, and in agreement with the Chapter III, article 10 of the Brazilian Forest Code (Brazil, 2012), the possibility of merging land sharing and sparing approaches through spatiotemporal mapping of landscapes may be more valuable because flood dynamics in farmlands hardly adequate land use exclusively to land sparing or to land sharing.

Long-term spatiotemporal mapping allows managing the farmland based on the proportion of landscape categories discriminated in relation to the influence of the flood cycle at several time scales, thus suitably identifying areas with vocation for intensification or conservation. The method allows conserving virtually all landscapes but grasses less susceptible to floods that can be targeted for intensification. In the present case of study, a land-use change in those areas may represent only 24% of the total farmland area (Table 2). Consequently, the integrity of the ecosystem services is preserved if one also considers the low risk of cultivated pasture colonizing often-flooded areas (Bao et al., 2014). Notwithstanding, it is recommended to keep intact a fraction of less flooding native grasses for equine herd (if any) during flood periods. Feeding equines only with cultivated pasture can lead to deficiencies in calcium that leads to imbalance in Ca:P ratio due to the high levels of calcium oxalate, which makes dietary calcium unavailable, and potentially causing maxillofacial fibrous osteodystrophy (Nunes et al., 1990).

Land sharing (grasslands as AUR) in combination with low level of land sparing (riverine floodplain as RL and eventually some woody forest as APP) complements the approach to setting fixed landscape percentages, as proposed by the Brazilian Forest Code (Brazil, 2012) and in the Embrapa Pantanal Technical Note (Embrapa Pantanal, 2014). Regardless of landscape and hydrodynamics complexities at each farm, Embrapa Pantanal (2014) suggested the following fixed quotas for the suppression of natural vegetation in the Pantanal:

- 35% of the savanna forest (Cerrado)
- 36% of woody forests (taller woody species)
- 45% of less flooded grasses
- 45% of flooded grasses (for areas with prevalence of unpalatable grasses such as red grass).

By considering suggestions from a broaden expertise committee, the State Decree 14273 (Mato Grosso do Sul, 2015), dated of October 8, 2015, in its article 9, defined that RL will be 20% of the area of the properties within the floodplain, while the article 14 established the criteria and limits for the replacement of native vegetation. Native vegetation suppression may only occur with the authorization of the Institute of the Environment of Mato Grosso do Sul (Imasul) and the ecological relevance of the species should be considered to preserve ecosystem services, which is in agreement with (Embrapa Pantanal, 2014). The first paragraph in article 14, items I and II, limits native vegetation suppression by 50% for Cerrado and woody forests and 60% for grasslands at the farm level (Mato Grosso do Sul, 2015).

3.3. A farm-based approach to guide land use in Pantanal for cattle intensification

The Pantanal is a complex biome subdivided in dozens of subregions due to intrinsic ecohydrologic and geoecologic particularities (Assine et al., 2018). Thus, fixing generic percentages for suppressing vegetation may not be the best solution for farmland management over the Pantanal. Each Pantanal farm has its peculiarities in terms of space-time flood dynamics and diversity of landscapes. For example, the ratio between elevated grasslands and the total available grasslands and forests may widely vary as a function of farm size and location. As an alternative to fixing quotas for native vegetation suppression, it might prove useful to appreciate landscapes proportions based on spatiotemporal mapping as shown in Fig. 5. Farmlands are large in Pantanal (usually ≫5000 ha), so a farm-based mapping can better define adequate degrees of sustainable intensification (percentage of native vegetation suppression).

For the case of Fazenda São Bento, the proportion between less flooding grasslands and total grasslands is 33% (2211 ha over

Table 2
Simulation of stocking rates for traditional and intensive systems in Fazenda São Bento.

	Area (hectares)	Without cultivated pasture in less flooding grasslands		With cultivated pasture in less flooding grasslands	
		Traditional herd (AU)	Stocking rate (AU/hectare)	Intensive herd (AU)	Stocking rate (AU/hectare)
Total farmland	9205	1868		3869	
Total available grasslands	6670 (72.5%)		0.28		0.58
Less flooding grasslands	2211 (24.0%)		0.84		1.75
Flooding grasslands (including RL)	4459 (48.4%)		0.42		0.87

6670 ha). A traditional farm in Pantanal can be characterized by a bovine every 3.6 ha. Hence, assuming a stocking rate of 0.28 AU per hectare in native grasslands, Fazenda São Bento may naturally sustain a bovine herd of 1868 AU. Assuming an intensified value of 0.58 AU per hectare – still lower than the values suggested by Comastri Filho (1997) – the introduction of cultivated pasture in less flooding grasslands potentially enhances the stocking rate, so that the herd more than doubles to 3869 UA (Table 2).

In this study case, the proper area for cultivated pasture is ~33%, well below the allowed limit fixed by the State Decree 14273 (Mato Grosso do Sul, 2015) (60% for the grasslands), or the quota recommended by the Technical Note of Embrapa (Embrapa Pantanal, 2014) (45% of less flooding or flooding grasslands). Moreover, for this case, the suppression of savanna or woody forests to cultivated pasture is pointless. In contrast, farmlands with minor rain/river flood influences, one may expect that demands for vegetation suppression for cattle intensification would put pressure over forested landscapes with broaden spectra of ecosystem services (D'Odorico et al., 2010; Griscom and Goodman, 2015). For those cases, land sparing would be advisable rather than land sharing (Phalan et al., 2011; Royal Society, 2014). As a result, to cope with the high complexity and variability of farmland landscapes in Pantanal, the proposed farm-based approach for mapping spatiotemporal landscapes seems very useful to guide public policies for land use and agricultural intensification.

3.4. Landscape methane emissions versus enteric methane emissions

Net Ecosystem Productivity is defined as NEP = NPP – R, where R denotes all type of decomposition processes that result in biogenic gases emissions. For dry and aired soils, R is restricted by respiration that leads to CO_2 emissions. Alternatively, for wet and anoxic soils, anaerobic microbial metabolisms result in CH_4 emissions hence accomplishing a fraction of R.

Diffusive carbon emissions (given in C-CH_4 and C-CO_2) measured in wet and dry landscapes of Fazenda São Bento are shown in Fig. 6. Dry soils of forest and less flooding grasslands showed CH_4 emissions slightly negative or null in relation to CO_2 emissions from soil and/or leaf litter respiration (open circles in Fig. 6). In contrast, the incidence of water and/or macrophytes/grasslands amplifies CH_4 emission rates (Joabsson et al., 1999; Belger et al., 2011; Hamilton et al., 2014). Methane emissions increased linearly with CO_2 emissions (dark circles in Fig. 6) indicating that, in terms of C mass, methanogenesis accounts for about 8.8% (slope = 0.0881) of R in wet landscapes of Fazenda São Bento.

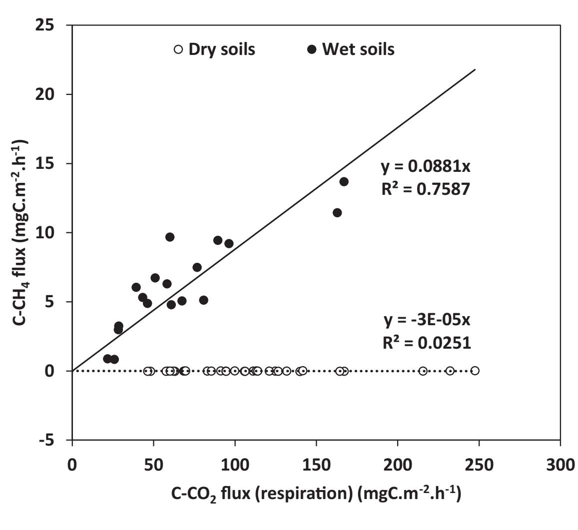

Fig. 6. Diffusive methane (C-CH_4) and carbon dioxide (C-CO_2) emissions from dry and wet soils of Fazenda São Bento obtained by stratified random sampling with the aid of the spatiotemporal map shown in Fig. 5. Offsets for both linear regressions were set as null, meaning lack of biological activity.

By considering uncertainties in methane emission distributions for wet and dry soils (Fig. 4), and uncertainties in relative area distributions in spatiotemporal landscapes (Fig. 5), it is possible to approximate an areal-integrated net methane emission from spatiotemporal landscapes distributed in the Fazenda São Bento. Monte Carlo emissions factors for dry and wet soils, the calculations of areal-integrated diffusive methane emissions to spatiotemporal landscapes, and the estimative of the net farmland methane emissions are presented in Table 3.

According to our calculations, areas of forests and less flooding grasslands in Fazenda São Bento are slight atmospheric sinks in between −3.2 and − 0.6 Mg CH_4 per year. However, net methane emissions between sources and sinks is highly positive ranging from +3.3 to +5.5 Gg CH_4 per year, defined by both duration and intensity of the annual flood (Junk et al., 1989; Hamilton et al., 2014).

Results in Table 3 allow discriminating bovine systems in Cerrado and Amazon biomes, based on forest substitution to pasture (deforestation), from bovine systems in Pantanal where land use is comparatively less impacting, and the background landscape is a large methane source to the atmosphere. Considering the uncertainties in enteric emission factors for Nellore in Pantanal, given in Oliveira et al. (2016), the annual enteric emissions can be estimated as 0.1–0.2 Gg CH_4 and 0.2–0.5 Gg CH_4 respectively for the traditional and intensive stocking rates given in Table 2. Note that these numbers are respectively only 4.3–10% and 8.9–20% of landscapes net CH_4 emissions given in Table 3. In addition, our calculations have neither taken into account bubble methane emissions (Bastviken et al., 2010) nor the magnification of diffusive methane emissions during episodic events of strong anoxia during the flooding water phase of the flood pulse (Bergier et al., 2016). Considering the great variability of interannual flood intensities, bovine enteric emissions in flooding farmlands located in the Pantanal can thus be negligible in relation to massive flooding grasslands and wetlands methane emissions.

For supporting this argument, consider a lack of cattle at the Fazenda São Bento. What would be the fate of the atmospheric CO_2 drowned by grasslands (NPP – $R_{grasses}$) naturally fertilized by the flood pulse? Overall, that biomass can follow any of the following pathways:

1) Ingested by primary consumers of the terrestrial food-web and returned to the atmosphere as biogenic gases;
2) Burned in lightning or man-made fires and returned to the atmosphere as pyrogenic gases;
3) Incorporated in the aquatic food-web, degraded by aquatic bacteria and returned to the atmosphere as biogenic gases; or
4) Buried in soils/sediments as inorganic/organic refractory C.

In the present study, we provide new R data from dry and wet soils. Additional whole ecosystem level data would be necessary to fathom whole ecosystem C budgets. Nevertheless, consider that cattle introduced >200 years ago (Abreu et al., 2010) replace ecological functions of herbivory by extinct megafauna (Galetti, 2004) that grazed potentially high NPP (profusely solar energy and water) of tropical freshwater wetlands (Sjögersten et al., 2014). If this premise is correct, it is very likely that the traditional (and sustainable) system, with a stocking rate between 0.2 (drier years) 0.5 (wetter years) AU/ha (Santos et al., 2003), could be making use mostly of R (Bergier and Salis, 2011) or a small fraction of NEP (Takahashi et al., 2010).

Furthermore, archaea methanogens represent a minority when compared to fibrolytic anaerobic bacteria in bovine rumen. Approximately 60 to 90% of the microbial mass in rumen are bacteria, whereas the remaining comprises fungi and protozoa. In diets rich in amylolytic and forage-concentrated, the proportion of protozoa and fungi increases. On the other hand, in highly fibrous diets, such as Pantanal grasslands and cultivated pasture, most of these bacteria are fibrolytic and their proportion is close to 90% or more. Archaea methanogens

Table 3
Diffusive methane emissions from spatiotemporal landscapes of Fazenda São Bento.

Spatiotemporal landscape	Area (hectares)	Area (%)	Emission factor range ($mg\ CH_4 \cdot m^{-2} \cdot h^{-1}$)		Areal-integrated fluxes ($Mg\ CH_4 \cdot y^{-1}$)		Data source of emission factors
Forests	885.5	10	−0.013	−0.002	−1.0	−0.2	This study
Less flooding grasslands	2010.4	22	−0.013	−0.002	−2.2	−0.4	This study
Aquatic macrophytes	607.5	7	6.327	10.423	336.7	554.5	This study
Fluvial floodplains	1501.3	16	6.327	10.423	832.1	1370.4	This study
Flooding grasslands	3185.9	35	6.327	10.423	1765.7	2908.0	This study
Wetlands	584.5	6	6.327	10.423	324.0	533.7	This study
Open waters	138.1	2	0.292	9.917	3.5	119.9	Alvalá and Kirchhoff (2000)
Roads	291.8	3	–	–	–	–	This study
Total	9205	100	–	–	3258.9	5487.4	This study

arise to remove the excess H^+, a natural derivative of fiber degradation in the ruminal milieu. In this case, the metabolic function of methanogens is secondary and related to the homeostasis of pH conditions in the rumen by removing the H^+ excess produced in the degradation of fibrous carbohydrates (Van Soest, 1994; Morgavi et al., 2010). Enteric bovine emissions can be comparable to methane emissions from methanogens (actual mammals e.g. *Ozotoceros bezoarticus* and *Mazama sp*., or insects e.g. termites) or from methanogens in flooded lands. However, by assuming that a typical extensive bovine system in Pantanal does not compete with native herbivory (Santos et al., 2003), also due to large NPP in tropical wetlands (Sjögersten et al., 2014), and the higher proportion of ruminal fibrolytic anaerobic bacteria, enteric emissions could be indeed negligible when compared to methane emissions by diffusion and bubbles from flood and wet landscapes of the farmland.

From these premises, we sustain that the traditional extensive cattle system, with a stocking rate between 0.2 and 0.5 AU/ha in flooding lands of the Pantanal, should be regarded as C neutral in elaborating official emission reports for international climate agreements like the Paris Agreement of the UNFCCC (United Nations Framework Convention on Climate Change). However, in cases of intensification, anthropogenic emissions should be considered as net enteric emissions derived from the increasing of the stocking rate. For the Fazenda São Bento case (Table 2), a quasi-sustainable intensification through land-use change provided an increase of the mean stocking rate from 0.28 to 0.58 AU/ha, a little above the upper limit of a sustainable system for wet years. To attain to the upper limit of the neutral enteric emission range, the herd should be lowered in 534 bovine animals; otherwise, it must be communicated a corresponding net annual enteric emissions of 27.5 to 63.0 Mg of methane.

The traditional extensive cattle breeding in Pantanal is a farmland system with high renewability since it uses few inputs of fossil origin and depends mostly on matter and energy maintained by the flood pulse (Takahashi et al., 2010; Bergier and Salis, 2011). The cattle affects the recycling of matter and energy, so that the traditional and sustainable livestock in Pantanal appropriates a small fraction of NEP and perhaps a large fraction of R for producing bovine products in balance with biodiversity (Santos et al., 2003) and with environmental services provided by floodplains and wetlands (Wantzen et al., 2008). The magnitude and uncertainties of methane emissions from the natural landscapes are much higher than those for cattle enteric emissions, and there are indications that, in the lack of livestock, methane emissions from flooded grasses ($R_{wetland}$) could be greater than enteric emissions that consume that biomass (R_{bovine}). Therefore, bovine livestock in flooding farmlands of the Pantanal, while maintained at sustainable stocking rates, should be considered as "Carbon Neutral Beef" or even mitigators of CH_4 emissions (to be evaluated by further studies) in national anthropogenic greenhouse gases reports and communications. Conversely, cattle intensification by land-use changes in the Pantanal should consider the net enteric emissions by looking at the sustainable stocking rate range. In summary, the results herein discussed, including the farm-based spatiotemporal mapping of landscapes, have also positive implications for the management of natural resources and ecosystem services at several space and time scales. Moreover, it can stimulate best practices and sustainable market niches for improving the competitiveness of bovine products delivered by the Pantanal floodplains and wetlands.

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