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The neglected contribution of mound-building termites on CH_4 emissions in Brazilian pastures

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ABSTRACT - Based on previous reports, our study aimed to obtain the first estimate on the contribution of termite mounds to CH_4 emissions in Brazilian Cerrado pastures. We estimated that termite mounds occupy an area larger than 200,000 ha in degraded pastures, an important loss of grazing area considering the current scenario of land-use change of pastures to other crops in Brazil. Moreover, mound-building termites in degraded pastures may be responsible for CH_4 emissions greater than 11 Mt CO_2 eq. yr^{-1}, which would notably affect the greenhouse gases (GHG) balance of grass-fed cattle production in Brazil. In this sense, it is urgent to conduct field-scale studies about the CH_4 emissions by mound-building termites in pastures and its contribution to the C footprint of Brazilian beef.

Keywords: biogenic CH_4, Brazilian Cerrado, greenhouse gases, pasture degradation

1. Introduction

Global average methane (CH_4) concentrations in atmosphere reached ~1875 parts per billion at the end of 2019, more than 2.5 times that of preindustrial levels (Dlugokencky, 2020). Unfortunately, CH_4 presents a potential greenhouse effect 25 times higher than CO_2 on a timespan of 100 years. Currently, more than 580 Tg yr^{-1} of CH_4 are released into the atmosphere, with more than 70% of this value originating from biogenic sources (Saunois et al., 2020). Among the biogenic sources of CH_4, importance must be given to ruminants, waterlogged areas, peatlands, and termites (Saunois et al., 2020). Although the less attention recently received, termites had been associated with about 15% of the entire CH_4 emitted globally (Rasmussen and Khalil, 1983).

Nowadays, Brazil is the second biggest beef exporter and has the second largest herd in the world, only surpassed by India. Most livestock production is grass-fed, extensive, and spread across the Cerrado biome. Cerrado occupies an area of 204.7 million ha in central Brazil. Pastures are the main land use in this biome, occupying more than 54 million ha (Sano et al., 2008). It is estimated that 60% of Cerrado pastures are degraded in some level (Andrade et al., 2014). Generally, degraded pastures exhibit low plant and animal productivity, reduced soil cover, soil erosion and compaction, and invasion of weeds. Despite the contentious relationship between termite infestation and pasture degradation (Lima et al., 2011), a high infestation of mound-building termites is certainly an indicator of pasture degradation (e.g., Spain and Gualdrón, 1988; Santos et al., 2007; Miranda et al., 2012).

Enteric fermentation is the main source of CH_4 in Brazil, being responsible for the emission of 246 million Gg CO_2 eq yr^{-1} (MCTI, 2014), whilst one of the main sources of N_2O emissions is the deposition of urine and feces from cattle in pasture areas. Certainly, these sources are the most important in the fluxes of greenhouse gases (GHG) from pastures. However, is possible that C inventories have neglected the role of an important component in CH_4 emissions from pastures: mound-building termites. The methanogenesis is beneficial to termites, by removing the H_2 (intermediate in the fermentation process), which permits reduced cofactors to be re-oxidized, increasing the fermentation of cellulosic material (Grieco et al., 2013). However, this process is responsible for CH_4 production, the main negative outcome of termite-microbe symbiosis. Studies carried out in Africa (Brümmer et al., 2009) and Oceania Savana (Jamali et al., 2011a) highlighted the notable contribution of mound-building termites in CH_4 emissions of these areas. In Brazil, oddly enough, there is no published study about the CH_4 emissions by mound-building termites from Cerrado pastures.

Pasture recovery and deforestation reduction are goals reinforced in the Brazilian intended Nationally Determined Contribution (iNDC) set during the United Nations Conference on Climate Change (iNDC Brazil, 2015). The Brazilian government has ambitious goals for the next years: reduce GHG emissions by 37% by 2025 and 43% by 2030, compared with 2005. To do so, one of the commitments of the Brazilian iNDC is to strengthen the Low Carbon Emission in Agriculture Program (ABC Program; Brasil, 2012) as the main strategy for sustainable agriculture development, including restoration of additional 15 million ha of degraded pastures by 2030. Pasture recovery and sustainable intensification of cattle farming is well-known for reducing GHG emissions and the C footprint of Brazilian beef (Silva et al., 2016). However, the magnitude of this mitigation could be greater if an important source of GHG in degraded pastures were accounted in inventories: mound-building termites.

In this sense, this study was the first attempt to obtaining an estimate regarding the contribution of mound-building termites in CH_4 emissions of Cerrado pastures. Specifically, based on previous reports, we aimed to identify Cerrado pastures under different degradation levels, estimate the average infestation by mound-building termites associated with each degradation level, calculate the loss of grazing area due to mound termite infestation, and estimate CH_4 emissions by termites in degraded pastures of Brazilian Cerrado.

2. Material and Methods

After a comprehensive literature review and using all available data from previous studies, our research estimated CH_4 emissions by termites in pastures from Brazilian Cerrado. In each stage, a compilation, analysis, and extrapolation using all the available data were carried out. Initially, it was assumed that 60% of Cerrado pastures are degraded (Andrade et al., 2014). Then, from the few studies regarding this topic, the pasture area under different degradation levels was estimated (low to moderate, high, and very high). As observed in studies used in our assessment, the model proposed by Spain and Gualdrón (1988) is still applied as a reference for diagnosis and classification of the degradation process in pastures. In this model, the occurrence of termite mounds is one of the indicators for highest degradation levels. Thus, infestation by mound-building termites and its associated CH_4 emissions were assumed as being significant only to pastures under high and very high degradation levels.

Split pastures by different degradation levels was very useful, considering that termite infestation is quite variable among areas. In this way, it was possible to associate a level of infestation by termites with a level of pasture degradation, as also proposed by Santos et al. (2007) and Miranda et al. (2012). The level of infestation by mound-building termites was estimated using different studies carried out across Brazilian Cerrado (Figure 1). Based on the approach proposed by Spain and Gualdrón (1988), we assumed infestations of 70 and 200 mounds ha^{-1} as the bottom limit associated to high and very high levels of pasture degradation, respectively. To calculate the area occupied by termite mounds, seven studies were used, all carried out in Brazilian Cerrado (Figure 1). Moreover, it was assumed that 88% of termite mounds are active, according to Lima et al. (2015), Senci and Junqueira et al. (2013), Lima et al. (2011), and Cunha and Morais (2010).

Studies carried out in other countries were used to estimate CH_4 emissions by termites. The total lack of this type of research in Brazil justifies our approach. However, the values utilized were obtained from savanna areas with termite mounds of *Termitideae* family, conditions that most closely mimicked those in Brazilian Cerrado. Although the relation between termite population weight and CH_4 emissions is widely used, estimates considering the CH_4 emissions per area of mound are assumed more realistic (Brümmer et al., 2009; Jamali et al., 2011a). In this respect, we opted for studies with measurements by a unit of area.

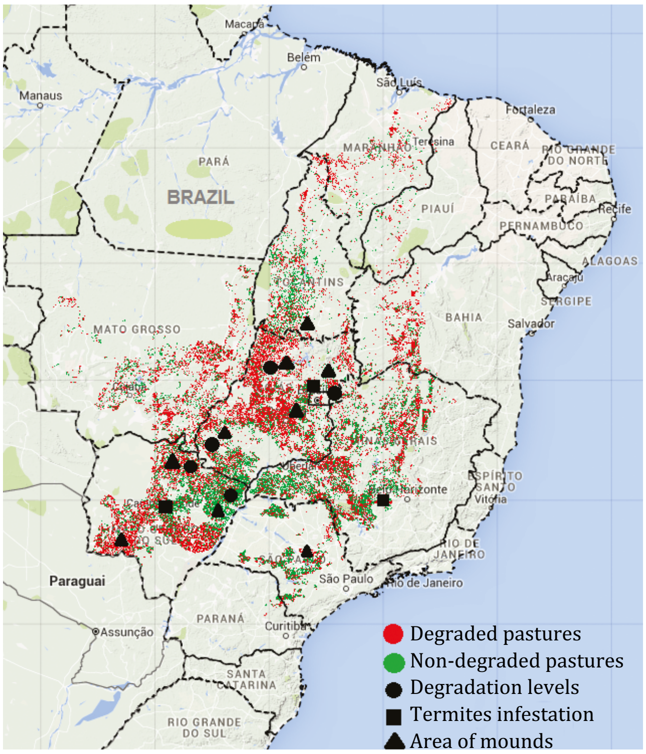


Figure 1 - Pastures in Brazilian Cerrado (adapted from Andrade et al., 2014) and locations of the studies available in literature and used in each step of this assessment.

3. Results

We estimated that 13.8±3.2 million ha of pastures in Brazilian Cerrado are low to moderately degraded, whilst 15.4±2.8 and 3.0±1.6 million ha are in high and very high degradation levels, respectively (Table 1). Thus, at least 50% of the degraded pastures are in advanced degradation stages. Levels of infestation by mound-building termites notably vary in degraded pastures of Brazilian Cerrado (Table 2). We assumed a bottom limit of 70 mounds ha^{-1} associated with a high degradation level, estimating an infestation of 145.1±48.3 mounds ha^{-1}. For degraded pastures in the very high level, a minimum number of 200 mounds ha^{-1} was assumed, with a mean infestation of 398.7±107.3 mounds ha^{-1} (Table 2). The mean basal area of termite mounds in Brazilian Cerrado pastures is 0.59±0.33 m^2 (Table 3). Thus, we estimated that in a high degradation level, termite mounds represent 0.9% of the total area, whilst in very high degradation level, they occupy 2.4% of the pasture area. Consequently, termite mounds could occupy 204,000 ha in severely degraded pastures from Brazilian Cerrado.

Mean annual CH_4 emissions by mound-building termites are 0.311±0.17 kg m^{-2} (Table 4). Using the previously mentioned results, we estimated that termites in degraded Cerrado pastures could emit 0.56 Tg CH_4 yr^{-1}, 0.364±0.022 Tg CH_4 yr^{-1} from pastures in a high level and 0.195±0.028 Tg CH_4 yr^{-1} from pastures in a very high degradation level (Figure 2). The CH_4 emissions by mound-building termites in degraded pastures from Cerrado could represent 3% of the GHG emissions of Brazilian agriculture (Figure 3), surpassing 11 Mt CO_2 eq. yr^{-1}.

Table 1 - Degradation levels in Cerrado pastures

Reference	Origin	Degradation level (%)		
		Low to moderate	High	Very high
Moreira and Assad (2000)	DF	54	39	7
Nascimento et al. (2006)	MG	37	56	6
Miranda et al. (2012)	MS	37	48	15
Mean		42.7±9.8	47.7±8.5	9.3±4.9
Cerrado (million ha)[1]		13.8±3.2	15.4±2.8	3.0±1.6

MS - Mato Grosso do Sul State; DF - Distrito Federal; MG - Minas Gerais State.
[1] Considering an area of 54 million ha of pasture in Cerrado, of which 60% are degraded (Andrade et al., 2014).

Table 2 - Levels of infestation by mound-building termites in Cerrado pastures in different degradation levels

Reference	Origin	Mounds ha^{-1}
	High degradation	
Valério (1995)	Mato Grosso do Sul	200
Czepak et al. (2003)	Goiás	73
Valério et al. (2006)	Mato Grosso do Sul	170
Cunha and Morais (2010)	Goiás	182
Cunha (2011)	Goiás	196
Lima et al. (2011)	Mato Grosso do Sul	128.5
Senci and Junqueira (2013)	São Paulo	113
Lima et al. (2015)	Mato Grosso do Sul	98
Mean		145.1±48.3
	Very high degradation	
Valério et al. (2006)	Mato Grosso do Sul	287
Oliveira et al. (2011)	Goiás	408
Oliveira et al. (2011)	Goiás	501
Mean		398.7±107.3

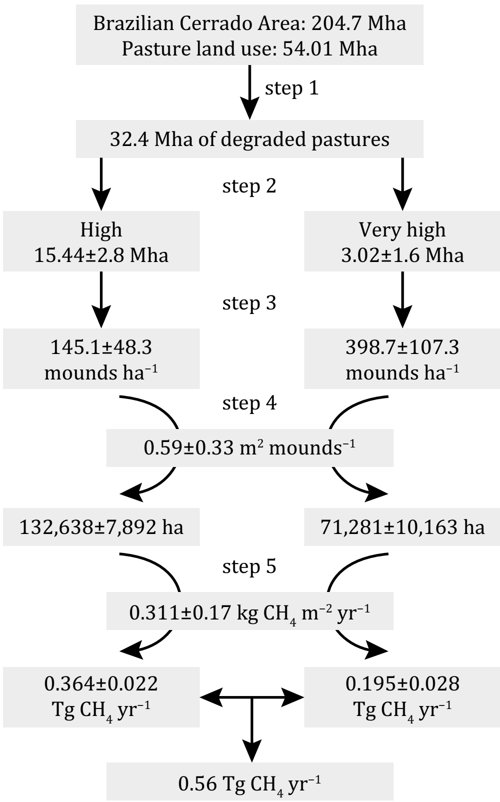
Table 3 - Mean basal area of termite mounds in Cerrado pastures

Reference	Origin	Area (m^2)
Valério (1995)	Mato Grosso do Sul	0.50
Czepak et al. (2003)	Goiás	0.53
Cunha and Morais (2010)	Goiás	0.96
Cunha (2011)	Goiás	1.05
Benito et al. (2007)	Distrito Federal	0.23
Oliveira et al. (2011)	Goiás	0.16
Lima et al. (2015)	Mato Grosso do Sul	0.71
Mean		0.59±0.33

Table 4 - Mean annual emissions of CH_4 by mound-building termites

Reference[1]	Origin	CH_4 (kg m^{-2} yr^{-1})
Khalil et al. (1990)	Australia	0.639
Brümmer et al. (2009)	Burkina Faso	0.246
Brümmer et al. (2009)	Burkina Faso	0.345
Jamali et al. (2011a)	Australia	0.423
Jamali et al. (2011b)	Australia	0.159
Jamali et al. (2011b)	Australia	0.236
Jamali et al. (2011b)	Australia	0.130
Mean		0.311±0.17

[1] Values obtained under savanna conditions in termite mounds of the *Termitideae* family.

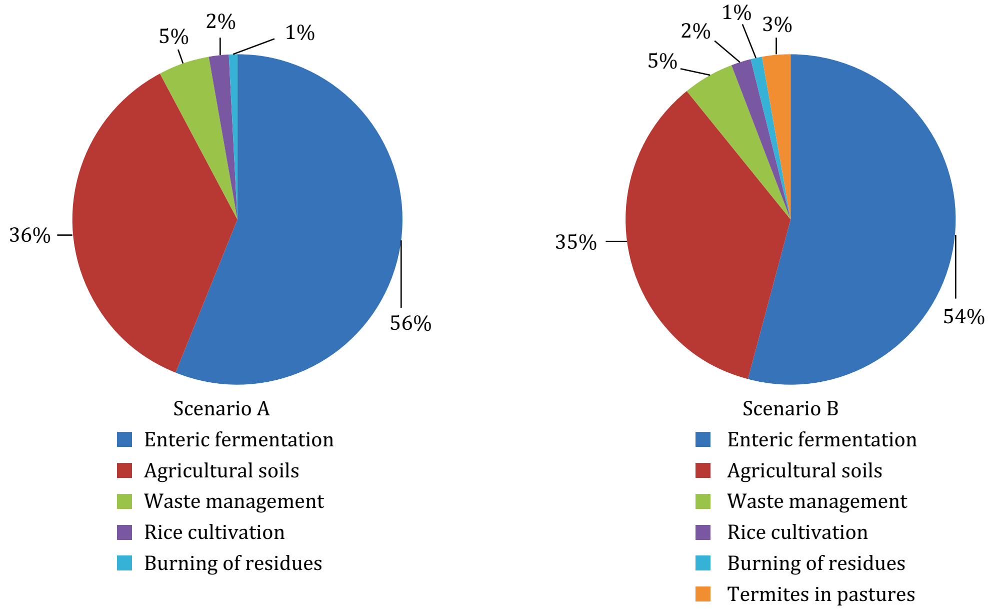


Currently, 60% of the pastures in Cerrado are degraded (1). We divided this area in different degradation levels (2) and estimated the average incidence of termite mounds for each one of these levels (3). Posteriorly, we estimated the average area occupied by each termite mound and used this value to calculate the total area occupied by termite mounds in degraded Cerrado pastures (4). Finally, using the available estimates of CH_4 emissions by mound-building termites in savanna regions and the total area occupied by termite mounds estimated in this research, we estimated the CH_4 emissions by mound-building termites in degraded Cerrado pastures.

Figure 2 - Step-by-step of the estimation of CH_4 emissions by mound-building termites in degraded pastures of Brazilian Cerrado.

4. Discussion

It was estimated that 46-63% of the degraded pastures in Brazilian Cerrado may be in a high or very high degradation level (Table 1). Pastures occupy 54 million ha in Cerrado (Sano et al., 2008), where approximately 60% is degraded (Andrade et al., 2014). Our assessment corroborates studies of Miranda et al. (2012) and Nascimento et al. (2006), both concluding that about 65% of the evaluated pastures was moderate to highly degraded. Moreover, Moreira and Assad (2000) highlighted that at least 45% of the Brazilian Cerrado pastures were in advanced degradation stages. The severe



Scenario A represents values currently accounted (MCTI, 2014), whilst scenario B also includes the emissions by mound-building termites in degraded pastures of Brazilian Cerrado estimated in this study.

Figure 3 - Greenhouse gas emissions from Brazilian agriculture by sources (Mt CO_2 eq.).

degradation scenario observed in most pastures brought out concerns about the sustainability of livestock production in Brazilian Cerrado, besides reiterating the importance of national policies to improve pasture conditions, such as the ABC Program.

Defining whether a given pasture is degraded or not is based on a set of indicators about plant and soil. Currently, there is no agreement in relation to the trustworthiness and feasibility of these indicators, as well as the closeness of the association between them and the degradation process. Mound-building termites are consumers of dead grass residues. Thus, in pastures approaching the final degradation stages, an explosion in the termite population may occur (Oliveira et al., 2012). Furthermore, there is a large incidence of termites in soils undergoing advanced degradation stages (Oliveira et al., 2012). Boddey et al. (2004) suggested that at least 50% of Brazilian pastures were in advanced degradation stages, with low grass yield and soil cover, invaded by weeds, and in many cases densely occupied by termite mounds. In addition, in degraded Cerrado pastures, the mound-building termite population is usually high (Lima et al., 2015). According to Cunha and Morais (2010), the density increment of termite mounds in pastures could occur due to the homogeneity of the environment and less competitors/predators. Finally, the conversion of native vegetation to pastures, coupled with pasture aging and degradation, can create a favorable environment to drastically increase the population of some termite species in Brazilian Cerrado (Carrijo et al., 2009). Thus, despite the contentious relationship between termite infestation and pasture degradation (Lima et al., 2011), all this evidence supports that termite infestation is a reliable indicator of pasture degradation in Brazilian Cerrado.

Severely degraded pastures in Brazilian Cerrado are densely infested by mound-building termites, which we estimate to have 145.1±48.3 and 398.7±107.3 mounds ha^{-1} under high and very high degradation levels, respectively. Estimating the infestation level and number of mound-building termites in Cerrado pastures, Oliveira et al. (2011) evaluated areas of 5 ha and found between 195 and 672 mounds ha^{-1}. Lima et al. (2015) and Cunha (2011) observed lower values, 68-127 and 196 mounds ha^{-1}, respectively. Finally, in a study carried out in 133 municipalities across Brazilian Cerrado, Czepak et al. (2003) obtained a mean of 73 mounds ha^{-1}, with a minimum of 3 mounds ha^{-1} and values reaching a maximum of 500 mounds ha^{-1}. The notable variability of infestation levels observed in these studies emphasize that the use of a general mean disregarding the degradation level would jeopardize the reliability of our assessment.

The basal area of termite mounds in degraded pastures of Brazilian Cerrado also notably fluctuate (Table 3). In a widespread assessment, Czepac et al. (2003) observed an average basal area of 0.53 m^2. However, Cunha (2011) concluded that the mean basal area of termite mound was 1.05 m^2. More recently, Lima et al. (2015) published a value of 0.71 m^2 for basal area of the termite mounds in degraded pastures. Factors that influence variations in the basal area of termite mounds in pastures are not well established. However, in more mature pastures, which commonly are in a more advanced degradation stage, termite mounds are usually older and have a larger basal area. Accordingly, as well as with the infestation level, the basal area of the termite mound may be used as an indicator of pasture degradation in further assessments.

Besides CH_4 emissions, impacts associated with the presence of termites in pastures range from the fact that the mounds could be shelters for venomous animals to damage associated with grazing area losses. However, several studies have reported that infestation by mound-building termites does not significantly affect the grazing area. Area losses associated with termite infestations vary among 0.1% (Lima et al., 2011) to 2.06% (Cunha, 2011) of the total grazing area. Considering the estimates from Table 3, termites are associated with grazing area losses of 132,628±7,892 ha under a high degradation level and 71,281±10,163 ha in pastures under a very high degradation level. Therefore, termite mounds could occupy an area larger than 200,000 ha in degraded pastures of Brazilian Cerrado, a remarkable loss that deserves more attention. In addition, in a scenario of land-use change of pastures to other crops, such as sugarcane and soybean (Lapola et al., 2014), any loss of grazing area must be considered.

Emissions of CH_4 by mound-building termites are determined by the balance between CH_4 production and CH_4 oxidation after release. Considering that there is no evidence that the intestines of these insects contain microbes that oxidize CH_4 (methanotroph), the CH_4 produced is directly released to the environment. However, the microbes present in the material that makes up the termite mound can act as a CH_4 sink, by the oxidation of this GHG (Brümmer et al., 2009; Nauer et al., 2018). Thus, CH_4 emissions could be greater if these methanotrophic organisms were not present in termite mounds, although the dynamics of this process, as well as the community responsible for the phenomenon, are not yet fully known (Chiri et al., 2020). In this way, estimates that consider the balance of CH_4 fluxes at the surface of the termite mounds assessed by chambers (e.g., studies of Table 4) are much more realistic when compared with emissions by a mass of termites under incubation in artificial conditions (Brümmer et al., 2009; Jamali et al., 2011a).

Termite species from the *Cornitermes* genus are the main responsible for the construction of epigeal mounds in Brazilian pastures, occupying 94% of the termite mounds in Cerrado (Valério et al., 2006). The predominant species of mound-building termites are *Cornitermes cumulans*, *C. bequaerti*, *C. silvestrii*, and *Syntermes Holmgren*, all included in the *Termitidea* family. In Brazil, studies have estimated CH_4 emissions by termites after deforestation in Amazonia (e.g., Martius et al., 1993). In these cases, termites are usually from other genera, consume the remaining biomass after burning, and do not build mounds. In this sense, using data from other savanna regions to estimate the CH_4 emissions of mound-building termites in Cerrado pastures, within the options available, is the most feasible and realistic approach.

We estimated annual CH_4 emissions of 0.311±0.17 kg m^{-2} by mound-building termites in other savanna regions (Table 4). The amplitude of termite CH_4 emissions are still debatable, and few estimates were carried out on national or biome scales. From the previous results mentioned, we estimated that termites present in degraded Cerrado pastures could emit 0.56 Tg CH_4 yr^{-1} (Figure 2). Because the large pasture area, coupled with the high level of infestation by mound-building termites, this first assessment of CH_4 emissions by termites in degraded pastures of Brazilian Cerrado are comparable with those from the African (0.9 Tg CH_4 yr^{-1}; Brümmer et al., 2009) and Australian (1.1 Tg CH_4 yr^{-1}; Jamali et al., 2011b) savannas.

The inclusion of CH_4 emissions by mound-building termites could impact GHG emissions by agriculture in Brazil (Figure 3). Disregarding emissions associated with deforestation and land-use change, Brazilian agriculture was responsible for the direct emission of 441 Mt CO_2 eq. in 2012 (MCTI, 2014). However, this calculation did not consider the CH_4 emissions by mound-building termites in degraded pastures, which in our assessment is associated to emissions greater than 11 Mt CO_2 eq. yr^{-1}. When scenario A (without termite emission) is compared with scenario B (including termite emissions), it is possible to notice that GHG emissions by termites exceed those from rice cropping and residue burning in Brazil (Figure 3).

We are sure that the lack of experimental data and all assumptions through our calculations jeopardize the applicability of our findings. Similarly, using data from other countries and spatial extrapolations about CH_4 emissions are prone to bias, since GHG emissions are known to be highly dependent on environmental constraints. In this sense, despite the limitations discussed above, the data presented in our research aim to show the likely direction and relative magnitudes of CH_4 emissions by termites in Brazilian pastures. Moreover, it is an indisputable evidence about the need for carrying out studies regarding these emissions and their possible contribution to C footprint of Brazilian beef or even to C savings in recovered pastures. The CH_4 emissions could be greater or smaller than estimated here, but this approximation would be a starting point for research development regarding the neglected contribution of mound-building termites on CH_4 emissions in Brazilian pastures.

5. Conclusions

The large population of mound-building termites generally observed in degraded pastures must not be ignored. It is estimated that termite mounds occupy an area larger than 200,000 ha in Cerrado pastures, an important grazing area loss considering the current scenario of land-use change of pasture to other crops in Brazil. Additionally, based on previous reports, our estimates indicate that the degradation of pastures is associated with the inclusion of a new component in the C balance of these areas: termites. Mound-building termites in degraded pastures could be associated to CH_4 emissions greater than 11 Mt CO_2 eq. yr^{-1}, which can notably affect the GHG balance of grass-fed cattle production in Brazil. Therefore, it is urgent to conduct field-scale studies about CH_4 emissions by mound-building termites and their contribution to C footprint of Brazilian beef or even to C savings in recovered pastures.

The large and increasing role CH_4 plays in climate change, in particular on a shorter timescale, makes emission reductions imperative. Assuming the relationship between termite infestation and pasture degradation, CH_4 emissions by mound-building termites in Cerrado pastures are mitigatable. In this sense, the restoration of additional 15 million ha of degraded pastures by 2030 suggested in the Brazilian iNDC would have an additional C saving. Pasture recovery drastically reduce the mound-building termite population and, therefore, the associated CH_4 emissions. Better emission inventories are mandatory to include the role of termites in GHG emissions of Cerrado pastures or even to account for CH_4 emissions mitigated by the reduction of mound-building termite population in recovered pastures. In the near future, we believe that CH_4 termite emissions mitigated by pasture recovery may be accounted for Brazil to achieve the iNDC commitments.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: D.M.S. Oliveira, E.M. Araújo and E.F. Frade Junior. Data curation: D.M.S. Oliveira, E.M. Araújo, E.F. Frade Junior and L.G. Pimentel. Formal analysis: D.M.S. Oliveira. Funding acquisition: C.E.P. Cerri. Methodology: D.M.S. Oliveira and E.M. Araújo. Supervision: C.E.P. Cerri. Validation:

D.M.S. Oliveira. Writing-original draft: D.M.S. Oliveira, E.M. Araújo, E.F. Frade Junior, L.G. Pimentel and C.E.P. Cerri. Writing-review & editing: D.M.S. Oliveira.

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