Mitig Adapt Strateg Glob Change (2015) 20:425–438
DOI 10.1007/s11027-013-9499-2

ORIGINAL ARTICLE

Towards a representative assessment of methane and nitrous oxide emissions and mitigation options from manure management of beef cattle feedlots in Brazil

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Received: 22 March 2013 / Accepted: 8 August 2013 / Published online: 3 September 2013

Abstract We conducted an inventory to estimate methane (CH_4) and nitrous oxide (N_2O) emissions from beef cattle feedlot manure in Brazil for the year of 2010. The aim was to determine (CH_4) and (N_2O) emissions from beef cattle feedlot manure in Brazil using the IPCC United Nations Intergovernmental Panel on Climate Change approach and present a framework that structures priority research for decreasing uncertainties and assessing mitigation scenarios. The analysis consisted of the use of specific farm-scale activity data applied to the 2006 (IPCC) guideline equations for animal manure management updated with specific parameters for Brazil conditions. Uncertainties were assessed by error-propagation technique. The results indicated that 376.6 $GgCO_2eq$ were emitted from the manure management of beef cattle feedlots in Brazil in 2010. Nitrous oxide accounted for 61 % of total emissions, out of which 69 % came from

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direct emissions. Uncertainties were high, comprising −30 to +80 %. Solid storage-heap and field application were the largest sources of greenhouse gas (GHG) emissions (81 % of total emissions) and held most of the variance in uncertainties. Although, due to limitations in the IPCC methodology for integrating GHG emissions at farm-scale, we could not account for emissions occurring from different lengths of time in each manure management compartment prior to field application. As a consequence, this GHG inventory lacks consistence. The use of more robust methodologies such as process-based models are recommended for improvements, however they are currently unavailable because there is a lack of key data for Brazil conditions for validating those models. Our literature revision shows that the most effective research for raising those data would track emissions from manure: generated from male Nellore (*Bos Indicus*) cattle fed for 90 days with a high-energy diet, removed only at the end of feeding period and held in heaps over 60 days before being applied to maize (*Zea mays* L.) cropping fields under clay soil. The proposed research and methodology approaches described in this work is required to establish a manure management emission assessment that will become more responsive to the changing practices on Brazilian beef cattle feedlots and, consequently, permitting implication of mitigation scenarios to be ascertained.

Keywords Animal manure · Activity data · Emission assessment · Methane · Nitrous oxide

1 Introduction

The Brazilian beef cattle feedlot industry more than doubled in the last 8 years (from 1.96 to 3.74 million heads in 2012), now representing almost 10 % of beef slaughter in Brazil (Millen et al. 2009; ANUALPEC 2012). Additionally, this intensive type of beef production is likely to increase in the next decades in order to supply future demands and growing populations (UNEP 2011).

A large amount of manure production in a limited space is an inevitable consequence of feedlots. Once excreted by the animals, manure undergoes a series of reactions, from which can be produced the three greenhouse gases (GHG), methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), in addition to ammonia (NH_3; Li et al. 2012). Additionally, the type of manure management adopted (housing, storage or treatment and field application) impacts these reactions and, consequently, the amount of both CH_4 and N_2O emitted (Chadwick et al. 2011).

The most representative manure management practice in Brazilian cattle feedlots consists of the removal of manure from pens only at the end of the feeding period. Subsequently, the manure is stored in heaps before being applied to crop and pasture lands (Costa Junior et al. 2013).

However, no data regarding GHG emissions from manure management in beef cattle feedlots are available for Brazilian conditions. Guidelines by the United Nations Intergovernmental Panel on Climate Change (IPCC) provide the best widely applicable defaults for compiling national GHG inventories. However, since livestock farms are complex systems with different interacting components including soils, crops, feeds, animals and manures, the approaches that best reduce GHG emissions will depend on local conditions, necessitating specific individual approaches to evaluate appropriate mitigations (Chadwick et al. 2011; VanderZaag et al. 2013).

Thus, the robustness of these inventories is dependent on developing country specific emission factors and verifying emissions inventories via modeling and/or direct measurement (IPCC 1997). Consequently, the IPCC developed a three-tier system for quantifying emissions sources and sinks with each successive tier having an increased level of detail and accuracy. This allowed for increased inventory refinement where data is available, while recognizing that there were considerable variations in data availability, technical expertise, and inventory capacity across countries, particularly in developing countries (Crosson et al. 2010).

Thus, raising information about the current limitations and pointing out priority research needed to better understand this important issue are mandatory for the identification of the most polluting systems and evaluation of feasible mitigation opportunities (VanderZaag et al. 2013).

The objective of this work was to determine (CH_4) and (N_2O) emissions from beef cattle feedlot manure in Brazil using the IPCC approach and present a framework that structures priority research for decreasing uncertainties and assessing mitigation scenarios. Though this framework can be applied to any GHG inventory from animal manure management.

2 Material and methods

2.1 Estimates of GHG emission

GHG emissions from Brazilian beef cattle feedlot manure management were calculated using formulas provided by IPCC 2006 guidelines for estimating national GHG emission inventories using the tier 2 approach (IPCC 2006). Greenhouse gas emissions from manure management consist of calculating CH_4 and both direct and indirect N_2O emissions. We only considered indirect N_2O emissions created via NH_3 volatilization and deposition.

Information regarding manure management was extracted from Costa Junior et al. (2013) that comprises a database representing nearly 30 % of all beef cattle fed in feedlots during 2010 and are describe the feedlot cycle duration, pen cleaning frequency and storage time before land applications (Table 1). IPCC default values were used along with specific values from beef cattle fed in feedlots in Brazil when available (Table 2). For the IPCC default data, we assumed a medium weight for beef cattle in Brazilian feedlots of 430 kg (Millen et al. 2009; Costa Junior et al. 2013) and an average temperature of 26 °C for all farms (Table 1).

GHG emissions were calculated for each of the 73 feedlots in the database (Table 1) and the results were summed as a total emission. The calculated CH_4 and N_2O emissions were converted into CO_2 equivalent (CO_2eq), using their global warming potential (GWP, over a 100 year period) of 25 for CH_4 and 298 for N_2O (IPCC 2006).

2.2 CH_4 emissions from manure management

CH_4 emissions from manure management were calculated using the following equation:

$$CH_4 = \sum_{(T)} \frac{EF_{(T)} \times EF_{(T)}}{10^6} \quad (1)$$

Where $EF_{(T)}$ is the annual CH_4 emission factor (kgCH_4 animal^{-1} yr^{-1}) for beef cattle in a feedlot , and $N_{(T)}$ is the number of cattle (T) and 10^6 is the conversion to Gg.

The CH_4 emission factor was calculated using the following equation:

$$EF_{(T,CH_4)} = (VS \times 365) \times \left[B_0 \times 0.67 \times \sum \left(\frac{MCF_S}{100} \right) \times MS_{T,S} \right] \quad (2)$$

Where $EF_{(T,\ CH4)}$ is the emission factor for CH_4 emission from manure management for beef cattle in a feedlot (T, kgCH_4 animal^{-1} yr^{-1}), VS is the daily volatile solid excreted by T (kg dry matter animal^{-1} yr^{-1}), 365 converts from daily to an annual emissions, B_o is the maximum methane producing capacity for manure produced by T (m^3 CH_4kg^{-1} of VS

Table 1 Number of animals and their respective solid manure management in Brazilian beef cattle feedlots in 2010

No. of feedlots (*n*=73)	No. of animals (*n*=831,450)	Feeding period – FP Days	Frequency of manure removal from pens, Days	Length of manure storage in heaps before field application Days
8	71,100	90 to 100	At the end of FP	90
5	94,000	90	At the end of FP	Final disposal
4	111,500	75 to 97	At the end of FP	60[a]
4	65,000	75 to 85	No cleaning	–
2	90,000	85 to 86	At the end of FP	7
2	53,500	117 to 135	At the end of FP	30
2	24,000	97 to 107	At the end of FP	Sold after removal
2	16,200	100 to 110	At the end of FP	120
2	13,900	100	50	180
2	11,600	90 to 95	At the end of FP	Donated after removal
2	6,100	80 to 86	At the end of FP	30
2	5,000	100	At the end of FP	180
2	2,200	63	At the end of FP	90
2	1,000	100 to 120	At the end of FP	Final disposal
1	60,000	90	At the end of FP	240
1	25,000	120	30	60[a]
1	24,500	70	At the end of FP	Final disposal
1	24,000	100	50	120
1	22,000	90	At the end of FP	180
1	20,000	100	50	60[a]
1	17,500	80	At the end of FP	Sold after removal
1	15,000	130	At the end of FP	90
1	10,000	94	At the end of FP	7
1	9,000	120	At the end of FP	7
1	7,000	100	14	35[b]
1	4,000	80	At the end of FP	60
1	3,500	105	30	14
1	3,200	70	At the end of FP	180
1	3,000	90	At the end of FP	120
1	3,000	90	45	Sold after removal
1	2,200	70	35	7
1	2,000	90	30	90
1	1,700	90	45	60
1	1,500	95	At the end of FP	30
1	1,500	90	No cleaning	–
1	1,200	120	No cleaning	–
1	1,200	78	At the end of FP	90
1	1,000	80	7	10
1	800	90	45	7
1	500	120	20	120
1	350	105	7	0 (directly applied to field)
1	300	120	60	120
1	300	84	7	180
1	300	70	No cleaning	–
1	300	60	30	30

Table 1 (continued)

No. of feedlots (n=73)	No. of animals (n=831,450)	Feeding period – FP Days	Frequency of manure removal from pens, Days	Length of manure storage in heaps before field application Days
1	200	60	At the end of FP	Final disposal

Costa Junior et al. (2013)

[a] Manure composting (for 60 days before field application)

[b] Anaerobic digestion (30 days of digestion followed by maintaining the digestate for 3 days in tanks before field application)

excreted), 0.67 is the conversion factor from m^3 CH_4 to kg CH_4, $MCF_{(S)}$ is the methane conversion factor for each manure management system (S), and $MS_{(T,S)}$ is the fraction of manure from T handled using S (dimensionless).

2.3 N_2O emissions from manure management

2.3.1 Direct emissions

Direct N_2O emissions from manure management were calculated using the following equation:

$$N_2O_{D(mm)} = \left[\sum_{S}\left[\sum_{T}\left(N_{(T)} \times N_{\left(ex_{(T)}\right)} \times MS_{(T,S)}\right)\right] \times EF_{(S)}\right] \times \frac{44}{28} \quad (3)$$

Where $N_2O_{D(mm)}$ is the direct N_2O emission from manure management in the country ($kgN_2O\ yr^{-1}$), $N_{(T)}$ is the number of beef cattle in feedlot (T), $Nex_{(T)}$ is the average annual excretion of N per head ($kgN\ animal^{-1}\ yr^{-1}$), MS(T, S) is the fraction of the total annual nitrogen excretion of T that is managed using the manure management system (S, dimensionless), EF(S) is the emission factor for the direct N_2O emissions from S (kgN_2O–N kgN^{-1}), and 44/28 is the conversion factor of N_2O–N emissions to N_2O emissions.

2.3.2 Indirect emissions

Indirect N_2O emissions from manure management were calculated using the following equation:

$$N_2O_{I(mm)} = \left(N_{volatilization-MMS} \times EF_{2(S)}\right) \times \frac{44}{28} \quad (4)$$

Where $N_2O_{I(mm)}$ is the indirect N_2O emissions from the volatilisation of Nitrogen (N) from manure management ($kgN_2O\ yr^{-1}$), EF_2(S) is the emission factor for N_2O emitted from atmospheric N deposited on soil and water surfaces from ammonia deposition (kgN_2O–N)$^{-1}$, and 44/28 is the conversion factor from N_2O–N emissions to N_2O emissions.

Table 2 Parameter values used to calculate both (CH_4) and (N_2O) emissions and its uncertainties of the management of beef cattle feedlot manure in Brazil

	EF	Uncertainty	Source
Housing			
N_2O emissions, %	0.02	−50 to +100	IPCC (2006)[a]
NH_3 emissions, %	30	−33 to +66	IPCC (2006)
Indirect N_2O emissions, %	0.01	−20 to +400	IPCC (2006)
CH_4 emissions			IPCC (2006)
B_0[b], kgCH$_4$/kg SV	0.3	±11	Orrico et al. (2012)
MCF[c], %	2	−50 to +100	IPCC (2006)
Storage / Composting			
N_2O emissions, %	0.005 / 0.1	−50 to +100	IPCC (2006)
NH_3 emissions, %	45	−78 to +44	IPCC (2006)
Indirect N_2O emissions, %	0.01	−20 to +400	IPCC (2006)
CH_4 emissions			IPCC (2006)
B_0, kgCH$_4$/kg SV	0.3	±11	Orrico et al. (2012)
MCF[c], %	5 / 1.5	−50 to +100	IPCC (2006)
Anaerobic digestion	0	–	IPCC (2006)
Total loss from MMS			
Housing, %	40	−50 to +25	IPCC (2006)
Storage / Composting, %	50	−60 to +40	IPCC (2006)
Field application			
N_2O emissions, %	0.01	−30 to +200	IPCC (2006)
NH_3 emissions, %	20	−30 to +200	IPCC (2006)
Indirect N_2O emissions, %	0.01	−20 to +400	IPCC (2006)
	Other parameters	Uncertainty	Source
Animal population	–	±35[d]	ANUALPEC (2012)
Manure management system	–	±35[d]	Costa Junior et al. (2013)
Volatile solids, g/day	2.7	±35	IPCC (2006)
N excretion, g/day	0.1	±16	Gomes et al. (2013)

MMS manure management system; *MCF* methane conversion factor

[a] For climate with an average temperature of 26 °C (IPCC 2006)

[b] Methane production potential

[c] Methane conversion factor. Uncertainties assumed to be equal to N_2O emission factors (there is no assumptions at IPCC 2006 and the related studies are not online assessable)

[d] Assumed according suggestion in IPCC 2006

The loss of N due to volatilisation from manure management was calculated using the following equation:

$$N_{volatilization-MMS} = \sum_S \left[\sum_T \left[\left(N_{(T)} \times Nex_{(T)} \times MS_{(T,S)} \right) \times \left(\frac{Frac_{GasMS}}{100} \right)_{(T,S)} \right] \right] \quad (5)$$

Where $N_{volatilisation\text{-}MMS}$ is the loss of manure nitrogen due to volatilisation of NH_3 and NO_x (kgN yr^{-1}), N(T) is the number of beef cattle in the feedlot (T), Nex(T) is the annual average N excretion per head in T (kgN animal^{-1} yr^{-1}), MS(T, S) is the fraction of the total annual nitrogen excreted from T managed by the manure management system (S, dimensionless), and $Frac_{GasMS}$ is the percent of the managed manure nitrogen in T that volatilises as NH_3 and NO_x for manure management system S (%).

2.4 Nitrous oxide emissions from "applied organic N fertiliser" manure

2.4.1 Direct emissions

The N_2O emitted by "applied organic N fertiliser" manure was calculated using the following equation:

$$N_2O\text{–}N_{inputs} = [F_{ON} \times EF_3] \tag{6}$$

Where N_2O–N is the annual direct N_2O–N emissions from the N input into managed soils (kgN_2O–N yr^{-1}), F_{ON} is the annual amount of animal manure (N) applied to the soil (kgN yr^{-1}), and EF_3 is the emission factor for N_2O emissions from the N input.

The N_2O–N emissions were converted to N_2O emissions for reporting purposes by multiplying the N_2O–N emission by the conversion factor 44/28.

F_{ON} was estimated based on the amount of managed manure (N) available amount of managed manure nitrogen available for application to soil (NMMSAvb) for soil application and was calculated using the following:

$$F_{ON} = F_{AM} = N_{MMSAvb} = \sum_S \left\{ \sum_{(T)} \left[\left[\left(N_{(T)} \times N_{ex_{(T)}} \times MS_{(T,S)} \right) \times \left(1 - \frac{Frac_{LossMS}}{100} \right) \right] + \left(N_{(T)} \times MS_{(T,S)} \times N_{beddingMS} \right) \right] \right\} \tag{7}$$

Where F_{ON} is the total annual amount of organic N fertiliser applied to soils other than by grazing animals (kg N yr^{-1}), F_{AM} is annual amount of animal manure N applied to soils (kg N yr^{-1}). (N_{MMS_Avb}) is the amount of N available from the manure applied to the managed soils (kg N yr^{-1}), N(T) is the number of beef cattle in the feedlot (T), Nex(T) is the annual average N excreted per head in T (kgN animal^{-1} yr^{-1}), MS(T, S) is the fraction of the total annual nitrogen excreted from T that is managed in a manure management system (S, dimensionless), and $Frac_{LossMS}$ is the amount of manure N lost from T in the manure management system, S (%).

2.4.2 Indirect emissions

The indirect N_2O emitted by manure applied to the land was calculated as follows:

$$N_2O_{(ATD)}\text{–}N = \left\{ \sum_i \left(F_{SN_i} \times Frac_{GASF_i} \right) + \left[\left(F_{ON} \times F_{PRP} \right) \times Frac_{GASM} \right] \right\} \times EF_4 \tag{8}$$

Where $N_2O_{(ATD)}$–N is the annual amount of N_2O–N produced by the atmospheric deposition of volatilised N from managed soils (kgN_2O–N yr^{-1}), F_{ON} is the annual amount of organic N fertiliser applied (kgN yr^{-1}), $Frac_{GasMS}$ is the fraction of the applied organic N fertiliser (FPRP) that volatilises as NH_3 (kgN deposited^{-1}), and EF_4 is the emission factor for N_2O emissions from N inputs and atmospheric deposition of N on soil and water surfaces.

The conversion of $N_2O_{(ATD)}$–N emissions to N_2O emissions for reporting purposes was accomplished by multiplying the $N_2O_{(ATD)}$–N by a conversion factor of 44/28.

2.5 Uncertainties

The uncertainties were calculated by error propagation using the equation as follows:

$$U_{Total} = \sqrt{U_1^2 + U_1^2 + \cdots + U_1^2} \quad (9)$$

Where Utotal is the percentage uncertainty in the product of the quantities and U_1 is the percentage uncertainties associated with each of the quantities.

3 Results and discussion

Analysis of the manure management of approximately one third (73 feedlots) of beef cattle feedlots in Brazil (831,450 animals, Table 1) using the formulas provided by the IPCC (2006) resulted in a GHG emission value of 101.7 Gg CO_2eq (Fig. 1). By extrapolation, the total national GHG emissions for the year of 2010 (3,050,000 animals) would be 376.6 GgCO_2eq for feedlots in Brazil.

The profile for beef cattle feedlot manure management in Brazil shows most of the animals had their manure managed in solid storage-heaps after housing floor cleaning followed by field application (Table 1). Hence, GHG emissions came predominantly from solid storage-heaps and field application, which comprised 60 % and 21 % of the total emissions respectively. N_2O accounted for 61 % of total emissions, out of which 69 % came from direct emissions. Nearly all CH_4 emissions (90 %) came from solid storage-heaps (Fig. 1).

Other emission sources came from farms that composted their manure (12 %) and those that left the manure in feedlot housing floor (6 %) (Fig. 1). Emissions from the only farm with anaerobic digesters came from application of manure to the field (0.2 Gg CO_2eq).

The uncertainty in total inventory was −30 to +79 % (Fig. 1). The largest contributors for this variance were CH_4 and indirect N_2O emission from solid storage-heaps as well as direct N_2O emissions from field application of manure (Fig. 1). The large uncertainty is a consequence of the use of the IPCC default N_2O, NH_3 and CH_4 emission factors (Fig. 1, Table 2). Thus, experiments measuring these systems and parameters would yield greatest reduction in uncertainties.

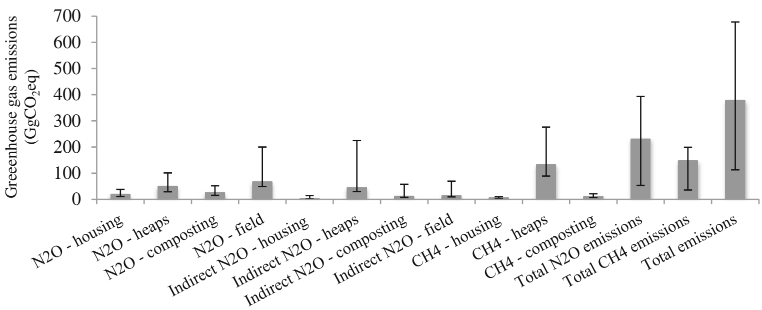

Fig. 1 Total and relative greenhouse gas emissions (direct and indirect nitrous oxide - N_2O- methane -CH_4) from beef cattle feedlot manure management in Brazil in 2010. *Error bars* represent uncertainties in the estimative

The use of information of specific values of the amount of N excreted (Nex) and CH_4 production potential (B_0) were incorporated in the analysis of N_2O and CH_4 emission (Table 2). They significantly decreased parameter uncertainties compared to IPCC default values (IPCC 2006), from 50 to 16 % and from 15 to 11 %, respectively. For activity data regarding manure management we assumed reduction in uncertainties from 100 % to 35 % (range of 25–50 %) (IPCC 2006). As a consequence of the use of these specific data, total uncertainty range was narrowed from −54 to +90 (not shown) to −30 to +80 %.

This emission of 376.6 GgCO_2eq also corresponds to between 20 % and 25 % of the total GHG emission from the animal basis (manure management and enteric fermentation) during a typical feedlot period of roughly 90 days in Brazil (Costa Junior et al. 2013) when considering an enteric fermentation emission between 43 kg and 56 kg of CH4 per animal per year (808–1,053 GgCO_2eq for 90 days) given by the last Brazilian inventory (MCT 2010).

Thus, we see that mitigating GHG from the manure management in Brazilian feedlots might help reducing significatively total GHG emission from beef production and, consequently, increase environmental sustainability of meat production in Brazil.

Since N_2O emissions comprise the largest emissions in the evaluation of manure management systems (Figs. 1 and 2), efforts to mitigate this gas without exacerbating the CH_4 emissions would be an efficient means of reducing total GHG emissions (Chadwick et al. 2011).

According to emission factors provided by the IPCC (2006), manure management through solid storage has the lowest N_2O emissions, with exception to anaerobic digestion (Table 2). Therefore, unless the number of anaerobic digesters in Brazilian feedlots increases, it at first glance appears that little can initially be done to reduce the GHG emissions of manure given that nearly all of animal manure was managed in heaps (Table 1).

Countering this assumption is research by Sommer et al. (2009) that reported different in-house manure storage time could alter GHG emissions by 0 to 40 % which is largely unchecked in literature for beef cattle and not examined in the IPCC equations. Increasing the frequency of manure removal from animal housing floor to solid storage-heaps might also be a mitigation option for Brazilian feedlots. Moreover, improvements in the application

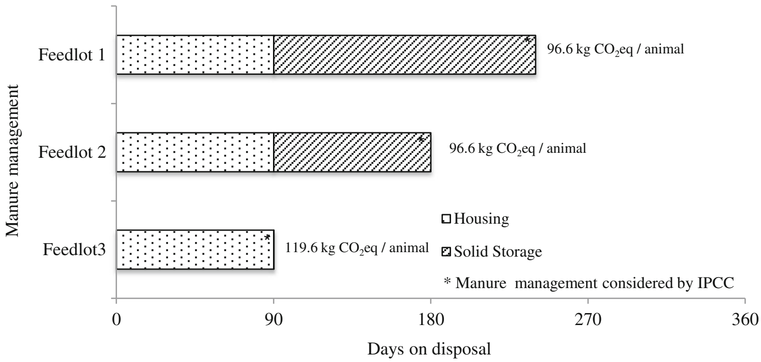

Fig. 2 Annual greenhouse gas emissions (direct and indirect N_2O and CH_4 emissions in kgCO_2eq per animal) from manure management (excluding field application) of three beef cattle feedlots in Brazil carrying out 90 days of animal feeding calculated using the 2006-IPCC guidelines (IPCC 2006). The manure generated during the feeding period (first 90 days) is removed from the housing floor and disposed in solid storage before field application in Feedlot 1 and 2, while in Feedlot 3 manure is not further managed, remaining on the housing floor throughout the year

of manure as fertilizer in agricultural fields could also increase the mitigation potential (Chadwick et al. 2011).

In spite of IPCC guidelines providing the most widely applicable defaults to compile national GHG inventories, its reporting protocols structure is not conducive to integrated farm-level emission assessments. As a consequence, the evaluation of mitigation options and their effects for Brazilian conditions cannot be adequately evaluated using this methodology.

To illustrate this issue, Fig. 2 shows three feedlots (named farms 1, 2 and 3) selected from Table 1. All three feedlots fed their animals for 90 days. Both farm 1 and 2 removed manure deposited on the housing floors during these 90 days only once, at the end of the feeding period, and stored it in heaps before being applied to the fields. Although, farm 1 and 2 stored manure in heaps for different lengths of time (90 and 150 days, respectively) and farm 3 did not remove manure from its feedlot pen, instead leaving it to decompose on the ground floor of pens without secondary management.

According to the boundaries assumed in this work, these farms produced the same amount of manure, and consequently, the same amounts of volatile solids and N were excreted within the pens. The time manure spent in heaps for farm 1 and 2 differed and therefore would cause different GHG emissions; however, according to the used IPCC methodology used in this work, these two farms have the same annual GHG emissions per animal under identical climatic conditions and animal characteristics (96.6 kgCO_2eq) due to inability to factor in time spent in heaps (Fig. 2). Additionally, emissions from the pens (during 90 days of feeding) were not considered.

On the other hand, farm 3 resulted in an annual emission per animal of 119.6 kgCO_2eq, which included emissions from the manure excreted during the 90 days of feeding that was decomposed in the pen post feeding. Emissions during the feeding period and from different storage time were not accounted for regarding farm 1 and 2 and not possible to calculate using IPCC methodology.

These results highlight the necessity for developing specific emission factors that could reflect the situations found in Brazilian feedlots in order to improve national inventory and address mitigation options. However, the development of emission factors reflecting all appropriate country specific situations and conditions would be very costly and time-consuming (IPCC 2006; Crosson et al. 2011; Reay et al. 2012; NRC 2002). Additionally, assessing the environmental impact of manure management is difficult due to high variability in the quality and quantity of animal waste, and in the numerous factors affecting the biogeochemical transformations of manure during storage, treatment and field application (Salas et al. 2008).

In this case, process-based models should be used in supplementing measurement programs in order to feasibly improve inventories and evaluate management practices able to mitigate GHG emissions (Li et al. 2012; Salas et al. 2008). The Manure-Denitrification-Decomposition model (DNDC) model for example, runs the dynamics of CH_4, N_2O and NH_3 production or consumption by simulating several biogeochemical reactions (decomposition, hydrolysis, nitrification, denitrification, ammonium adsorption, chemical equilibriums of ammonium/ammonia, and gas diffusion) associated with manure production, storage, treatment and land application according to environmental conditions and farm-scale specifications (Li et al. 2012). The model also allows for greater control of timing of manure in each management compartment.

Varying farm conditions in a process-based model would improve accuracy for all emissions estimates for comprehensive assessments of mitigation efforts and further define measurement requirements to achieve desired accuracy and uncertainties (Li et al. 2012; Salas et al. 2008).

However, model validation is critical for comprehensive analyses that capture all manure emissions as well as to allow sensitivity to local conditions and permit implication of alternative site specific factors to be ascertained (Salas et al. 2008; Stewart et al. 2009; Rotz et al. 2010).

In spite of a useful range of information that has already been available (ANUALPEC 2012; IBGE 2006; Millen et al. 2009; Costa Junior et al. 2013; Gomes et al. 2013), the lack of experiments evaluating GHG fluxes for Brazilian conditions are limiting proper exploration of process-based models. This is also limiting accuracy as process-based models are needed for decreasing uncertainties using IPCC methodology.

We built Table 3 from national surveys that determines the most common characteristics found in beef cattle feedlots in Brazil. Following that information, future research would maximize results in obtaining GHG emissions factor for Brazilian conditions. Basically, it would track emissions from manure generated from male Nellore (*Bos Indicus*) genotype fed a high-energy corn (*Zea mays* L.) based diet that remain in pens for around 90 days, with manure removed and held in heaps over 60 days before being applied to corn field on clay soil (Table 3). Experiments setting up those conditions would represent at least 20 % of the cattle fed in feedlots (Millen et al. 2009; Costa Junior et al. 2013). This would be the starting point for improving GHG estimate, reducing uncertainties and building mitigation scenarios for Brazilian conditions as well as evaluating the importance of manure in the GHG emissions from beef production. Moreover, it is a good practice for all specific parameters to be examined, revised, improved and published.

The quantification methods for the GHG emissions from manure management in animal systems are widely described in the literature but need to be better applied for determining emission factors and model parameters (Chadwick et al. 2000; Saggar et al. 2010; Hao et al. 2004; Rochette and Eriksen-Hamel 2008; Wang et al. 2011).

It is also a good practice to report flux as they are measured with a detailed characterisation of the emitting substrate (i.e., manure composition over time) accompanied by a description of the animals generating the manure and the manure management system used at the facility (Kebreab et al. 2006).

Environmental conditions are also an important factor on emissions and data are often available from local weather stations; however, these variables should be monitored by research during the study period if unavailable from such sources or to improve accuracy at the farm location (Saggar et al. 2004; Kebreab et al. 2006).

In spite of the recent significant annual increase in Brazilian beef production at feedlots and its economical importance for the country, our study clearly demonstrated what further research should accomplish for improving GHG emission estimates from manure management. It also highlighted that farm scale data is critical to better understanding this issue and when paired with future directed research should provide necessary information for evaluate mitigation scenarios. Furthermore, as reported by Crosson et al. (2011), farm level evaluations are necessary to support policy makers with regard to development of GHG emissions mitigation strategies, otherwise there might be lower than expected abatement outcomes and unintended adverse consequences.

4 Conclusions

The manure management of beef cattle feedlots in Brazil emitted 376.6 $GgCO_2eq$ in 2010. These emissions came predominantly from storage heaps (60 %) and field application

Table 3 Top characteristics of beef cattle and manure management in feedlots in Brazil selected from country surveys

Item	Characteristic / Value	Source
Brazilian Region	Southeastern and Central-West	ANUALPEC (2012)
Animal		
Breed and genre	Nellore (*Bos indicus*) - Male	Millen et al. (2009) Costa Junior et al. (2013)
Age, months	24	Millen et al. (2009)
Initial and final body weight, kg	350–500	Millen et al. (2009) Costa Junior et al. (2013)
Diet		
Days on fed	84–100	Costa Junior et al. (2013) Millen et al. (2009)
Dry matter intake (DMI), kg day-1	10	Millen et al. (2009) Costa Junior et al. (2013)
Grain Source	Corn (*Zea mays* L.)	Millen et al. (2009) Costa Junior et al. (2013)
Roughage Source, % of DM	Corn (*Zea mays* L.) silage and fresh and chopped sugarcane (*Saccharum officinarum* L.), 10–28 %	Millen et al. (2009) Costa Junior et al. (2013)
Crude protein (CP), % of DM	13–14	Millen et al. (2009) Costa Junior et al. (2013)
Protein source	Soybean (*Glycine max* L. Merrill) meal	Millen et al. (2009)
Manure management		
Pen floor and coverage	Bare soil with no cover	Costa Junior et al. (2013)
Frequency of manure removal from pens	The end of feeding period	Costa Junior et al. (2013)
Storage system and length of time before field application, months	Heaps, 2–4	Costa Junior et al. (2013)
Manure applied to soil, ton/ha	>20	Costa Junior et al. (2013)
Crops receiving manure	Corn (*Zea mays* L.) and sugar cane (*Saccharum officinarum* L.)	Costa Junior et al. (2013)
Soil texture receiving manure	Clay	Costa Junior et al. (2013)

(21 %). N_2O accounted for 61 % of total emissions, out of which 69 % came from direct emissions. Uncertainties were high (−30 to +80 %) and the IPCC methodology does not integrate GHG emissions at the farm-scale well, preventing the assessment of mitigation options. As a consequence, this GHG inventory lacks consistence. To establish a GHG emission assessment that responds to changing feedlot management is recommended the development of country-specific emission factors coupled with oriented process-based models. Thus, filling the gap for experiments dealing with field measuring CH_4 and N_2O emission from the whole cycle of manure management under Brazilian conditions (housing, storage and field application) are of primary importance for improving the GHG assessments of these feedlots. The most effective of these experiments for Brazilian conditions would track emissions from manure generated from male Nellore genotype fed with high-energy corn based diet that remain in pens for around 90 days, manure removed and held in heaps over 60 days before being applied to corn field on clay soil. Finally, this paper contributes to the literature illustrating critical information to guide experiments towards a representative manure management emission assessments in Brazil and elsewhere.

Acknowledgments We would like to thank São Paulo Research Foundation (FAPESP 2010/05111-7, 2010/17837-2 and 2012/02642-7) for funding this research.

References

ANUALPEC (2012) Anuário da Pecuária Brasileira (Yearbook of Brazilian livestock production), 1st edn. Instituto FNP and Agra FNP Pesquisas Ltda, São Paulo

Chadwick DR, Pain BF, Brookman SKE (2000) Nitrous oxide and methane emissions following application of animal manures to grassland. J Environ Qual 29:277–287

Chadwick D, Sommer S, Thorman R et al (2011) Manure management: implications for greenhouse gas emissions. Anim Feed Sci Technol 166–167:514–531

Costa Junior C, Goulart RS, Albertini TZ et al (2013) Brazilian beef cattle feedlot manure management: a country survey. J Anim Sci 91:1811–1818

Crosson O, Shalloo L, O'Brien D et al (2011) A review of whole farm system models for greenhouse gas emissions from beef and dairy cattle production systems. Anim Feed Sci Technol 166–167:29–45

Gomes RG, Sainz RD, Leme PR (2013) Protein metabolism, feed energy partitioning, behavior patterns and plasma cortisol in Nellore steers with high and low residual feed intake. Rev Bras Zootecn 42:44–50

Hao X, Chang C, Larney FJ (2004) Carbon nitrogen balances and greenhouse gas emission during cattle feedlot manure compositing. J Environ Qual 33:37–44

IBGE (2006) Censo Agropecuário (IBGE Census of Agriculture), Brasil, Grandes Regiões e Unidades da Federação (Brazil, Major Regions and Federation Units), Fundação IBGE, Rio de janeiro

IPCC (1997) Intergovernmental Panel on Climate Change. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/gl/invs6.htm. Cited 23 Sept 2012

IPCC (2006) Intergovernmental Panel on Climate Change. IPCC guidelines for national greenhouse gas inventories. In: Eggleston H, Buendia L, Miwa K, Ngara T, Tanabe K (eds) The national greenhouse gas inventories programme. IPCC-IGES, Japan

Kebreab E, Clark K, Wagner-Riddle C et al (2006) Methane and nitrous oxide emissions from Canadian animal agriculture: a review. Can J Anim Sci 86:135–158

Li C, Salas W, Zhang R et al (2012) Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutr Cycl Agroecosyst 93:163–200

MCT (2010) Ministério da Ciência, Tecnologia e Inovação (Brazilian Department of Science, Technology and Innovation) 2010 Segundo Comunicado Nacional das Emissões de Gases de Efeito Estufa (Second National Advisory on Greenhouse Gas Emissions). http://www.mct.gov.br/index.php/content/view/4004.html. Cited 02 Jan 2013

Millen DD, Pacheco RDL, Arrigoni MDB et al (2009) A snapshot of management practices and nutritional recommendations used by feedlot nutritionists in Brazil. J Anim Sci 87:3427–3439

NRC (National Research Council) (2002) Air emissions from animal feeding operations: current knowledge, future needs. The National Academies Press, Washington

Orrico MAP Jr., Amorim AC, Lucas J Jr et al (2012) Biodigestão anaeróbia dos dejetos da bovinocultura de corte: influência do período, genótipo e dieta. Rev Bras Zootecn 41:1533–1538

Reay DS, Davidson EA, Smith KA et al (2012) Global agriculture and nitrous oxide emissions. Nature Clim Change 2:410–416

Rochette P, Eriksen-Hamel NS (2008) Chamber measurements of soil nitrous oxide flux: are absolute values reliable? Soil Sci Soc Am J 72:331–342

Rotz CA, Montes F, Chianese DS (2010) The carbon footprint of dairy production systems through partial life cycle assessment. J Dairy Sci 93:1266–1282

Saggar S, Andrew RM, Tate KR et al (2004) Modelling nitrous oxide emissions from dairy-grazed pastures. Nutr Cycl Agroecosyst 68:243–255

Saggar S, Harvey M, Singh J et al (2010) Chambers, micrometeorological measurements, and the New Zealand Denitrification–Decomposition model for nitrous oxide emission estimates from an irrigated dairy grazed pasture. J Integr Environ Sci 7:61–70

Salas W, Li C, Mitloehner F et al (2008) Developing and applying process-based models for estimating greenhouse gas and air emission from California dairies. California Energy Commission, PIER Energy-Related Environmental Research, CEC- 500-2008-093

Sommer G, Olesen JE, Petersen SO et al (2009) Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones. Glob Chang Biol 15:2825–2837

Stewart AA, Little SM, Ominski KH, Wittenburg KM, Janzen HH (2009) Evaluating greenhouse gas mitigation practices in livestock systems: an illustration of a whole-farm approach. J Agric Sci 147:367–382

UNEP (United Nations Environment Programme) (2011) Keeping track of our changing environment—from Rio to Rio+20 (1992–2012). Division of Early Warning and Assessment—DEWA, Nairobi

VanderZaag AC, MacDonald JD, Evans L, Verge XPC, Desjardins RL (2013) Towards an inventory of methane emissions from manure management that is responsive to changes on Canadian farms. Environ Res Lett. doi:10.1088/1748-9326/8/3/035008

Wang Y, Sun GJ, Zhang F et al (2011) Modeling impacts of farming management practices on greenhouse gas emissions in the oasis region of China. Biogeosciences 8:2377–2390