Dynamics of animal performance, and estimation of carbon footprint of two breeding herds grazing native neotropical savannas in eastern Colombia

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Abstract: The savannas of eastern Colombia located in the Orinoco river basin represent 18% of the Latin American neotropical savannas, and those areas that are tillable and closer to markets are subject to considerable anthropic pressure in the quest for intensification. Historically, and even today, beef cattle production constitutes the main land use, and much of it is subjected to extensive management. This paper describes for the first time, the use of cattle grazing experiments to assess methane (CH4) emissions from neotropical savanna-based beef breeding systems, and with the support of published research conducted next to them, and estimate of the carbon (C) footprint in carbon dioxide equivalents (CO2-eq) for the whole system. Over 5 years and covering complete reproductive cycles, conventional weaning (CW) herd system was compared to an early weaning (EW) herd system, that represented a modest degree of more intensive savanna management. Differences were found between the two management practices in total CH4 emissions, emission intensities [kg CH4 kg -1 calf born and kg CH4 kg -1 liveweight gain (LWG)] and emission efficiencies (kg CO2-eq kg -1 calf born and kg CH4 kg -1 LWG), that mostly associated with the different lactation lengths. When both herd systems were carried over until calves, later yearlings, reached to 25 months of age, the differences in favor of EW breeding herd system were diminished. The calculated C footprint in (CO2-eq) of both management practices was near neutral subjected to a number of assumptions and the use of limited published information on savanna C stocks and CH4 and nitrous oxide (N2O) emissions from soil, and it is posited that both herd systems were nearly in equilibrium. The available data and results show the need for further information on the neotropical savanna C stocks and C sequestration potential of soils of the Orinoco river basin. More reliable datasets regarding below-ground C inputs and CH4 and N2O emissions from soil are needed to provide a useful basal benchmark for, and approach to, future analyses of environmental impact of more intensive beef herd systems in the region.

Townsville, Australia 24 March 2019

Mr Sundar Ananthakrishnan
Journal Manager
Agriculture, Ecosystems and Environment

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Dear Mr Sundar Ananthakrishnan,

Many thanks for forwarding to us the Reviewers' comments and full instructions to revise the manuscript. We found the comments to be very objective, constructive and helpful, and we have done our best to employ them wherever possible for the improvement of the manuscript. We describe below our response to Editor and Reviewers' comments. Italics font is used for the comments, while standard font is used for our response.

We hope that the revised manuscript will be suitable for publication in Agriculture, Ecosystems & Environment.

Points to note

Editor

"Both reviewers have critical remarks about this research. It seems that the carbon stocks part is weak and not based on new experimental data. I recommend a major revision with a good justifications of the changes and choice made".

Response: We greatly appreciate the recommendation for major revision of the manuscript. To estimate carbon (C) stocks and fluxes at the system level we used field data collected over a significant span of time, and in neighbouring savanna sites, by one of the co-authors and others. That field data has been published and is widely cited in the text, but had not been used previously to assess C balances at the level of production systems.

We have now revised Table 6 with additional information on soil C accumulation rate per year. We also provided in Table 6 the calculated values of: (1) C content of animal feces; (2) methane (CH_4) emissions from the bull; (3) CH_4 emissions from dung of the animals; and (4) nitrous oxide (N_2O) emissions from dung and urine of the animals (details provided as Supplementary material 1). We used these values to estimate the overall C footprint as carbon dioxide equivalents (CO_2-eq) at system level (Table 6). We have provided the needed justification for the used data to estimate the C footprint.

Changes made in the revised manuscript are highlighted using yellow (Reviewer 1), blue (Reviewer 2) and green (our own minor editorial change) colour backgrounds. Compared with the original submission, modifications suggested by both Reviewers are also described in terms of the new line numbers in the clean copy of the revised manuscript.

Reviewer 1

General comments

This manuscript reports results from a study aimed at quantifying the beef cattle performance, enteric CH4 emissions and the C footprint of savanna-based beef breeding herds subject to conventional weaning (CW) vs early weaning (EW) in Llanos of Colombia. It is hypothesized that the management intensive EW system is biologically and *environmentally more efficient per unit of output than the traditional extensive CW systems. Cattle performance data are from a 5-yr, replicated experiment conducted in the region and enteric CH4 emissions from cattle have been modeled using a mechanistic model of which the algorithms for estimating CH4 emissions were derived using measured CH4 emissions from tropical beef cattle determined by respiratory chamber method in Northern Australia. The data related to carbon stocks in the two production systems were based on published research conducted in the region and assumed values (although not clearly provided in the manuscript).*

Overall, the results are relevant to the readers of AGEE and the scientific and policy community and likely to fill a gap in the scientific literature by presenting CH4 emissions data from beef cattle production in one of geographically important regions of the world. Nevertheless, I have a number of points that should be addressed to improve the clarity of the manuscript.

Response: We greatly appreciate the positive feedback on the scientific value of the results reported in the study. We have addressed the comments and suggestions made by the Reviewer to improve the clarity and quality of the manuscript.

"Although it is stated that one of the objectives of the study was 'to quantify the carbon footprint (CF) of beef breeding herds subjected to conventional weaning (CW) vs. early weaning (EW)' (line 108), it doesn't appear that a 'whole system analysis' has been performed. For example, nowhere in the Materials and Methods authors have explained what is the system boundary, what GHG sources included/excluded in the CF calculation, and what is the functional unit for expressing the whole systems GHG emissions? Also, an important GHG source contributing to the CF of beef cattle: emissions from manure excreted on pasture are not included in this analysis and therefore, the results are incomplete in terms of CF of beef cattle in the two production systems compared".

"Potentially, there may be appreciable differences in emissions from manure excreted on pasture in the two production systems, given that early weaned calves in the EW system grazed an improved pasture grass-legume mixture (Andropogon gayanus associated with forage legumes (Pueraria phaseoloides, Centrosema acutifolium (lines 189-190) that may lead to differences in N content in excreted manure due to biological N fixation in forage legumes in the EW system which in turn likely to cause differences in N2O emissions. This need to be addressed to complete the CF of beef cattle".

Response: Considerable attention has been given to the important comments and suggestions made by the Reviewer. The system boundary has been portrayed in Fig. 2 and it is now mentioned in the revised manuscript between lines134 and 135.

We have also used values published by our colleagues (cited in the Supplementary material 1) and recorded in nearby savanna paddocks to estimate fecal output and reported the calculated values of: (1) C content of animal feces; (2) CH_4 emissions from the bull; (3) CH_4 emissions from dung of the animals; and (4) N_2O emissions from dung and urine of the animals. We have not included the contribution of the improved pasture of grass-legume mixture to the EW system and this was noted in the M & M (lines 229-230) and Discussion (line 513) sections.

"It is not clear how soil C balance is estimated. Although it is mentioned (lines 203-204) that C balance was determined by estimated C accumulation in the soil, no information on the soil organic carbon sequestration rate is provided".

Response: We welcome the comments made by the Reviewer because we believe that in fact our research can be considered from different angles. The data we used to assume the

C balance (based on above- and belowground C stocks and soil C accumulation rate per year) were from the nearby native savanna field sites. We have now revised the results presented in Table 6 with additional data on soil C accumulation rate per year which was used to estimate C balance (footprint) at system level. We have provided the needed justification for the used data to estimate C balance. It should be noted that the assumptions are based on research work published by one of the co-authors (IMR) as cited in the manuscript. All the relevant references are included in the Supplementary material 1.

"Furthermore, I would like to suggest Authors could use one functional unit (e.g. a unit of beef live weight output such as kg live weight) compare the environmental impact of the two systems. This could potentially simplify the presentation of results in Table 1-5".

Response: We understand the Reviewer's point of view and we are confident that we have shown the relevance of a beef functional unit [i.e. kg live weight (LW)]. This is because the base model using ordinary least squares revealed the significance of LW fluctuations in adult and young cattle to calculate individual dry matter intake (DMI) and CH_4 emissions as well as to generate multiple environmental outputs per kg LW. Thus, our parametric estimations facilitated the comparison of environmental impacts between two contrasting extensive production systems not only in terms of individual or cow-calf pairs CH_4 emissions (Tables 1 and 2), but formulating variable intensity and efficiency emission indices using LW in kg as a functional unit for output expression (i.e. kg $^{-1}$ calf born, kg $^{-1}$ final LW, kg $^{-1}$ calf weaned; see Tables 2, 3, 4 and 5). It is also noteworthy to say that our mechanistic model similarly and alternatively uses beef LW gain (LWG) as an efficient unit to derive CH_4 intensity (kg kg $^{-1}$ LWG) and CH_4 efficiency (CO_2-eq kg $^{-1}$ LWG) output indices (See relevant new text between lines 308 and 318). Therefore, there are obvious reasons at this stage for not using a unique beef environmental unit output because any extensive beef breed system does not constitute a homogenous entity.

Overall, this scientific reasoning on LW ensures, reproducibility and applicability of research outcomes as it has been previously demonstrated by Allard et al. (2007), Ramírez-Restrepo et al. (2017) and Ramírez-Restrepo and Vera (2019). However, to reflect differences not captured by the initial explanatory characteristics of the Excel spread mechanistic model, particular equations used to derive DMI and CH_4 emissions (Ramírez-Restrepo and Vera 2019) have been included between lines 194 and 199 in the revised manuscript. In summary, we are confident that in presenting those equations, we essentially demonstrated the impact of the requested LW functional unit to give further clarity to the manuscript and its tabular data in terms of function and the requested characteristics at output scale.

"Table 6 should be revised to clarify how C balance was estimated. For example:

Check the units for: Methane emitted by cow-calf pair (should be: kg CH4 day-1), C emitted over inter-calving period (should be: kg ha-1), insert a line to present C emitted from cattle in (kg C ha-1 yr-1), most importantly present the value for soil carbon sequestration rate (kg C ha-1 yr-1) assumed for this study".

Response: Comments from the Reviewer are valued and special attention was paid to revise Table 6. Thus, a new Table layout is presented considering the Referee's input as well as some additional information to estimate CO_2-eq footprint (kg ha $^{-1}$ year $^{-1}$) at system level.

"Additionally, please check for some occasional use of awkwardly long sentences (e.g. lines 147-154). Such long sentences could lead to grammatical inconsistencies making it difficult to understand".

Response: We understand the Referee's suggestion and the text (lines 163 to 168) is revised to improve clarity.

Specific comments

Abstract

“Lines 23-26: Regarding the claim that: 'This paper describes for the first time, use of cattle grazing experiments to assess CH4 emissions from savanna-based beef breeding systems….' Is it correct? There are at least few previous studies focusing on CH4 emissions from savanna-based systems in Northern Australia (Bray et al 2016 The Rangeland Journal, 2016, 38, 207-218, Bray et al 2014 Animal Production Science, 2014, 54, 1988-1994). Perhaps, authors meant to say: this is the first study from this particular region (savannas in eastern Colombia). Please clarify and revise accordingly”.

Response: The important issue has been considered and the word ‘neotropical” has been included in the sentence to provide the sentence a specific context.

“…to assess methane (CH_4) emissions from neotropical savanna-based beef breeding systems,...”. See line 24.

“Line 30: The indicator: 'emission efficiencies' is not clear. Please define”.

Response: Both intensity and efficiency indices are defined between lines 31 and 32, respectively.

Introduction

“Line 51-53: Please add some relevant references to support these statements related to savanna system”.

Response: Fixed. Relevant references as suggested have been included from line 56 to line 59.

“Line 56: Should read as: Historically, well-drained savannas in Colombia evolved…”

Response: Corrected as suggested in line 62.

“Lines 83-91: This paragraph may be amalgamated with the previous paragraph as both culminated in the same conclusion (). For example, the text may be revised as (beginning from line 78):

'…Kleinheisteramp and Habich (1985) conducted a large and intensive on-ranch study to characterize existing systems in biological terms, which gave rise to the view that the amount and quality of feed resources are the major constraining factors, rather than management ability or intensity. Rivera (1988) confirmed these results by using a designed 5-year long and large (2,700 ha, 345 cows replicated on a medium-texture and a sandy soil) experiment, demonstrating that the introduction of small areas of introduced grass plus regular supplementation of complete mineral supplements had a modest but noticeable impact on the performance of beef production systems. This trend was further supported by subsequent modelling exercises (Thornton and Vera, 1988) that also addressed the need for more intensive management supervision. Nevertheless, none of these studies focused on the issue of environmental impact of these systems”.

Response: The suggestion has been accepted and the text from line 83 to 94 has been accordingly improved.

Materials and Methods

“Line 123: it is not necessary to define CW and EW here again, as they are defined in line109”.

Response: Revised the text in line 128.

“Line 133: should be: …where soil research on C stocks referred in the present study…”

Response: Revised the text in line 141.

“Line 139: delete m2; it should read as: …annual precipitation was 2790 mm with 94% of the rainfalls recorded…”

Response: Issue fixed in line 147.

“Line 147-154: Within this paragraph, briefly explain that the data used to derive LW-CH4 emissions and LW-DMI algorithms used in the mechanistic model have been developed using Red Belmont Composite X Brahman X Hereford-Shorthorn and Brahman steers in respiratory chamber experiments conducted in northern Australia and explained in details in Ramírez-Restrepo and Vera (2018). Then you can continue on to explain that The Excel® spreadsheet mechanistic model extends the LW-derived CH4 emissions and dry matter intake (DMI) simulation of Ramírez-Restrepo and Vera (2018) adding calculations for…”

Response: The suggestion is appreciated. A corresponding text has been inserted from line 155 to line 162 in the updated manuscript. The citations used there Fisher et al. (1987) and Ramírez-Restrepo et al. (2014, 2016a, b) have been accordingly added to the list of references.

“Also, try to avoid using very long sentences. For example, the sentence in lines 147 to 154 tries to cram too much information into one long sentence (102 words!”).

As example this could be done as follows:

'The Excel® spreadsheet mechanistic model extends the LW-derived CH4 emissions and dry matter intake (DMI) simulation of Ramírez-Restrepo and Vera (2018) adding calculations for reproductive parameters (i.e. gestation, lactation and weaning conception intervals) to estimate CH4 emissions from suckling weaned calves and stockers until yearlings (24.0 ± 0.05 months) are sold. The model estimates CH4 emissions in terms of mass [g or kg per animal unit (AU; 450 kg) or per ha] or energy loss basis (MJ per animal unit). Methane emissions were converted to CO2 equivalents (CO2 eq) using the value of 34 as the global warming potential (GWP100) factor for CH4 (Myhre et al., 2013; Mueller and Mueller, 2017).

The phrase: 'in order to evaluate the C footprint impact of beef cow-calf systems' is not necessary here since it is stated in the objectives”.

Response: The constructive criticism is appreciated and the text is modified between lines 168 and 175.

“Line 156: Explain the reason for not including emissions from bulls (Line 156-157). Due to small number of bulls in the cattle population? What is the bulls:cow ratio in these systems?”

Response: We appreciate the comment. In this view a documented response is presented between lines 172 and 174. In parallel, the information on bulls in terms of enteric and fecal

CH_4 emission and N_2O emission from animal excreta (both urine and dung) is included in the Supplementary material 1.

"Line 158-162: Revise this awkward sentence. For example, the sentence could be revised as:

'In the first step, herd structure over the first RC [i.e. gestation (285 days), calving, lactation length and weaning] and the second RC (i.e. post-weaning-conception, gestation, calving, lactation length and weaning) was determined by the number of cow-calf pairs originally managed under CW and EW practices in 1984 (Replicate 1; 9 vs 10) and 1985 (Replicate 2; 13 vs 16)".

Response: The suggestion has been considered and relevant changes to improve the sentence has been included in lines 176, 177 and 178.

"Line 162: In the second step…"

Response: Text revised in line 181.

"Line 197: Explain the basis for using assumed vales indicate where they have been used in the analysis".

Response: The basis for assumed values is provided in the Supplementary material 1 by including the source of information with relevant references (See lines 228-229).

Results

"Line 229: should be: Daily estimated CH4 emissions (g animal-1)…"

Response: Revised the text in line 255.

"Line 245: kg head-1"

Response: Revised the text in line 271.

"Line 251-254: What is the reason for presenting data in two indices?: 'CH4 emissions efficiency' is just a value derived by multiplying CH4 (kg/kg calf born) by the GWP 34?"

Response: We used two indices because CH_4 expressed in CO_2-eq is a standard unit for measuring C footprints that is the ultimate aim of our study (i.e. evaluate the C footprint of beef cow-calf systems at different productive stages). We also consider that previous grazing studies by Allard et al. (2007) demonstrated the effect of CH_4 CO_2eq units on annual budgets of C and greenhouse gas (GHG) fluxes in intensive and extensive treatments. Under such circumstances, our results also imply the need to reflect that our 34 GWP_{100} differs to standard published data that considers 25 as the GWP for CH_4 (Menezes et al., 2016). Accordingly, as the present manuscript is part of a related series of planned peer-reviewed publications, the current information is required to facilitate the development of a systems approach analysis where total emissions from the bulls' herd must be considered.

Discussion

"Line 308: should be: …sandier vs heavier soils (6-7 kg ha-1 day-1 vs 18 kg ha-1 day-1…)"

Response: We are grateful for the suggestion. Nevertheless, the authors consider that the actual scientific writing from line 362 to line 336 is appropriate.

"Line 341-342: Check this sentence for correct English: …may be influenced by…?"

Response: Revised the text in line 396.

"Line 389: sinks for C in the absence of…"

Response: Revised the text in line 445.

Reviewer 2

General comments

"This is another modelling paper which seeks to use scant data to draw conclusions about livestock ghg emissions, emissions intensities, and in this case C stocks. The main conclusion of the paper appears to be that early weaning systems in Latin savannahs are (slightly) more beneficial environmentally. However the (posited) differences are small and the assumptions large, bringing into question the value, both practical and theoretical, of the exercise".

Response: We understand the concern of the Reviewer on the value of the study. We consider that the results reported from our study are important because of the following five reasons: (1) there is no published experimental data for the neotropical savannas of northern South America, based on actual animal performance and outputs using herds that approximate commercial practices, including CH_4 outputs; (2) the contribution of cattle to the calculation of the countries' GHG balances is controversial, and the extremely limited information that is being used so far is based solely on IPCC emission factors; (3) the study brings together quantitative field data obtained under highly representative environmental and management conditions; (4) the only available method to estimate a system level C footprint is through a modelling exercise, given the very different spatial scales involved in savanna-based extensive beef systems; and (5) the authors have used extremely conservative estimates, such as maximizing estimated CH_4 outputs by using only fertile cows (as explained in the paper), and using low estimates of soil and vegetation C stocks.

In addition, to estimate the C footprint in CO_2-eq at system level, we also included the contribution of cow-calf pairs and bulls to CH_4 emission as well as N_2O emission from urine and dung of animals. As stated above in the Response to Reviewer 1 comments, this information is provided in the Supplementary material 1.

It is also important to note that the value of the comparison between the two herd management systems is that EW is a prototype of a feasible, low cost, but more management intensive intervention, an aspect that constitutes a classical trade-off of extensive systems. As shown in the Supplementary material 1 and the new text between lines 293 and 302, the difference between the two systems over the productive lifetime of the system is considerable (Vera and Ramírez-Restrepo, 2017).

Specific comments

"Firstly the methodology for deriving CH4 emissions needs explanation, it is simply not good enough to cite one of the authors other, recent papers, and say "that's it"

Response: This constructive comment has deserved special attention for the authors and the issue has been resolved as indicated in the response to Reviewer 1 (See new text between lines 155 and 162 as well as the related input from line 194 to line 199).

"A key concern here is that there seems to be no inclusion of energy expenditure from locomotion, which would surely be a significant contributor to energy expenditure in an extensive system like the one "studied"".

Response: We agree with the Reviewer that locomotion is energy expenditure for the animal as the issue has been reviewed by several authors (CSIRO, 2007).

In this scenario, standing (compared with lying), changing body position (double movement of lying down and standing again), walking (horizontal component), walking (vertical component), eating (prehension and chewing) and ruminating represent to the animal an energy cost of 10 kJ day $^{-1}$, 0.26 kJ day $^{-1}$, 2.6 kJ km $^{-1}$, 28.0 kJ km $^{-1}$, 2.5 kJ h $^{-1}$ and 2.0 kJ h $^{-1}$, respectively. Thus, 550 kg dairy cow walking 3 km day $^{-1}$ grazing would expend 500 x 2.6 x 3 = 3.9 MJ metabolizable energy (ME), but if it was 0.5 km to the shed and she was milked twice a day, this would add 2 km. However, distance walked during grazing would be less (break feeding), so maybe a total of 4 km; 5.2 MJ day $^{-1}$. If she had to go up a 50 m (vertical distance) hill, this would add 500 x 28 x 0.05 = 0.7 MJ ME

If the heat of combustion for CH_4 is about 55.7 kJ g $^{-1}$ and the cow emits 21 g CH_4 kg $^{-1}$ DMI, then intakes of 8, 12 and 16 kg DM will yield 168, 252 and 336 g CH_4 day $^{-1}$, with heats of combustion of 9.3, 14.0 and 18.7 MJ. Thus, ME for grazing for a dry cow might be 3.9/9.3 = 42% of loss to CH_4; a dry cow on hill country where she went up and down 250 m day $^{-1}$ would expend (3.9 + 0.7 x 5) = 7.4 MJ day $^{-1}$ walking; 7.4/9.3 = 80% as much ME as lost through CH_4.

In this context, we have not included in our manuscript and/or model any value regarding energy expenditure from locomotion because the objectives of the study and our stated methodology never considered the quantification of such energy expenditure in our linear interpolation. Therefore, we cannot comment further because scientific statements must be based on facts rather than on speculative assumptions.

In parallel, it is relevant to consider that although the efficiency of the use of energy for maintenance and LWG can be affected by animal age and feed quality and composition, Pinares et al. (2007) found that feed intake rather than feed digestibility in Holstein-Friesian heifers is the major factor affecting CH_4 emissions. Moreover, it is relevant to say that Pinares et al. (2007) reported that across two consecutive years, CH_4 emissions (g day $^{-1}$) expressed as overall CH_4 yield (% gross energy intake) did not differ between cattle grazing under low or high stocking rates ha $^{-1}$.

In summary as those heifers and their temperate environment differ to the context of our study, to our knowledge, further and more complex studies in extensive neotropical savanna beef systems are required to corroborate not only those findings; and accurately elucidate the understood criticism regarding the effect of energy expenditure in locomotion vs CH_4 energy losses.

"Next, there is no rationale for bulls being excluded, but in any case I can think of no justification for doing so. Their contribution to GHG are significant, and in the case of calculation of emissions intensities, crucial. This is data that MUST be included".

Response: We appreciate and respect the Reviewer's point of view. In this regard and considering the above response to Reviewer 1 regarding emissions from bulls in our extensive beef systems, it is important to note once more that based on our original experimental records, the bulls-cows ratio was 1:25 and each bull was present in the herd for 9 months year $^{-1}$.

Thus, given that cows were stocked at a ratio of 1:5 ha, the maximum stocking rate of bulls in the breeding system is no more than 0.008 bull ha $^{-1}$ (this is a maximum figure, not adjusted for the 3 months during which they do not serve). In other words, on a per cows' herd base, bulls would contribute 0.04 animals. Admittedly, bulls are much heavier than cows (about 600 kg at the beginning of the breeding season) but under our extensive savanna conditions, they lose approximately 60-100 kg in a period of the mating season; nevertheless, we kept the high value of 600 kg throughout the reproductive cycle.

In this context, our calculations do not concur with the Referee's criticism because using our algorithms, a healthy bull over the mating period should produce 210.85 g CH_4 day $^{-1}$, which is equivalent to say that the animal is emitting 1.687 g CH_4 ha day $^{-1}$. Therefore, considering that those emissions are constant for all the treatments, the possibility of any bias related to our present outcomes (Tables 1-5) due to the exclusion of bulls' emissions is unlikely.

However, to satisfy the demand from the Referee, those marginal values and a related explanatory text to support our decision has been included from line 172 to line 174, while lines 468 and 501-502, Table 6 and Supplementary material 1 provides additional relevant information.

"Finally, I see no justification for including conclusions on C stocks in this paper. There is a total absence of data from the authors, or previously applying to the operations considered. This needs to be removed".

Response: We removed the statement on soil C stocks (Comparing C … balances; from line 460 to line 463) in the Conclusions section of the reviewed manuscript. Thus, the previous and subsequent sentences of that statement are linked now in line 529 (… maximum estimates. Our estimates…).

References

Allard, V., Soussana, J.-F., Falcimagne, R., Berbigier, P., Bonnefond, J.M., Ceshia, E., D'hour, P., Hénault, C., Laville, P., Martin, C., Pinares-Patiño, C., 2007. The role of grazing management for the net biome productivity and greenhouse gas budget (CO_2, N_2O and CH_4) of semi-natural grasslands. Agric Ecosyst Environ. 121, 47–58.

CSIRO., 2007. Nutrient Requirements of Domesticated Ruminants. CSIRO Publications, Melbourne.

Menezes, A.C.B., Valadares Filho, S.C., e Silva, C., Pacheco, M.V.C., Pereira, J.V.M., Rotta, P.P. Zanetti, D., Detmann, E., Silva, F.A.S., Godoi, L.A., Rennó, L.N., 2016. Does a reduction in dietary crude protein content affect performance, nutrient requirements, nitrogen losses, and methane emissions in finishing Nellore Bulls? Agric Ecosyst Environ. 223, 239–249.

Pinares-Patiño, C.S., D'hour, P., Jouany, J.-P., Martin, C., 2007. Effects of stocking rate on methane and carbon dioxide emissions from grazing cattle. Agric Ecosyst Environ. 121, 30–46.

Ramírez-Restrepo, C.A., Van Tien, D., Le Duc, N., Herrero, M., Le Dinh, P., Dinh Van, D., Le Thi Hoa, S., Vu Chi, C., Solano-Patiño, C., Lerner, A., Searchinger T., 2017. Estimation of methane emissions from local and crossbreed beef cattle in Dak Lak province of Vietnam. Asian-Australas J Anim Sci. 30, 1054–1060.

Ramírez-Restrepo, C.A., Vera, R.R., 2019. Body weight performance, estimated carcass traits and methane emissions of beef cattle categories grazing *Andropogon gayanus*, *Melinis minutiflora* and *Stylosanthes capitata* mixed swards and *Brachiaria humidicola* pasture. Anim Prod Sci. 56(4), 729–750.

Vera, R.R., Ramírez-Restrepo, C.A., 2017. Complementary use of neotropical savanna and grass-legume pastures for early weaning of beef calves, and effects on growth, metabolic status and reproductive performance. Trop. Grassl-Forrajes Trop. 5(2), 50–65.

Kind regards,

Dr Carlos Alberto Ramírez Restrepo

Highlights

- Methane emissions were found to be markedly lower than IPCC estimations
- Calculated net carbon balance at system level is close to equilibrium
- Extensive beef herds may be environmentally viable
- Farming interventions may reduce the carbon footprint of extensive beef production systems

Dynamics of animal performance, and estimation of carbon footprint of two breeding herds grazing native neotropical savannas in eastern Colombia

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ABSTRACT

The savannas of eastern Colombia located in the Orinoco river basin represent 18% of the Latin American neotropical savannas, and those areas that are tillable and closer to markets are subject to considerable anthropic pressure in the quest for intensification. Historically, and even today, beef cattle production constitutes the main land use, and much of it is subjected to extensive management. This paper describes for the first time, the use of cattle grazing experiments to assess methane (CH_4) emissions from neotropical savanna-based beef breeding systems, and with the support of published research conducted next to them, and estimate of the carbon (C) footprint in carbon dioxide equivalents (CO_2-eq) for the whole system. Over 5 years and covering complete reproductive cycles, conventional weaning (CW) herd system was compared to an early weaning (EW) herd system, that represented a modest degree of more intensive savanna management. Differences were found between the two management practices in total CH_4 emissions, emission intensities [kg CH_4 kg^{-1} calf born and kg CH_4 kg^{-1} liveweight gain (LWG)] and emission efficiencies (kg CO_2-eq kg^{-1} calf born and kg CH_4 kg^{-1} LWG), that mostly associated with the different lactation lengths. When both herd systems were carried over until calves, later yearlings, reached to 25 months of age, the differences in favor of EW breeding herd system were diminished. The calculated C footprint in (CO_2-eq) of both management practices was near neutral subjected to a number of assumptions and the use of limited published information on savanna C stocks and CH_4 and nitrous oxide (N_2O) emissions from soil, and it is posited that both herd systems were nearly in equilibrium. The available data and results show the need for further information on the neotropical savanna C stocks and C sequestration potential of soils of the Orinoco river basin. More reliable datasets regarding below-ground C inputs and CH_4 and N_2O emissions from soil are needed to provide a useful basal benchmark for, and approach to, future analyses of environmental impact of more intensive beef herd systems in the region.

Keywords

carbon footprint, liveweight, methane emissions, Orinoco basin, reproductive performance, soil emissions

1. Introduction

Savannas have been extensively managed by humans for different production purposes, driving ecological processes such as fire frequency and biomass accumulation, and consequently affecting the carbon (C) cycle (Grace et al., 2006). However, little is known about the long-term impacts of climate change and altered disturbance regimes on savanna C fluxes. Reducing C emissions -the so-called "carbon footprint"- is critical to confront global challenges of both climate change and land degradation. This is mainly because savanna systems may directly mitigate greenhouse gas emissions by (i) increasing soil organic C (SOC; Sanhueza and Donoso, 2006; Fisher et al., 2007; Rao et al., 2015); (ii) reducing ruminant methane (CH_4) emissions per unit of livestock product (Vélez-Terranova et al., 2015; Durmic et al., 2017); and (iii) decreasing nitrous oxide (N_2O) emissions (Byrnes et al., 2017; Chirinda et al., 2019).

The Llanos of Colombia and Venezuela are a significant part (18%) of the neotropical savannas of Latin America that are subject to strong human pressures (Ayarza et al., 2007). Historically, well-drained savannas in Colombia evolved from natural ecosystems inhabited by indigenous communities (Navas-Ríos, 1999), to extensive grazing of beef breeding herds (Huertas-Ramírez and Huertas-Herrera, 2015).

The use of Colombian savannas, in areas that can be tilled, has been rapidly changing with the agricultural frontier expanding into the region (Vera and Ramírez-Restrepo, 2017), with new land use practices such as intensive grazing (introduced pastures), tree plantations (oil palm, rubber, and timber), and intensive high input cropping (rice, maize, soybean, sorghum, sugarcane). Consequently, adaptation and transformation of agricultural industries in the region lead to changes such as (i) reduction in fire frequency; (ii) increase in tree cover; and (iii) increase in cattle stocking rates [(SRs) Etter et al., 2011] among others. Nevertheless, extensive systems persist in the majority of the non-tillable area, and adoption of technological innovations in these systems incur in management constraints such as the required frequent muster of grazing animals and increased supervision (Vera and Ramírez-Restrepo, 2017).

The Llanos region has not been the subject of detailed and long-term field experimentation regarding the environmental impact of existing cattle production systems, and the subject has infrequently been approached by using secondary information drawn from numerous international sources (Lerner et al., 2017). In the Brazilian Cerrados, Bogaerts et al. (2017) and Figueiredo et al. (2017) estimated C balances for a number of surveyed farms, using the Intergovernmental Panel on Climate Change (IPPC) parameters, but to our knowledge, locally collected long-term data have not been used for the same purpose in the remaining areas of neotropical savannas. Using results from a large and detailed on-ranch study, Kleinheisteramp and Habich (1985) characterized the existing beef production systems in bioeconomic terms and concluded that the quantity and quality of feed resources are the two major constraining factors, rather than management ability or intensity. Rivera (1988) confirmed these results by using a designed 5-year long and large experiment (2,700 ha, 345 cows replicated on a medium-texture and a sandy soil), demonstrating that the introduction of small areas of introduced grass plus regular supplementation of complete mineral supplements had a modest but noticeable impact on the performance of beef production systems. This trend was further supported by subsequent modelling exercises (Thornton and Vera, 1988) that also addressed the need for more intensive management supervision. Nevertheless, none of these studies considered the impact of these systems on the environment.

Tropical savannas may contribute to the global C sink. An early review by Scurlock and Hall (1998) noted the importance of above- and below-ground net primary production (NPP) as a possible contributor to C stocks in grasslands; and Lehmann et al. (2014)

reported large quantitative differences between savannas in different continents. Variable, and environment-specific, root:shoot ratios (Mokany et al., 2005) may contribute to the above differences.

In light of views expressed in the above studies and the lack of substantial funding to carry out long-term research on sustainable beef production systems' interventions on the well-drained savannas, it is necessary to substantiate assertions with a detailed computer-aided interrogation of medium-term cattle investigations conducted at the local level. This degree of sound science, elaboration and collaboration has recently provided the fullest and most up-to-date picture of the productive-environmental impact of contrasting beef cattle categories in fattening grazing systems (Ramírez-Restrepo and Vera, 2019), and the biological impact of strategic cow-calf beef grazing operations (Vera and Ramírez-Restrepo, 2017) in the neotropical savannas of Colombia.

In this scenario, the investigation described here aimed to quantify animal performance, and differences in CH_4 emissions and the C footprint of beef breeding herds subject to conventional weaning (CW) vs early weaning (EW), where the latter represents a prototype of a more management-intensive farm system than traditional farming systems. Data from 5 years of locally conducted field studies were used, complemented with the modelled C inputs and outputs from each herd system, and supplemented with published soils research conducted in the same site. In this study, we tested the hypothesis that the management-intensive EW system is biologically and environmentally more efficient per unit of output than the traditional extensive CW systems. Our main objective was to use a combined approach that integrates: (i) long-term field research on animal performance with CH_4 emissions from animals managed under a similar tropical environment; (ii) locally derived estimates of soil C stocks and annual soil C accumulation; and (iii) published information on CH_4 and N_2O emissions from animal excreta and soil, to provide an initial assessment of C footprint in carbon dioxide equivalents (CO_2-eq) at system level.

2. Materials and methods

2.1. Description of data used for modelling

Data from Brahman (*Bos indicus*) and crossbred Brahman x San Martinero (native *B. taurus*) cow-calf pairs subject to CW and EW farming management over two full and consecutive reproductive cycles (RCs), replicated twice in consecutive years, were sourced from the commercial herd at Carimagua Research Centre (CRC: 4°36’44.6” N latitude, 74°08’42.2” West longitude) in the Meta Department on the Llanos of Colombia (Fig. 1). The grazed savanna was moderately managed with fire applied to different fractions of the paddock (i.e. one or two times per year) as in commercial farming practice. Figure 2 shows the model limits and the main variables of the various management strategies compared. The original database (Vera and Ramírez-Restrepo, 2017) covering the years 1984, 1985 1986 and 1987 contained animal (i.e. cows and calves) numbers, first and second calving and first weaning dates plus liveweights (LWs) at approximately 4-monthly intervals and at weaning. Animal data are common to an estimated area of 2.38 million ha of savanna in the municipalities of Puerto López and Puerto Gaitán, 3°55’ to 4°20’ N, and 72°1’ to 72°55’ W, where soils research on C stocks referred in the present study were also conducted (Vera and Hoyos, 2019). The fluctuations observed in the present animal dataset are modest and agree with data collected from on-station (CRC) experiments (Rivera, 1988; Vera and Ramírez-Restrepo, 2017) and on-farm reports (Kleinheisterkamp and Habich, 1985; Vera and Hoyos, 2019).

2.2. Environmental conditions

Mean annual ambient temperature during the field study was 26.5 ^{o}C ranging from 25.2 ^{o}C in July to 28.1 ^{o}C in March, while the average annual precipitation was 2,790 mm with 94% of rainfalls recorded between April and November. Soils at CRC are well-drained sandy loam or clay loam Oxisols (tropeptic haplustox isohyperthermic) with the following characteristics: moderate to high values of bulk density (1.28 to 1.52 g cm $^{-3}$), low values of soil pH (4.30 to 5.18) and available phosphorus (1.30 to 3.65 mg kg $^{-1}$), low to moderate values of soil organic matter (SOM; 1.30% to 4.84%), and high values of aluminum saturation (70% to 90%; Fisher et al., 1994; Rao, 1998; Rao et al., 2001).

2.3. Methane emissions

Recent modelling studies (Ramírez-Restrepo and Vera, 2019) demonstrated a linear relationship between LW and CH_4 emissions (g day $^{-1}$; Eq. 1), and between LW and dry mater intake (DMI; Eq. 2) when Belmont Red Composite [Africander (African Sanga) X Brahman X Hereford-Shorthorn (3/4 *B. taurus*) and Brahman steers were fed *ad libitum* (i.e. 2.1% of total LW; Fisher et al., 1987) on a non-additive DM basis in open-circuit respiratory chambers. Ramírez-Restrepo et al. (2014., 2016a, b) reported the full details on feeding, metabolic and rumen microbiology studies conducted at Lansdown Research Station, near Townsville on the east coast of north QLD, Australia.

The Excel® spreadsheet mechanistic model extends the LW-derived CH_4 emissions and DMI simulation of Ramírez-Restrepo and Vera (2019) by adding calculations for reproductive parameters (i.e. gestation, lactation and weaning-conception intervals) to estimate CH_4 emissions from suckling weaned calves and stockers [Least squares mean ± standard error of the mean (SEM); 10.1 ± 1.71 months of age] until yearlings (24.0 ± 0.05 months) are sold. The model estimates CH_4 emissions in terms of mass [g or kg per day, ha, animal unit (AU; 450 kg)], LW unit or energy expenditure basis (MJ per animal unit). Methane emissions were converted to CO_2-eq using the value of 34 as the global warming potential (GWP_{100}) factor for CH_4 (Myhre et al., 2013; Mueller and Mueller, 2017). Methane emissions (i.e. 210.8 g day $^{-1}$) from Brahman bulls (Mean; 600 kg LW) at 1:25 bull to female ratio (Rivera, 1988; Bernal Adan, 2010) were small at the system level given the SR used. Complementary information on reproductive performance is also presented in an Excel® file (Supplementary material 1).

For simplicity, the procedure followed four steps. In the first step, herd structure over the first RC [i.e. gestation (285 days), calving, lactation length and weaning] and the second RC (i.e. post-weaning-conception, gestation, calving, lactation length and weaning) was determined by the number of cow-calf pairs originally managed under CW and EW practices in 1984 (Replicate 1; 9 vs 10) and 1985 (Replicate 2; 13 vs 16). In the second step, cows' conception LWs in the first RC and cows' weaning LWs in the second RC were derived by regression (Eq. 3 and Eq. 4) from pooled data at CRC (Rivera 1988; Vera et al., 1993, 2002). Calving-weaning intervals for the second RC in CW and EW for 1984 and 1985 herds were respectively assumed from those weaning practices followed at CRC in 1986 (319 ± 29 days vs 93 ± 4 days) and 1987 (319 ± 29 days vs 86 ± 5 days).

In the third step, recorded calves' LWs in the first and second RCs were apportioned to monthly growth rates, DMI and CH_4 emissions up to 25 months. However, emissions are considered only after 56 days of age (Rey et al., 2014; Huws et al., 2018). Targeted weaning LWs for CW in the second RC were simulated from pooled savanna data (Eq. 5; Rivera, 1988) or respectively assumed for EW 1984 and 1985 herds from 1986 (68 ± 13 kg) and 1987 (81 ± 9 kg) weaning farming routines (Vera and Ramírez-Restrepo, 2017).

The resulting predictive equations are as follows:

Eq 1.

CH_4 g day $^{-1}$ = 16.176 (± 21.0879) + 0.324 (± 0.0577) LW

$r^2 = 0.663$, $P < 0.0001$; CV = 16.78; r.s.d = 30.82; r = 0.814, $P < 0.0001$

Eq. 2.

DMI = 2.216 (± 1.3156) + 0.014 (± 0.0036) LW

$r^2 = 0.491$, $P < 0.01$; CV = 18.94; r.s.d = 1.34; r = 0.701, $P < 0.01$

Eq. 3.

Conception LW = - 14.447 (± 67.082) + 1.142 (± 0.210) weaning LW

$r^2 = 0.786$, $P < 0.001$; CV: 6.83; r.s.d = 45.49; r = 0.886, $P < 0 .001$

Eq. 4.

Weaning LW = 77.597 (± 44.407) + 0.687 (± 0.126) conception LW

$r^2 = 0.786$, $P < 0.001$; CV: 6.83; r.s.d = 35.29; r = 0.886, $P < 0.001$

Eq. 5.

Calf weaning LW = -91.000 (± 99.529) + 9.590 (± 3.874) birth LW

$r^2 = 0.605$, $P = 0.06$; CV: 6.76; r.s.d = 12.98; r = 0.777, $P = 0.06$

In the final step, the model accounted for environmental impact from EW calves considering effects of body growth and SR while grazing improved pastures until calves on savanna were conventionally weaned. Early weaned calves grazed improved forage grass, *Andropogon gayanus* associated with improved forage legumes, either *Pueraria phaseoloides* (146 days; 1984) or *Centrosema acutifolium* (148 days; 1985), after which they joined their contemporary CW counterparts in stockers' herds and grazed on savanna for 441 additional days (Vera and Ramírez-Restrepo, 2017). The only external physical input used in these systems was the provision of mineral supplements whose C footprint is also included in the present work to assess C balance (Supplementary material 1).

2.4. Estimation of carbon stocks and carbon footprint in CO_2-eq

Estimation of differences in C stocks and C footprint in CO_2-eq between CW and EW strategies of savanna management was based on both published reports and assumed values. Soil organic C stocks were determined as described by Fisher et al. (1994). Net primary productivity of savanna biomass of both above-ground (Fisher et al., 1998; Rao, 1998; Rao et al., 2001; Grace et al., 2006) and below-ground (Rao, 1998; Rao et al., 2001; Trujillo et al., 2006) were used to estimate the C footprint. Carbon concentration in the savanna biomass was estimated as 40%, while the C footprint was estimated based on CH_4 emissions of the breeding herd including bull emissions, CH_4 and N_2O emissions from animal excreta (dung and urine) embracing the bull and the estimated C accumulation (in CO_2-eq) from both shoot and root biomass into soil (Supplementary material 1). Carbon stocks in the *A. gayanus* pastures are not included in the calculations that followed.

2.5. Statistical analysis

Data were analyzed using the Statistical Analysis System (SAS, University Studio 3.5, Cary, NC, USA). Measurements of LW, DMI, calculated CH_4 emissions and derived intensity and efficiency emission indices were analyzed using the GLIMMIX procedure. The linear fitted model included the fixed effects of replicate (i.e. 1 and 2; years 1984 and 1985), weaning practice (i.e. CW and EW), RC (i.e. 1 and 2), the interactions between weaning practice and RC; and between replicate, weaning practice and RC. These analyses included cow as random effect.

Analysis of variance for post-weaning conception (dry) periods were assessed using the MIXED procedure, with a fitted linear model that considered the effects of replicate, weaning practice and the replicate by weaning practice interaction. Predictive equations and correlation values between (i) conception and weaning LW; and (ii) calf weaning LW and birth were obtained based on the Rivera (1988) and Vera et al. (1993, 2002); and Vera and Ramírez-Restrepo (2017) datasets, respectively using the REG and CORR procedures. Results are presented as least squares means (LSM) and their standard errors of the means (SEM), unless otherwise noted, and precise *P*-values are shown when available.

3. Results

Cows' mean LWs and days taken to reach different reproductive events determined the amounts and timing of CH_4 emissions, and these differences are shown in Fig. 3. During gestation, LW was increased by conceptus growth, while the design of the experiments and the following modelling approach influenced ($P < 0.0001$) calves' LW at calving and weaning between CW (25.5 ± 0.22 kg and 152.2 ± 2.64 kg) and EW (24.0 ± 0.20 kg and 82.1 ± 2.50 kg) treatments, respectively.

Daily CH_4 (g animal $^{-1}$) emissions at specific reproductive points and phases are shown in Table 1. At conception, there was a RC x weaning practice interaction ($P < 0.05$), while the RC x weaning routine x replicate interaction was stronger ($P < 0.001$). Gestation values showed that the RC x weaning practice interaction ($P < 0.0001$) and the RC x weaning routine x replicate interaction ($P < 0.01$) contributed to the explanation of the data. However, we did not detect differences at calving between replicates or due to the RC x weaning routine interaction, whilst weaning practices and the plotted RC x weaning routine x replicate interaction had a proportionate effect ($P < 0.05$).

The RC x weaning routine x replicate relation had effects ($P < 0.05$) on emissions over the lactation stage. Similarly, although there are no direct field CH_4 emissions data to compare the simulation against, it does illustrate the effect of weaning treatment ($P < 0.05$) and the interactions between RC and weaning practice, and among RC x weaning routine x replicate ($P < 0.0001$). On the whole, given the weaning settings used in this simulation, the model indicates a significant variation among the RC, replicate, and weaning treatment effects and their interactions. Emissions during the dry empty period in the first RC was similar among treatments.

Cumulative CH_4 emissions (kg head $^{-1}$) over the gestation phase were associated with variation ($P < 0.01$) in the RC x weaning scheme interaction (Table 2), whilst emissions during the lactation period were ($P < 0.0001$) affected by replicate, weaning activities and all the interaction terms. As is indicated in Table 2, this pattern ($P < 0.0001$) was similarly followed by calves' emissions and their derived intensity and efficiency indices.

Averaged indices of CH_4 emissions intensity (kg kg $^{-1}$ calf born) and efficiency (kg CO_2-eq kg $^{-1}$ calf born) were higher ($P < 0.0001$) in CW calves (0.48 ± 0.005 and 16.46 ± 0.190) than in EW calves (0.10 ± 0.005 and 3.46 ± 0.182). Values over the weaning-conception period were similar.

Cow-calf pairs' CH_4 emissions in Table 3 exhibited a consistent weaning practice effect ($P < 0.0001$) across all measured parameters. However, interaction effects influenced to a lesser extent emission profiles and derived emission indices. Overall, indices of CH_4 emissions intensity (kg kg $^{-1}$ calf born) and efficiency (kg CO_2-eq kg $^{-1}$ calf born) were larger ($P < 0.0001$) for CW (3.74 ± 0.057 and 127.19 ± 1.950) than for EW (2.47 ± 0.055 and 84.20 ± 1.870) treatments.

Estimates of CH_4 emissions from calves at a comparable commercial stocker age for the first and second RCs are presented in Table 4. Overall, irrespective of expression units, daily emissions were significantly different between replicates, but similar in their derived indices. Nevertheless, variation between weaning practices and all interaction effects were significantly different across all modelled issues. There were lower ($P <$ 0.0001) absolute CH_4 efficiency indices (kg CO_2-eq kg $^{-1}$ calf final LW) in CW (2.30 ± 0.015) calves than in their EW (2.88 ± 0.015) counterparts.

To summarize, the results of the present analyses on enteric CH_4 emissions showed very large practical differences (5 fold) that are significant ($P < 0.0001$) between management weaning practices in terms of CH_4 intensity and efficiency absolute LSM indices per kg of calf born (Table 2). We also found a 18.5% difference in kg CO_2-eq per calf weaned (Table 3), and 24.9% difference per calf FLW (Table 4), parameters. Similarly, although there were no significant differences in cumulative CH_4 emissions over the reproductive cycles (i.e. gestation plus lactation) of cows (Table 2), when expressed on a per calf born emission index, the differences amounted to 79%, indicating large differences with significance for improving both biological and environmental efficiencies at a system level.

Table 5 mirrored the effects on key aspects of CH_4 emissions from yearlings. The comparison demonstrated the differential impact of weaning treatments on the measured variables but also, and more importantly, the critical role of the combined effects of animal LWs, reproduction and management variables on the dynamics of both weaning systems.

Using the LW change as a functional unit, complementary derived CH_4 intensity (kg kg $^{-1}$ LWG) and CH_4 efficiency (CO_2-eq kg $^{-1}$ LWG) indices were lower in CW than in EW practices at a comparable commercial weaning age (0.1023 ± 0.0012 and 3.47 ± 0.042 vs 0.1371 ± 0.0012 and 4.66 ± 0.040, $P < 0.0001$) and from birth to yearling age (0.2161 ± 0.0004 and 7.34 ± 0.014 vs 0.2177 ± 0.0004 and 7.40 ± 0.013, $P < 0.01$). In contrast, the respective emission indices were higher for CW than for EW treatments over the stocker-yearling phase (0.4000 ± 0.0045 and 13.59 ± 0.155 vs 0.2880 ± 0.0045 and 9.79 ± 1.468, $P < 0.0001$).

Differences observed in animal performance between the CW and EW s while grazing a savanna are shown in Table 6. The values of average annual LWs were slightly higher with CW than EW, while EW markedly reduced ($P < 0.05$) the inter-calving period (Vera and Ramírez-Restrepo, 2017).

Estimated C stocks and C balance for fertile beef cows with suckling calves subjected to CW and EW strategies are listed in Table 6. The values of CH_4 emitted by cow-calf pairs and C emitted over the inter-calving period were lower with EW than with CW management system. To estimate C balance based on above-ground and below-ground biomass, we assumed similar values for both CW and EW management systems. The net sources and sinks of C in CW and EW breeding herd management systems were estimated by summarizing the data from: (a) changes in CH_4 emissions from animals and their excreta; and (b) changes in above-ground and below-ground C including root turnover and soil C accumulation (using valuers from the studies conducted in nearby experimental sites). We also included de C contribution from both urine and dung and the CH_4 and N_2O emissions from soil in the estimation of C footprint in CO_2-eq at system level (Supplementary material 1). Our conservatively estimated C footprint in CO_2-eq of the CW and EW systems suggest a slightly reduced C footprint with EW compared to the CW system (Table 6).

The magnitude and variability in the parameters recorded and in those simulated can be judged from the standard errors in Tables 1-5, and in the supplementary material 1.

4. Discussion

The present study dealt with a more complex production-environmental scenario than that quantified by Ramírez-Restrepo and Vera (2019) that referred to animals gaining weight without the complications of physiological dynamics characteristic of fertile, breeding cows during complete RCs. In this context, McAuliffe et al. (2018) noted that emissions, C balances and life cycle assessments of animal production systems are most frequently carried out based on aggregate data from farm surveys (Gaitán et al., 2016) or stochastic simulation approaches (Toro et al., 2017). On the contrary, analyses are seldom based on actual, individual, animal performance (McAuliffe et al., 2018) and even less frequently, on observations of individual animals replicated over long periods of time (Ramírez-Restrepo and Vera, 2019), an approach that allows assessment of within herd, and between years, variability (Tables 1-5 and supplementary material 1).

Cows' LWs were relatively low, and comparable to those reported by Kleinheisterkamp and Habich (1985) for ranch animals and also by Rivera (1988) in a large long-term and replicated grazing experiment. Liveweight showed large oscillations associated with changing physiological states, but the effect of weaning treatments was small even when statistically significant, with the largest difference between CW and EW amounting to no more than 2% that is probably indicative of the limited potential to increase cows' LWs based exclusively on the native savanna (Fisher et al., 1992). On the contrary, there was a large, and cumulative, difference in the length of the RCs imposed by the design of the experiment that required different lactation lengths in CW vs EW. This effect was compounded by cows on savanna being unable to reconceive until after 2-3 months elapsed from weaning, but the interval was shorter in EW than in CW, a finding generally encountered in extensive beef tropical savanna systems in northern Australia (Dixon et al., 2011; Fordyce et al., 2014), and that leads to higher reproductive performance per animal and per ha in EW. Low LW's were likely due to aggregate effects of poor savanna daily growth rates in sandier and heavier soils (6-7 kg ha $^{-1}$ vs 18 kg ha $^{-1}$; Rivera, 1988; Rao et al., 2001), and low nutritive value, which contribute to long inter-calving intervals.

Liveweight fluctuations, empirical and theoretical equations, and the nature of datasets emphasize the usefulness of deductive estimations CH_4 emissions from beef cattle in smallholder (Ramírez-Restrepo et al., 2017; Goopy et al., 2018) and neotropical savanna (Ramírez-Restrepo and Vera, 2019) farming systems. This may explain why our results provided evidence to support the view that physiological events and weaning strategies in extensive cow-calf herd systems heavily influence the dynamics of CH_4 emissions. However, our C estimates are not consistent with the C aggregated modelled work of Etter et al. (2011) in the Colombian Llanos. This is mainly driven by SRs in their work exceeding by 36% the values from our field work, and their simultaneous use of CO_2-eq emission factors derived from Canadian-temperate dairy beef (*B. taurus*) cattle fed on mixed-balanced diets that do not represent the interaction among quality of DMI, cattle genetics, ruminant physiology and farming practices that were observed on neotropical savannas. This overestimation of emissions has strong implications for C cycle analysis and impacts on climate discussions because in extensive tropical beef systems, *B. indicus* and crossbred *B. indicus* x *B. taurus* cattle rather than temperate dairy cattle interplay naturally with inhabitants and land resources to become competitive and sustainable (O' Neill et al., 2013; Ramírez-Restrepo and Charmley, 2015; Vandermeulen et al., 2018a, b).

In this connection, the overall picture emerging from our results is in agreement with Ku-Vera et al. (2018) study that measured CH_4 yields (g CH_4 kg $^{-1}$ DMI) feeding *ad libitum* on low-quality tropical grasses that were discretely supplemented to crossbred *B. indicus* x *B. taurus* heifers. Ku-Vera et al. (2018) reported 18.07 g CH_4 kg $^{-1}$ DMI from 287 kg (range 204-350) cattle, while irrespective of treatments and reproductive factors our approach linked an averaged CH_4 yield of 18.21 g CH_4 kg $^{-1}$ DMI from 340 kg (range 280-400) cows. Analogously, a simulated median CH_4 yield of 17.97 g CH_4

kg $^{-1}$ DMI from 347 kg (range 285-407) of old cull cows was recently reported (Ramírez-Restrepo and Vera, 2019).

This means that outside the tropics, those CH_4 yields are unlikely to be achieved in pastoral conditions mainly due to differences in genetic x environmental x diet x management interactions (O'Neill, 1995; O'Neill et al., 2016; Vandermeulen et al., 2017). Adding together CH_4 yields from young and mature dairy cattle (Ramírez-Restrepo et al., 2016c) reinforce the notion that extensive soil-grass-beef C systems may be influenced by, but not limited to, the biodiversity and methanogenic role of improved forage grasses and legumes (Sanhueza and Donoso, 2006; Vélez-Terranova et al., 2015; Durmic et al., 2017).

Thus, our overall annual CW and EW CH_4 estimates (kg head $^{-1}$ year $^{-1}$) for breeding (i.e. gestation plus lactation) cows (39.20 ± 0.506 vs 42.74 ± 0.476; $P < 0.0001$); weaning-conception period (42.81 ± 0.928 vs 42.73 ± 0.895; $P > 0.05$); commercial weaned stockers (15.35 ± 0.194 vs 14.00 ± 0.185; $P < 0.0001$); stocker-yearlings (27.59 ± 0.328 vs 25.32 ± 0.311; $P < 0.0001$); and yearlings (22.42 ± 0.263 vs 20.56 ± 0.250; $P < 0.0001$) raise questions about the accuracy of the CH_4 emission Tier 1 default factor (56 kg head $^{-1}$ year $^{-1}$) provided by IPCC (2006) to estimate beef C footprints on the Colombian neotropical savannas.

Therefore, there is a need to consider the potential effect of these differences and the geographical extrapolation of those values in the national GHG inventory by the Institute of Hydrology, Meteorology and Environmental Studies [IDEAM (2016)]. Secondly, differences between CW and EW on an annual basis are small in absolute terms, although some are significant. Nevertheless, the large temporal difference in Fig. 3 between the two herd systems clearly indicates that the differences favor the biological, and also the environmental efficiency of EW if considered over the lifetime of the breeding cows (Supplementary material 1). In effect, the data in Table 6 shows that CW emits 46% more C in each inter-calving period than EW, and that over comparable periods (507 days), EW weans 2 calves for each 1.49 of CW. Interestingly, another complex aspect of these comparisons relates to the systems' boundaries adopted since outputting born and weaned calves vs producing 2.5 years old yearlings give rise to, or mask, differences between systems in all of the biological and environmental indices examined, but the residual effect of the respective inter-calving periods persists. In our view, these aspects therefore reinforce the need to consider the limits of the various feasible production systems before making broad generalization.

Further, given that our LW-derived CH_4 flux model is based on detailed field records of individual animals and long-term knowledge of neotropical extensive beef farming systems, current biological and environmental simulated outcomes could be scaled up to an additional 10 million ha of savanna in the Vichada Department of the Colombian Orinoco river basin. This is particularly important if differences in carrying capacity are taken into account (Bernal Adan, 2010). Nevertheless, in the development of knowledge and for the foreseeable future, there is a need, therefore, to tie the uniqueness of this study to mirrored rural spaces without promoting further expansion of the beef industry on those fragile and diverse socio-cultural savanna ecosystems.

Aboveground standing biomass values from native savanna in the Llanos of Colombia and Venezuela ranged from 1.2 to 4.8 megagram (Mg) ha $^{-1}$ (without fertilizer application) and with a maximum value of 8.88 Mg ha $^{-1}$ with uneconomical fertilizer application (Rao et al., 2001). Data on annual rate of soil C accumulation under native savanna are limited because this requires information on NPP based on production, turnover and decomposition of above-ground and below-ground biomass. Long et al. (1989, 1992) found NPP values from five natural grassland sites in the tropics to range from 0.14 to 10 kg m $^{-2}$ year $^{-1}$ (0.61 to 5.68 Mg ha $^{-1}$ of aboveground standing biomass) of DM indicating that all five sites were potential sites of net C accumulation. In the absence of fires, they noted accumulation of 144 g m $^{-2}$ year $^{-1}$ C, and 40 g m $^{-2}$ year $^{-1}$ C with occasional fires (0.5 year $^{-1}$). They also found a net loss of 70 g m $^{-2}$ year $^{-1}$ C with more frequent fires and drought, suggesting that the balance, in terms of the sites being a sink or source of C, was delicate. These studies and Grace et al. (2006) indicated that the grass-dominated communities have the potential to act as significant sinks for C in the absence of fire or where fire frequency is low. Armenteras et al. (2005) estimated that burned areas during the 2001 dry season amounted to 5.18% of the Colombian eastern savannas, but Romero-Ruiz et al. (2010) noted very large year-to-year variation with an average of 24%. This wide range reflects in part, differences in methodology and calculation algorithms.

Savanna C fluxes are highly seasonal, with fire causing high inter-annual variability. Fire has the potential to alter soil C storage by influencing rates of NPP, C allocation patterns, and rates of OM decomposition (Ojima et al., 1994). But fire is also known to improve biodiversity in native savanna (Abreu et al., 2017). The net C emissions from savanna fires in Colombia have been diminishing with the changing land use trends in both absolute terms and per unit area, because the more fertile areas with higher biomass are undergoing a faster conversion (Etter et al., 2011). However, this is largely compensated by CH_4 emissions from increased cattle SRs in the improved pastures replacing the savannas, notwithstanding the potential C sequestration of some sown pastures (Fisher et al., 1994). Management effects on C stocks and fluxes across the Orinoco savannas were estimated by San José and Montes (2001) and they concluded that the Orinoco system was an atmospheric sink of -17.53 million metric tons (Tg) C year $^{-1}$.

The IPCC (2006) has provided a framework for estimating and simulating emission reductions resulting from grassland management. The magnitude of the C footprint associated with the production of any livestock product from savanna varies depending on the extent of the system selected, which defines the up and downstream processes that are included in the assessment. The C footprint calculated in the present paper from enteric CH_4 emissions from cow-calf pairs and the bull amounted to 3,580 and 4,832 kg CO_2-eq for a full RC (i.e. interval between two consecutive conceptions) for EW and CW, respectively. These figures should be viewed as an upper estimate, since beef breeding herds are also composed of replacement heifers of 1-3 years of age, non-fertile cows, and old cull cows with lower nutrtional requirements and emissions. Cows may represent up to 63% of the females in the herd, but only half of them raise a calf in any given year under extensive management (Corporación Colombiana de Investigación Agropecuaria [CORPOICA, 1998]; De Armas, 2005; Ezanno, 2005) and calved, lactating cows contribute the most to herd emissions (Casey and Holden, 2006). A somewhat more accurate figure for CO_2-eq emissions of the full breeding herd can be estimated using the figures presented above for bred cows and empty, non-lactating cows, and those of Velásquez and Ríos (2010) and Ramírez-Restrepo and Vera (2019) for replacement heifers and cull cows, yielding 153 kg C ha over the full RC for a herd with 63% of breeding cows. These estimates should be considered relatively high and conservative values for herds bred and maintained exclusively on savannas based on clay-loam soils and SRs of 0.20 cows ha $^{-1}$. Sandy-loam soils with a much reduced carrying capacity (0.10-0.15 cows ha $^{-1}$) would exhibit correspondingly lower values of kg CO_2-eq ha $^{-1}$.

The savannas on clay-loam soils have a C stock of 180-200 Mg ha $^{-1}$ to a depth of 1 m (Fisher et al., 1994), whereas above- and below ground biomass C and that of litter may amount to 2.2 Mg ha $^{-1}$ (range 1-5; Rao et al., 2001; Trujillo et al., 2006). Fire will of course have a dramatic effect on aboveground biomass, but in absence of yearly fires (Grace et al., 2006), the daily growth rate of native vegetation (Rao et al., 2001), together with its low nutritive value, result in utilizaton rates as low as 20% leading to rapid accumulation of rank forage. Numerous plant traits influence how plant biomass affect C sequestration, as reviewed by De Deyn et al. (2008). Reliable and repeatable estimates of C sequestration under savannas are scarce (Grace et al., 2006; Trujillo et al., 2006; Fisher et al., 2007), but the latter authors found that SOC contributed by roots after 1 year of decomposition in the soil amounted to 1.1 Mg ha $^{-1}$ year $^{-1}$. If this value is applied to the *A. gayanus* pastures used for the EW calves, the C footprint of the EW strategy would be substantially improved. Soil C contributes substantially more to total C stock than does biomass C (Wise et al., 2009). We used a conservative value of 150 kg CO_2-eq ha $^{-1}$ year $^{-1}$ for soil C sequestration rate to estmate the C footprint of both systems.

The details on estimation of enteric and fecal CH_4, and N_2Oemissions from dung and urine are listed in Supplementary material 1. In the estimation of overall C footprint for each system, we have also inlcude the contribution of emissions from the bull. We estimated a value of 242 kg CO_2-eq fecal CH_4 ha $^{-1}$ year $^{-1}$ using the emission factor value of 0.034% from Zhu et al. (2018). We estimated fecal N output to 3.81 kg N ha $^{-1}$ year $^{-1}$. Using the N_2O emission factor of 0.0015 g of N g $^{-1}$ of dung from Lessa et al. (2014) and the GWP_{100} value of N_2O of 298 (Zhu et al., 2018), we calculated a value of 0.471 kg CO_2-eq ha $^{-1}$ year $^{-1}$. Based on the published values of Whitehead (2000), we estimated that the N output from urine is 15.33 kg N cow $^{-1}$ year $^{-1}$ and using the N_2O emission factor for urine of 0.012 g of N g $^{-1}$ of urine (Lessa et al., 2014), we calculated a value of 11.71 CO_2-eq ha $^{-1}$ year $^{-1}$. We used the published values from Castaldi et al. (2006) and estimated the emissions from soil (separately for both dry and wet seasons) of CH_4 as 26.2 CO_2-eq ha $^{-1}$ year and N_2O as 518 kg CO_2-eq ha $^{-1}$ year $^{-1}$. Using these values and not taking into account of the possible contribution of the *A. gayanus* pastures, the presently calculated C footprint of both CW and EW systems is near to neutral with small positive values, which is consistent with the sustainable use of these savannas, under extensive management, that has persisted for over 200 years. From a broader perspective, this environmental, productive, profitable and socio-cultural dynamic coexistence remarkably extends our understanding of natural beef herd farming systems in terms of eco-efficient stability. This is an important sustainability issue that needs to be maintained in the foreseeable future as oulined by Tedeschi et al. (2015).

5. Conclusions

The present study is the first one conducted in the tropical savannas of northern South America using 4-5 years data collected locally in designed, medium-term grazing experiments using records of individual animals. Cattle management systems used in this study closely resembled to what was recorded in long-term ranch surveys in the region, while the savannas used experimentally are representative of those commonly found on medium-texture soils, that were subjected to comparable management. In parallel, CH_4 emissions were derived from similar phenotypical cattle and plant resources, and therefore, we are confident that they constitute reliable maximum estimates. Our estimates are conservative, since they derive only from bred, lactating cows that are the most demanding animals and are also the largest CH_4 emitters in the commercial herds. There is clearly a need for a larger database regarding C stocks in the savannas and their rates of change, particularly for belowground C balance and also emissions from soil under varying management strategies. Similarly, C emissions from full herds composed of the numerous breeds, types, ages, and LWs commonly encountered in commercial ranches need to be estimated, particularly as systems intensify with the incorporation of fertilized sown pastures and other feed resources with varying impacts on the systems' performance, demography, C stocks, C sequestration rate in soil and CH_4 and N_2O emissions from soil. Intensification will affect the herd structure over time, thereby modifying also the balance between physical inputs and outputs, a situation best dealt with via simulation modeling.

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References

Abreu, R.C.R., Hoffmann, W.A., Vasconcelos, H.L., Pilon, N.A., Rossato, D.R., Durigan, G., 2017. The biodiversity cost of carbon sequestration in tropical savanna. Sci Adv. 3(8), e1701284, 1–7.

All things Nittany., 2018. https://www.flickr.com/photos/ciat

(accessed 18 November 2018).

Armenteras, D., Romero, M., Galindo, G., 2005. Vegetation fire in the savannas of the Llanos Orientales of Colombia. World Resource Review. 17(4), 531–543.

Ayarza, M., Barrios, E., Rao, I. M., Amézquita, E., Rondon, M., 2007. Advances in improving agricultural profitability and overcoming land degradation in savanna and hillside agroecosystems of tropical America, in: Bationo, A., Waswa, B., Kihara, J., Kimetu, J. (Eds.), Advances in integrated soil fertility research in sub Saharan Africa: challenges and opportunities. Springer, The Netherlands, pp. 209–229.

Bernal Adan, J.S., 2010. Evaluación contextual de la ganadería bovina en el Departamento del Vichada (Bachelor Thesis). Universidad de los Llanos, Villavicencio.

http://bibliotecadigital.agronet.gov.co/bitstream/11348/3942/1/041.pdf

(accessed 10 February 2019).

Byrnes, R.C., Nùñez, J., Arenas, L., Rao, I., Trujillo, C., Alvarez, C., Arango, J., Rasche, F., Chirinda. N., 2017. Biological nitrification inhibition by *Brachiaria* grasses mitigates soil nitrous oxide emissions from bovine urine patches. Soil Biol Biochem. 107, 156–163.

Bogaerts, M., Cirhigiri, L., Robinson, I., Rodkin, M., Hajjar, R., Costa Junior, C., Newton, P., 2017. Climate change mitigation through intensified pasture management: Estimating greenhouse gas emissions on cattle farms in the Brazilian Amazon. J Clean Prod. 162, 1539–1550.

Casey, J.W., Holden, N.M., 2006. Quantification of GHG emissions from sucker-beef production in Ireland. Agr Syst. 90(1-3), 79–98.

Castaldi, S., Ermice, A., Strumia, S., 2006. Fluxes of N_2O and CH_4 from soils of savannas and seasonally-dry ecosystems. J. Biogeog. 33, 401–415.

Chirinda, N., Loaiza, S., Arenas, L., Ruiz, V., Faverín, C., Alvarez, C., Savian, J.V., Belfon, R., Zuniga, K., Morales-Rincon, A., Trujillo, C., Arango, M., Rao, I., Arango, J., Peters, M., Barahona, R., Costa Jr., C., Rosenstock, T.S., Richards, M., Martinez-Baron, Cardenas, L., 2019. Adequate vegetative cover decreases nitrous oxide emissions from cattle urine deposited in grazed pastures under rainy season conditions. Sci. Rep. 9, 908.

Cochrane, T.T., Sánchez, L.G., Porras, J.A., Azevedo, L.G. de., Garver, C.L., 1985. Land in tropical America = La tierra en América tropical = A terra na América tropical. Centro Internacional de Agricultura Tropical (CIAT); Empresa Brasileira de Pesquisa Agropecuária, Centro de Pesquisa Agropecuária dos Cerrados (EMBRAPA), Cali.

CORPOICA.,1998. Avances y experiencias en las empresas ganaderas del piedemonte y altillanura del Meta. Corporación Colombiana de Investigación Agropecuaria, Villavicencio.

De Armas L.R., 2005. Sistemas de pastoreo en sabanas de Trachypogon en el Estado Bolivar. in: Tejos, M.R., García, J.A., Contreras, J.P., Molina, Ch.J.A., Zambrano, A.C., Castellanos, L., Valbuena, T.N.J., Lucena, A.S., Delgado, A., Zambrano, R.A. (Eds.), IX Seminario de Pastos y Forrajes. Universidad Nacional Experimental del Táchira, Táchira, (pp. 97–111).

De Deyn, G.B., Cornelissen, J.H., Bardgett, R. D., 2008. Plant functional traits and soil carbon sequestration in contrasting biomes. Ecology Lett. 11(5), 516–531.

Dixon, R.M., Playford, C., Coates, D.B., 2011. Nutrition of beef breeder cows in the dry tropics. 2. Effects of time of weaning and diet quality on breeder performance. Anim Prod Sci. 51(6), 529–540.

Durmic Z, Ramírez-Restrepo, C.A., Gardiner, C., O'Neill, C.J., Hussein, E., Vercoe, P. E., 2017. Differences in the nutrient concentrations, *in vitro* methanogenic potential and other fermentative traits of tropical grasses and legumes for beef production systems in northern Australia. J. Sci. Food Agric. 97, 4075–4086.

Etter, A., Sarmiento, A., Romero, M.H., 2011. Land use changes (1970-2020) and carbon emissions in the Colombian Llanos, in: Hill, M.J., Hanan, N.P. (Eds.), Ecosystem function in savannas. Measurement and modeling at landscape to global scales. CRC Press, Boca Raton, pp. 383–402.

Ezanno, P., 2005. Dynamics of a tropical cattle herd in a variable environment: a modelling approach in order to identify the target period and animals on which concentrating management efforts to improve productivity. Ecol Modell. 188, 470–482.

Figueiredo, E.B.d., Jayasundara, S., Bordonal, R.d.O., Berchielli, T.T., Reis, R.A., Wagner-Riddle, C., Newton, L.S.Jr., 2017. Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in Brazil. J Clean Prod. 142, 420–431.

Fisher, D., Burns, J., Pond K., 1987. Modeling *ad libitum* dry matter intake by ruminants as regulated by distension and chemostatic feedbacks. J Theor Biol 126, 407–408.

Fisher, M.J., Lascano, C.E., Vera, R.R., Rippstein, G., 1992. Integrating the native savanna resource with improved pastures, in: Hardy, B. (Ed.), Pastures for the tropical lowlands: CIAT's contribution. CIAT, Cali, pp. 75–100.

Fisher, M.J., Rao, I.M., Ayarza, M.A., Lascano, C.E., Sanz, J.I., Thomas, R.J., Vera, R. R., 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature. 371, 236–238.

Fisher, M.J., Thomas, R.J., Rao, I.M., 1998. Management of tropical pastures in acid-soil savannas of South America for carbon sequestration in the soil, in: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of carbon sequestration in soil (Advances in soil science). CRC Press, Boca Raton, pp. 405–420.

Fisher, M.J., Braz, S.P., Dos Santos, R.S.M., Urquiaga, S., Alves, B.J.R., Boddey, R.M., 2007. Another dimension to grazing systems: Soil carbon. Trop Grasslands. 41, 65–83.

Fordyce, G., McGowan, M., McCosker, K., Burns, B., 2014. Reproductive wastage in extensively-managed beef cattle, in: Beggs, D.S. (Ed.), Proceedings of the XXVIII Word Buiatrics Congress: Keynote lectures. Australian Veterinary Association, Cairns, pp. 94–100.

Gaitán, L., Läderach, P., Graefe, S., Rao, I., van der Hoek, R., 2016. Climate-smart livestock systems: an assessment of carbon stocks and GHG emissions in Nicaragua. PLoS ONE 11(12), e0167949.

Goopy, J.P., Onyango, A.A., Dickhoefer, U., Butterbach-Bahl, K., 2018. A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa – Results for Nyando, Western Kenya. Agr Syst. 161, 72–80.

Grace, J., San José, J., Meir, P., Miranda, H.S.P., Montes, R.A., 2006. Productivity and carbon fluxes of tropical savannas. J. Biogeogr. 33, 387–400.

Huertas-Ramírez, H., Huertas-Herrera, A., 2015. Historiagrafía de la ganadería en la Orinoquia. Actas Iberoamericanas de Conservación Animal AICA. 6, 300–307.

Huws, S.A., Creevey, C.J., Oyama, L.B., Mizrahi, I., Denman, S.E., Popova. M., Muñoz-Tamayo, R., Forano, E., Waters, S.M., Hess, M., Tapio, I., Smidt, H., Krizsan, S.J., Yáñez-Ruiz, D.R., Belanche, A., Guan, L., Gruninger, R.J., McAllister, T.A., Newbold, C.J., Roehe, R., Dewhurst, R.J., Snelling, T.J., Watson, M., Suen, G., Hart, E.H., Kingston-Smith, A.H., Scollan, N.D., do Pardo, R.M., Pilau, E.J., Mantovani, H.C., Attwood, G.T., Edwards, J.E., McEwan, N.R., Morrison, S., Mayorga, O.L., Elliott, C., Morgavi, D.P., 2018. Addressing global ruminant agricultural challenges through understanding the rumen microbiome: Past, present, and future. Front Microbiol. 9: 2161.

IDEAM., 2016. Inventario nacional y departamental de gases efecto invernadero – Colombia. Tercera comunicación nacional de cambio climático. IDEAM, PNUD, MADS, DNP, CANCILLERIA, FMAM, Bogotá, DC.

IGAC., 2018. Instituto Geográfico Agustín Codazzi Mapas Departamentales Físicos. https://geoportal.igac.gov.co/es/contenido/mapas-departamentales-fisicos (accessed 18 November 2018).

IPCC., 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_0_Cover.pdf (accessed 10 September 2018).

Kleinheisterkamp, I., Habich, G., 1985. Colombia. 1, Estudio biológico y técnico, in: Vera, R.R., Seré C. (Eds.), Sistemas de producción pecuaria extensiva. Brasil, Colombia, Venezuela. CIAT, Cali, pp. 213–278.

Ku-Vera, J.C., Valencia-Salazar, S.S., Piñeiro-Vázquez, A.T., Molina-Botero, I.C., Arroyave-Jaramillo, J., Montoya-Flores, M.D., Lazos-Balbuena, F.J., Canul-Solís, J.R., Arceo-Castillo, J.I., Ramírez-Cancino. L., Escobar-Restrepo. C.S., Alayón-

Gamboa, J.A., Jiménez-Ferre,r G., Zavala-Escalante, L.M., Castelán-Ortega, O.A., Quintana-Owen, P., Ayala-Burgos, A.J., Aguilar-Pérez, C.F., Solorio-Sánchez, F.J., 2018. Determination of methane yield in cattle fed tropical grasses as measured in open-circuit respiratory chambers. Agric and For Meteor. 258: 3-7.

Lehmann, C.E.R., Anderson, T.M., Sankaran, M., Higgins, S.I., Archibald, S., Hoffmann, W.A., Hanan, N.P., Williams, R.J., Fensham, R.J., Felfili, J., Hutley, L.B., Ratnam, J., San José, J., Montes, R., Franklin, D., Rusell-Smith, J., Ryan, C.M., Durigan, G., Hiernaux, P., Haidar, R., Bowman, D.M.J.S., Bond, W.J., 2014. Savanna vegetation-fire-climate relationships differ among continents. Science. 343(6170), 548–552.

Lerner, A.M., Zuluaga, A.F., Chará, J., Etter, A., Searchinger, T., 2017. Sustainable cattle ranching in practice: Moving from theory to planning in Colombia’s livestock sector. Environ Manage. 60(2), 176–184.

Lessa, C.R., Madari, B.E., Paredes, D.S., Boddey, R.M., Urquiaga, S., Jantalia, C.P., Alves, B.J.R., 2014. Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions. Agric. Ecosys. Environ. 190, 104–111.

Long, S.P., Jones, M. B., Roberts, M.J., 1992. Primary Productivity of Grass Ecosystems of the Tropics and Subtropics. Chapman and Hall, New York.

Long, S.P., Moya, E.G., Imbamba, S.K., Kamnalrut, A., Piedade, M.T.F., Scurlock, J.M. O., Shen, Y.K., Hall, D.O., 1989. Primary productivity of natural grass ecosystems of the tropics: A reappraisal. Plant Soil. 115(2), 155–166.

McAuliffe, G.A., Takahashi, T., Orr, R.J., Harris, P., Lee, M.R.F., 2018. Distributions of emissions intensity for individual beef cattle reared on pasture-based production systems. J Clean Prod. 171, 1672–1680.

Mokany, K., Raison, R.J., Prokushkin, A.S., 2006. Critical analysis of root: shoot ratios in terrestrial biomes. Global Change Biol. 12(1), 84–96.

Mueller, R.A., Mueller, E.A., 2017. Fugitive methane and the role of atmospheric half-life. Geoinformatics & Geostatistics: An Overview. 5(3), 1–7.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing, in: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 659–740.

Navas-Ríos, C.L., 1999. Caracterización socioeducativa, evaluativa y comparativa de cuatro comunidades en los Llanos Orientales de Colombia (Master Thesis). Universidad de Antioquia, Medellín.

O’Neill, C.J., 1995. A study of the growth and fertility of different beef cattle genotypes in a tropical environment with implications for the genetic improvement of productivity (Master Thesis). Central Queensland University, Rockhampton.

O’Neill, C.J., Ramírez-Restrepo, C.A., González, L.A., 2013. Breed, environment and management factors affecting diet selection and growth of steers, in: Charmley, E., Watson, I. (Eds.), Proceedings of the Northern Beef Research Update Conference. The North Australia Beef Research Council, Cairns, p.178.

O’Neill, C.J., Ramírez-Restrepo, C.A., Cozzolino, D., González, L.A., Swain, D.L., 2016. Improving beef productivity through increased genetic and ecological diversity – cattle genotype and pasture management options, in: Central Queensland

University (Ed.), Proceedings of the RUN Regional Futures Conference. CQ University, Rockhampton, p. 34.

Ojima, D.S., Galvin, K.A., Turner, B.L., 1994. The global impact of land-use change. BioScience. 44, 300–304.

Ramírez-Restrepo, C.A., O'Neill, C.J., López-Villalobos, N., Padmanabha, J., Wang, J.K., McSweeney, C., 2016b. Effects of tea seed saponin supplementation on physiological changes associated with blood methane concentration in tropical Brahman cattle. Anim Prod Sci. 56, 457–465.

Ramírez-Restrepo, C.A., O'Neill, C.J., López-Villalobos, N., Padmanabha, J., McSweeney, C., 2014. Tropical cattle methane emissions: the role of natural statins supplementation. Anim Prod Sci. 54, 1294–1299.

Ramírez-Restrepo, C.A., Tan, C., O'Neill, C.J., López-Villalobos, N., Padmanabha, J., Wang, J.K., McSweeney, C., 2016a. Methane production, fermentation characteristics and microbial profiles in the rumen of tropical cattle fed tea seed saponin supplement. Anim Feed Sci Tech. 216, 58–67.

Ramírez-Restrepo, C.A., Van Tien, D., Le Duc, N., Herrero, M., Le Dinh, P., Dinh Van, D., Le Thi Hoa, S., Vu Chi, C., Solano-Patiño, C., Lerner, A., Searchinger T., 2017. Estimation of methane emissions from local and crossbreed beef cattle in Dak Lak province of Vietnam. Asian-Australas J Anim Sci. 30, 1054–1060.

Ramírez-Restrepo, C.A., Vera, R.R., 2019. Body weight performance, estimated carcass traits and methane emissions of beef cattle categories grazing *Andropogon gayanus*, *Melinis minutiflora* and *Stylosanthes capitata* mixed swards and *Brachiaria humidicola* pasture. Anim Prod Sci. 56(4), 729–750.

Ramírez-Restrepo, C.A., Charmley, E., 2015. An integrated mitigation potential framework to assist sustainable extensive beef production in the tropics, in: P. K. Mahanta, P.K., Singh, J.B., Pathak, P.S. (Eds.), Grasslands: A Global Research Perspective. Range Management Society of India, Jhansi, pp. 417–436.

Ramírez-Restrepo, C.A., Clark, H., Muetzel, S., 2016c. Methane emissions from young and mature dairy cattle. Anim Prod Sci. 56, 1897–1905.

Rao, IM., 1998. Root distribution and production in native and introduced pastures in the south American savannas, in: Box, J.E. Jr. (Ed.), Root Demographics and Their Efficiencies in Sustainable Agriculture, Grasslands, and Forest Ecosystems. Kluwer Academic Publishers, Dordrecht, pp. 19–42.

Rao, I.M., Rippstein, G., Escobar, G., Ricaurte, J., 2001. Producción de biomasa vegetal epígea e hipógea en las sabanas natives, in: Rippstein, G., Escobar, G., Motta, F. (Eds.), Agroecología y biodiversidad de las sabanas en los llanos orientales de Colombia. CIAT, Cali, pp. 198–222.

Rao, I., Arango, J., Ishitani, M., Peters, M., Miles, J., Tohme, J., Castro, A., Cardoso, J.A., Worthington, M., Selvaraj, M., van der Hoek, R., Schultze-Kraft, R., Rincón, A., Plazas, C., Mendoza, R., Cuchillo, M., Tapasco, J., Martinez, J., Hyman, G., Moreta, D., Mena, M., Karwat, H., Nunez,J., Subbarao, G., Cadisch, G., 2015. Strategic management for forage production and mitigation of environmental effects: Development of Brachiaria grasses to inhibit nitrification in soil, in: A. R. Evangelista, A.R., Avila, C.L.S., Casagrande, D.R., Lara, M.A.S., Bernardes, T.F. (Eds.), Proceedings of the 1st international conference on forages in warm climates. Universidade Federal de Lavras, Lavras, pp. 85–102.

Rey, M., Enjalbert, F., Combes, S., Cauquil, L., Bouchez, O., Monteils, V., 2014. Establishment of ruminal bacterial community in dairy calves from birth to weaning is sequential. J Appl Microbiol. 116, 245–257.

Rivera, B.S., 1988. Performance of beef cattle herds under different pasture and management systems in the Llanos of Colombia (Doctoral dissertation). Technische Universitat, Berlin.

Romero-Ruiz, M.H., Etter, A., Sarmiento, A., Tansey, K., 2010. Spatial and temporal variability of fires in relation to ecosystems, land tenure and rainfall in savannas of northern South America. Global Change Biol. 16, 2013–2023.

San José, J.J., & Montes, R.A., 2001. Management effects on carbon stocks and fluxes across the Orinoco savannas. For Ecol and Manage. 150, 293–311.

Sanhueza, E., Donoso, L., 2006. Methane emissions from tropical savanna *Trachypogon sp*. grasses. Atmos. Chem. Phys. 6, 5315–5319.

Scurlock, J., Hall, D.O., 1998. The global carbon sink: a grassland perspective. Global Change Biol. 4(2), 229–233.

Tedeschi, L.O., Muir, J.P., Riley, D.G., Fox, D.G., 2015. The role of ruminant animals in sustainable intensification programs. Int J Sust Dev World. 22(5), 452–465.

Thornton, P.K., Vera, R., 1988. Modelo de simulación para los sistemas de producción de carne en los Llanos Orientales de Colombia. Pasturas Tropicales. 10, 8–13.

Toro-Mujica, P., Aguilar, C., Vera, R.R., Bas, F. 2017. Carbon footprint of sheep production systems in semi-arid zone of Chile: A simulation-based approach of productive scenarios and precipitation patterns. Agr Syst. 157, 22–38.

Trujillo, W., Fisher, M.J., Lal, R., 2006. Root dynamics of native savanna and introduced pastures in the Eastern Plains of Colombia. Soil Till Res. 87, 28–38.

Vandermeulen, S., 2017. Effects of trees and shrubs browsing on the behavior of grazing cattle and on rumen protein metabolism (PhD Thesis). University of Liège Gembloux. Agro-bio Tech, Gembloux.

Vandermeulen, S., Ramírez-Restrepo, C.A., Marche, C., Decruyenaere V., Beckers, Y., Bindelle, J., 2018a. Behaviour and browse species selectivity of heifers grazing in a temperate silvopastoral system. Agroforest Syst. 92(3), 705–716.

Vandermeulen, S., Singh, S., Ramírez-Restrepo, C.A., Kinley, R.D., Gardiner, C.P., Holtum, J.A.M., Hannah, I., Bindelle, J., 2018b. *In vitro* assessment of rumen fermentation, digestibility and methane production of three species of *Desmanthus* for application in northern Australian grazing systems. Crop Pasture Sci. 69(8), 797–807.

Velásquez, J. C., Ríos, M., 2010. Evaluación de la producción de carne a partir de vacas cebú de descarte. Revista de Ciencia Animal. 3, 23–29.

Vélez-Terranova, M., Gaona, R.C., Sánchez-Guerrero, H., 2015. In vitro antimethanogenic properties of some plants adapted to the floodable savanna conditions of Arauca Department, Colombia. Trop. Subtrop. Agroecosyst. 18, 335–345.

Vera, R. R., Hoyos, F., 2019. Long-term beef production from pastures established with and without annual crops compared with native savanna in the high savannas of Eastern Colombia: a compilation and analysis of on-farm results 1979-2016. Trop. Grassl-Forrajes Trop. 7(1), 1–13.

Vera, R.R., Ramírez-Restrepo, C.A., 2017. Complementary use of neotropical savanna and grass-legume pastures for early weaning of beef calves, and effects on growth, metabolic status and reproductive performance. Trop. Grassl-Forrajes Trop. 5(2), 50–65.

Vera, R. R., Ramírez, C. A., Ayala, H., 1993. Reproduction in continuously underfed Brahman cows. Anim Prod. 57,193–198.

Vera, R. R., Ramírez, C.A., Velásquez, N., 2002. Growth patterns and reproductive performance of grazing cows in a tropical environment. Arch Latinoam Prod Anim. 10, 14–19.

Wise, R.M., von Maltitz, G.P., Scholes, R.J., Elphinstone, C., Koen, R., 2009. Estimating carbon in savanna ecosystems: rational distribution of effort. Mitig Adapt Strat Gl. 14, 579–604.

Whitehead, D.C., 2000. Nutrient elements in grassland. Soil-plant-animal relationships. CABI, Wallingford.

Zhu, Y., Merbold,L., Pelster, D., Diaz- Pines, E., Wanyama, G.N., Butterbach- Bahl, K., 2018. Effect of dung quantity and quality on greenhouse gas fluxes from tropical pastures in Kenya. Global Biogeochem Cycles. 32,1589–1604.

Table1

Effects of conventional (CW) weaning or early weaning (EW) savanna farming practices on calculated methane (CH_4) emissions (g day $^{-1}$ animal) from cows and calves across two reproductive cycles (RC) in each of the two temporal replicates in mixed herds of commercial Brahman (*Bos indicus*) and Brahman crossbred cattle.

	Replicate 1		**Replicate 2**		**Effects**			
	CW	EW	CW	EW	RP	Weaning	RC x Weaning	RC x Weaning x RP
Cows	**9**	**10**	**13**	**16**				
First conception	115.3 ± 4.32h	125.1 ± 4.10a	123.6 ± 3.59a	121.3 ± 3.24j	NS	NS	*	***
Gestation phase	127.5 ± 2.68d	140.1 ± 2.54g	139.8 ± 2.23i	139.1 ± 2.01c	.08	NS	****	**
Calving	137.5 ± 3.34a	127.9 ± 3.17j	127.0 ± 2.78h	125.7 ± 2.50f	NS	*	NS	*
Lactation stage	122.2 ± 3.22d	115.6 ± 3.06d	114.3 ± 2.68h	112.3 ± 2.41h	NS	NS	NS	*
Weaning	107.0 ± 2.96h	133.4 ± 2.81g	132.5 ± 2.46g	131.9 ± 2.22g	*	*	****	****
Dry empty period	118.9 ± 3.78	117.1 ± 3.78	118.3 ± 3.15	118.1 ± 3.03				
Cows	**9**	**9**	**13**	**14**				
Second conception	130.9 ± 4.32g	120.9 ± 4.20a	122.8 ± 3.59a	125.7 ± 3.34i				
Gestation phase	135.8 ± 2.68d	128.2 ± 2.65h	135.4 ± 2.23j	132.4 ± 2.12c				
Calving	139.7 ± 3.34a	134.9 ± 3.34i	146.1 ± 2.78g	138.4 ± 2.67e				
Lactation[†] stage	130.0 ± 3.22c	124.4 ± 3.16c	130.2 ± 2.68g	127.7 ± 2.52g				
Weaning[†]	120.2 ± 2.96g	113.3 ± 2.88h	114.33 ± 2.46h	116.6 ± 2.29h				
Suckling calves								
First weaning	62.5 ± 1.56f	52.5 ± 1.48g	62.6 ± 1.30f	38.3 ± 1.17j	**	****	****	****
Second weaning[†]	68.5 ± 1.56e	39.4 ± 1.55h	68.3 ± 1.30e	40.8 ± 1.24i				

[†] Modelled data. Least squares means (± SEM) values between similar parameters bearing different letters in the same column and replicate (RP) are significantly different (ab: $P < 0.05$; cd: $P < 0.01$; ef: $P < 0.001$; gh: $P < 0.0001$; ij: $P \leq 0.10$). Comparisons between RPs, weaning management and RC interactions in each row for each parameter are declared at *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < .0001$, $P \leq 0.10$. NS: Not significant.

Table 2

Cumulative calculated methane (CH_4) emissions (kg head $^{-1}$) and derived environmental indices from cows and calves grazed on neotropical savannas managed under conventional weaning (CW) or early weaning (EW) routines.

	Replicate 1		Replicate 2		Effects			
	CW	EW	CW	EW	RP	Weaning	RC x Weaning	RC x Weaning x RP
Cows	**9**	**10**	**13**	**16**				
First RC								
Gestation	36.35 ± 0.863d	38.02 ± 0.819i	37.78 ± 0.718a	37.38 ± 0.647a	NS	NS	**	NS
Lactation	38.14 ± 0.929b	21.22 ± 0.881g	33.86 ± 0.773g	13.76 ± 0.697c	****	****	****	****
Calves suckling phase	12.72 ± 0.393j	4.99 ± 0.373g	10.03 ± 0.327h	1.95 ± 0.295i	****	****	****	****
CH_4 intensity (kg kg $^{-1}$ calf born)	0.50 ± 0.012a	0.20 ± 0.011g	0.40 ± 0.010h	0.08 ± 0.009c	****	****	****	****
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ FLW)	3.02 ± 0.064i	1.52 ± 0.060g	2.47 ± 0.053h	0.97 ± 0.048g	****	****	****	****
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf born)	17.24 ± 0.410a	7.12 ± 0.389g	13.80 ± 0.341g	3.04 ± 0.308c	****	****	****	****
Weaning-conception period	12.91 ± 3.036	11.27 ± 3.036	13.67 ± 2.526	9.48 ± 2.434				
Cows	**9**	**9**	**13**	**14**				
Second RC								
Gestation	38.70 ± 0.863c	36.65 ± 0.847j	38.60 ± 0.718a	37.81 ± 0.676a				
Lactation†	41.07 ± 0.929a	11.51 ± 0.930h	41.61 ± 0.773h	11.12 ± 0.746d				
Calves suckling phase†	13.58 ± 0.393i	1.46 ± 0.392h	13.34 ± 0.327g	1.28 ± 0.314j				
CH_4 intensity (kg kg $^{-1}$ calf born) †	0.51 ± 0.012a	0.05 ± 0.012h	0.50 ± 0.010g	0.05 ± 0.009d				
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ FLW)†	2.86 ± 0.064j	0.69 ± 0.064h	2.81 ± 0.053g	0.56 ± 0.051h				
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf born)†	17.54 ± 0.410a	1.92 ± 0.411h	17.25 ± 0.341h	1.76 ± 0.330d				

† Modelled data. CO_2-eq: Carbon dioxide equivalent. FLW: Final liveweight over the phase. RC: Reproductive cycle. RP: Replicate. Values between similar parameters bearing different letters in the same column and RP are significantly different (ab: $P < 0.05$; cd: $P < 0.01$; ef: $P < 0.001$; gh: $P < .0001$; ij: $P \leq 0.10$). Comparisons between RPs, weaning management and RC interactions in each row for each parameter are declared at *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$, $P \leq 0.10$. NS: significant.

Table 3

Calculated methane (CH_4) emissions and derived environmental indices from commercial Brahman (*Bos indicus*) and Brahman crossbred cattle grazed on neotropical savannas subject to conventional weaning (CW) or early weaning (EW) farming systems.

	Replicate 1		**Replicate 2**		**Effects**			
	CW	EW	CW	EW	RP	Weaning	RC x Weaning	RC x Weaning x RP
Cow-calf pairs first RC	**9**	**10**	**13**	**16**				
CH_4 (g day $^{-1}$)	146.0 ± 2.99i	142.4 ± 2.83g	148.0 ± 2.49a	134.6 ± 2.24a	NS	****	****	**
CH_4 (g/ha $^{-1}$ day $^{-1}$)	29.2 ± 0.59i	28.4 ± 0.56g	29.6 ± 0.49a	26.9 ± 0.44a	NS	****	****	**
CH_4 (g AU $^{-1}$ day $^{-1}$)	259.5 ± 1.29g	247.5 ± 1.22g	255.8 ± 1.07g	245.5 ± 0.96g	NS	****	**	NS
CH_4 (g AU $^{-1}$ ha $^{-1}$ day $^{-1}$)	51.9 ± 0.25g	49.5 ± 0.24g	51.1 ± 0.21g	49.1 ± 0.19g	NS	****	**	NS
CH_4 intensity (kg kg $^{-1}$ calf born)	3.51 ± 0.115f	2.70 ± 0.109a	3.31 ± 0.096h	2.42 ± 0.089a	NS	****	****	NS
CH_4 intensity (kg kg $^{-1}$ calf weaned)	0.62 ± 0.033a	0.58 ± 0.032h	0.58 ± 0.028b	0.78 ± 0.025a	NS	****	.08	****
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf born)	119.40 ± 3.927f	91.83 ± 3.726a	112.83 ± 3.268h	82.41 ± 3.044a	NS	****	****	NS
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf weaned)	21.32 ± 1.152a	19.76 ± 1.093h	19.74 ± 0.095b	26.81 ± 0.864a	NS	****	.08	****
Cow-calf pairs second RC[†]	**9**	**9**	**13**	**14**				
CH_4 (g day $^{-1}$)	149.8 ± 2.99j	128.8 ± 2.91h	149.2 ± 2.49a	132.2 ± 2.31a				
CH_4 (g/ha $^{-1}$ day $^{-1}$)	29.9 ± 0.59j	25.7 ± 0.58h	29.8 ± 0.49a	26.4 ± 0.46a				
CH_4 (g AU $^{-1}$ day $^{-1}$)	238.1± 1.29h	221.6 ± 1.28h	236.9 ± 1.07h	222.3 ± 1.02h				
CH_4 (g AU $^{-1}$ ha $^{-1}$ day $^{-1}$)	47.6 ± 0.25h	44.3 ± 0.25h	47.3 ± 0.21h	44.4 ± 0.20h				
CH_4 intensity (kg kg $^{-1}$ calf born)	4.04 ± 0.115e	2.37 ± 0.115b	4.08 ± 0.096g	2.41 ± 0.092a				
CH_4 intensity (kg kg $^{-1}$ calf weaned)	0.66 ± 0.033a	0.85 ± 0.033g	0.66 ± 0.028a	0.78 ± 0.027a				
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf born)	137.52 ± 3.927e	80.62 ± 3.931b	139.00 ± 3.268g	81.95 ± 3.152a				
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf weaned)	22.46 ± 1.152a	29.04 ± 1.153g	22.72 ± 0.095a	26.56 ± 0.925a				

[†] Includes postweaning-conception data. AU: animal unit. CO_2-eq: Carbon dioxide equivalent. FLW: Final liveweight over the phase. RC: Reproductive cycle. RP: Replicate.

Values between similar parameters bearing different letters in the same column and RP are significantly different (ab: $P < 0.05$; cd: $P < 0.01$; ef: $P < 0.001$; gh: $P < 0.0001$; ij: $P \leq 0.10$).

Comparisons between RPs, weaning management and RC interactions in each row for each parameter are declared at $*P < 0.05$, $**P < .01$, $***P < 0.001$, $****P < 0.0001$, $P \leq 0.10$.

NS: Not significant.

Table 4

Comparable modelled period of methane (CH_4) emissions and resulting environmental indices from beef calves subject to conventional weaning (CW) on savanna or early weaning (EW) on savanna plus grazing on improved pastures until commercial CW age is achieved.

	Replicate 1		**Replicate 2**		**Effects**			
	CW	EW	CW	EW	RP	Weaning	RC x Weaning	RC x Weaning x RP
First RC	**9**	**10**	**13**	**16**				
CH_4 (g day $^{-1}$)	56.1 ± 1.50a	57.1 ± 1.43g	54.2 ± 1.25a	44.7 ± 1.16h	**	****	*	****
CH_4 (g ha $^{-1}$ day $^{-1}$)	11.2 ± 4.82a	343.0 ± 4.57g	10.8 ± 4.01a	268.5 ± 3.73g	****	****	**	****
CH_4 (g AU $^{-1}$ day $^{-1}$)	233.0 ± 3.59g	208.8 ± 3.41f	259.5 ± 2.99g	231.8 ± 2.79g	****	**	****	****
CH_4 (g AU $^{-1}$ day $^{-1}$ ha $^{-1}$)	46.6 ± 0.72g	41.7 ± 0.68f	51.9 ± 0.59g	46.3 ± 0.55g	****	**	****	****
CH_4 intensity (kg kg $^{-1}$ calf born)	0.32 ± 0.005h	0.35 ± 0.005h	0.32 ± 0.004h	0.30 ± 0.004h	NS	****	****	****
CH_4 intensity (g kg $^{-1}$ FLW)	57.2 ± 0.95h	67.0 ± 0.90h	57.3 ± 0.79h	68.9 ± 0.73h	NS	****	****	*
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf born)	11.14 ± 0.198h	11.90 ± 0.188h	10.88 ± 0.16h5	10.23 ± 0.154h	NS	****	****	****
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf FLW)	1.96 ± 0.032h	2.27 ± 0.030h	1.95 ± 0.026h	2.34 ± 0.025h	NS	****	****	*
Second RC	**9**	**9**	**13**	**14**				
CH_4 (g day $^{-1}$)	55.2 ± 1.50a	46.8 ± 1.49h	54.8 ± 1.25	48.5 ± 1.19g				
CH_4 (g ha $^{-1}$ day $^{-1}$)	11.0 ± 4.82a	279 ± 4.82h	10.9 ± 4.01a	291.9 ± 3.86h				
CH_4 (g AU $^{-1}$ day $^{-1}$)	202.3 ± 3.59h	226.9 ± 3.60e	213.9 ± 2.99h	213.9 ± 2.89h				
CH_4 (g AU $^{-1}$ day $^{-1}$ ha $^{-1}$)	40.4 ± 0.72h	45.3 ± 0.72e	42.7 ± 0.59h	42.7 ± 0.57h				
CH_4 intensity (kg kg $^{-1}$ calf born)	0.47 ± 0.005g	0.41 ± 0.005g	0.48 ± 0.004g	0.45 ± 0.004g				
CH_4 intensity (g kg $^{-1}$ FLW)	77.3 ± 0.95g	102.8 ± 0.95g	79.1 ± 0.79g	100.3 ± 0.76g				
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf born)	16.11 ± 0.198g	13.93 ± 0.199g	16.46 ± 0.165g	15.49 ± 0.159g				
CH_4 efficiency (kg CO_2-eq kg $^{-1}$ calf FLW)	2.62 ± 0.032g	3.49 ± 0.032g	2.69 ± 0.026g	3.40 ± 0.025g				

AU: animal unit. CO_2-eq: Carbon dioxide equivalent. FLW: Final liveweight. RC: Reproductive cycle. RP: Replicate. Values between similar parameters bearing different letters in the same column and RP are significantly different (ab: $P < 0.05$; cd: $P < 0.01$; ef: $P < 0.001$; gh: $P < 0.0001$; ij: $P \leq 0.10$). Comparisons between RPs, weaning management and RC interactions in each row for each parameter are declared at *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$, $P \leq 0.10$. NS: Not significant.

Table 5

Calculated methane (CH$_4$) emissions and derived environmental indices from commercial beef yearlings up to 25 months of age grazed on savannas after conventional weaning (CW) or early weaning (EW) farming systems.

	Replicate 1		**Replicate 2**		**Effects**			
	CW	EW	CW	EW	RP	Weaning	RC x Weaning	RC x Weaning x RP
First RC	**9**	**10**	**13**	**16**				
CH$_4$ (g day^{-1})	72.7 ± 1.61f	74.7 ± 1.53g	71.5 ± 1.34h	64.7 ± 1.24f	.08	****	****	****
CH$_4$ (g ha^{-1} day^{-1})	18.1 ± 0.40f	18.6 ± 0.38g	17.8 ± 0.33h	16.1 ± 0.31f	.08	****	****	****
CH$_4$ (g AU^{-1} day^{-1})	186.9 ± 1.20c	185.0 ± 1.14f	187.6 ± 1.00g	193.5 ± 0.93g	*	****	***	****
CH$_4$ (g/AU/ha day^{-1})	37.3 ± 0.24c	37.0 ± 0.22f	37.5 ± 0.20g	38.7 ± 0.18g	*	****	***	****
CH$_4$ intensity (kg kg^{-1} calf born)	1.20 ± 0.012j	1.29 ± 0.111g	1.19 ± 0.010d	1.21 ± 0.009e	NS	**	****	****
CH$_4$ intensity (g kg^{-1} FLW)	136.3 ± 0.05c	137.9 ± 0.05h	136.3 ± 0.04e	136.3 ± 0.04c	****	****	****	****
CH$_4$ efficiency (kg CO$_2$-eq kg^{-1} calf born)	35.9 ± 0.398h	44.1 ± 0.377g	40.7 ± 0.331d	41.4 ± 0.308e	****	NS	****	****
CH$_4$ efficiency (kg CO$_2$-eq kg^{-1} calf FLW)	4.63 ± 0.001c	4.68 ± 0.001h	4.63 ± 0.001e	4.63 ± 0.001c	****	****	****	****
Second RC	**9**	**9**	**13**	**14**				
CH$_4$ (g day^{-1})	78.7 ± 1.61e	67.4 ± 1.60h	78.5 ± 1.34g	69.8 ± 1.28e				
CH$_4$ (g ha^{-1} day^{-1})	19.6 ± 0.40e	16.8 ± 0.40h	19.6 ± 0.33g	17.4 ± 0.32e				
CH$_4$ (g AU^{-1} day^{-1})	182.2 ± 1.20d	190.2 ± 1.20e	182.4 ± 1.00h	188.8 ± 0.96h				
CH$_4$ (g/AU/ha day^{-1})	36.4 ± 0.24d	38.0 ± 0.24e	36.4 ± 0.20h	37.7 ± 0.19h				
CH$_4$ intensity (kg kg^{-1} calf born)	1.23 ± 0.012i	1.08 ± 0.012h	1.23 ± 0.010c	1.17 ± 0.009f				
CH$_4$ intensity (g kg^{-1} FLW)	136.1 ± 0.05d	138.2 ± 0.05g	136.1 ± 0.04f	136.2 ± 0.04d				
CH$_4$ efficiency (kg CO$_2$-eq kg^{-1} calf born)	42.1 ± 0.398g	36.8 ± 0.398h	42.1 ± 0.331c	39.8 ± 0.319f				
CH$_4$ efficiency (kg CO$_2$-eq kg^{-1} calf FLW)	4.62 ± 0.001d	4.70 ± 0.001g	4.62 ± 0.001f	4.62 ± 0.001d				

AU: animal unit. CO$_2$-eq: Carbon dioxide equivalent. FLW: Final liveweight. RC: Reproductive cycle. RP: Replicate. Values between similar parameters bearing different letters in the same column and RP are significantly different (ab: $P < 0.05$; cd: $P < 0.01$; ef: $P < 0.001$; gh: $P < 0.0001$; ij: $P \leq 0.10$). Comparisons between RPs, weaning management and RC interactions in each row for each parameter are declared at *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$, $P \leq 0.10$. NS: Not significant.

Table 6

Estimated carbon (C) footprint from greenhouse gas (GHG) fluxes, and animal performance for fertile beef cows with suckling calves subjected to conventional weaning (CW) and early weaning (EW) systems while grazing a savanna that was moderately managed with fire (applied to different fractions of the paddock), one or two times per year. Data in parentheses represent observed range of values.

Parameters	**CW**	**EW**	**Observations and source of referenced data**
Animal performance and methane (CH_4) emissions			
Average annual liveweight (LW; kg cow $^{-1}$)	350 (280-380)	340 (300-380)	Present study-results; LWs oscillate with reproductive state
Stocking rate (SR; cows ha $^{-1}$)	0.20	0.20	Average on-ranch and on-station, on medium texture soils; SR on sandy soils ≤ 0.1 cows ha $^{-1}$
LW gain (LWG; kg day $^{-1}$)	0	0	Net gain over the reproductive cycle (RC)
CH_4 emitted by cow-calf pair (kg cow $^{-1}$ day $^{-1}$)	0.127	0.126	Present study-results
CH_4 emitted by cow-calf pair (kg ha $^{-1}$ year $^{-1}$)	9.256	9.191	
Carbon dioxide equivalent (CO_2-eq) factor for CH_4	34	34	Myhre et al. (2013); Mueller and Mueller (2017)
CO_2-eq of CH_4 by cow-calf pair (kg ha $^{-1}$ year $^{-1}$)	315	312	
CO_2-eq of CH_4 by cow-calf pair over RC period (kg)	4,624	3,448	
CH_4 emitted by bull (kg ha $^{-1}$ year $^{-1}$)	0.287	0.287	
CO_2-eq of CH_4 by bull (kg ha $^{-1}$ year $^{-1}$)	9.750	7.750	
CO_2-eq of CH_4 by bull over RC period (kg)	208	132	
C stocks and soil C accumulation from savanna			
Soil organic C to 1 m depth, medium texture soil (Mg ha $^{-1}$)	(120-150)	(120-150)	Fisher et al. (1994); Rao (1998); Rao et al. (2001); Trujillo et al. (2006)

Table 6 Continued

Parameters	**CW**	**EW**	**Observations and source of referenced data**
C stocks and emissions from savanna			
Standing aboveground (shoot) biomass (DM kg ha $^{-1}$)	2,000-6,000	2,000-6,000	Fisher et al. (1998); Rao (1998); Rao et al. (2001); Grace et al. (2006)
Standing root biomass (DM kg ha $^{-1}$)	1,500-3,000	1,500-3,000	Rao (1998); Rao et al. (2001); Trujillo et al. (2006)
Total C stock in shoot and root biomass (kg ha $^{-1}$)	3,500-9,000	3,500-9,000	
Soil C accumulation rate (kg ha $^{-1}$ year $^{-1}$)	150 (100-200)	150 (100-200)	Fisher et al. (1994); Rao (1998); Rao et al. (2001); Trujillo et al. (2006)
GHG emissions from animals and C in soil in CO_2-eq			
Enteric CH_4 from cow-calf + bull (kg ha $^{-1}$ year $^{-1}$)	331	327	Present study-results
Fecal CH_4 from cow-calf + bull (kg ha $^{-1}$ year $^{-1}$)	242	242	Present study-results; emission factors (Zhu et al., 2018)
Total CH_4 from enteric + fecal (kg ha $^{-1}$ year $^{-1}$)	573	569	
Nitrous oxide (N_2O) emission from dung of cow-calf + bull (kg ha $^{-1}$ year $^{-1}$)	0.471	0.471	
N_2O emission from urine of cow-calf + bull (kg ha $^{-1}$ year $^{-1}$)	11.71	11.71	
CH_4 emission from soil (kg ha $^{-1}$ year $^{-1}$)	25.7	25.7	Castaldi et al. (2006)
N_2O emission from soil (kg ha $^{-1}$ year $^{-1}$)	518	518	Castaldi et al. (2006)
Soil C accumulation in CO_2-eq (kg ha $^{-1}$ year $^{-1}$)	-550	-550	
Overall estimated C footprint at system level in CO_2-eq (kg ha $^{-1}$ year $^{-1}$)	**583**	**579**	

Figure Headings

Fig. 1. Meta Department in Colombia extending from the east Andean mountains to the neotropical savanna regions of Puerto López, Puerto Gaitán y Carimagua Research Centre in the east. In the reference box, dark green shows the Meta (running west to east) and Manacacías (flowing south to north) rivers; light green corresponds to the high savannas where cropping activities are expanding; lighter colors refer to the dissected savannas. North of the Meta river (Casanare Department) is covered by seasonally flooded savannas. Numbers and dots indicate different land classes and the location of previously surveyed ranches, respectively, including some in which long-term monitoring of savannas, sown pastures and soils were carried out [Adapted from Cochrane et al. (1985); “All things Nittany” (2018); Instituto Geográfico Agustín Codazzi-Geoportal (IGAC, 2018)].

Fig. 2. Farming system boundary, inputs and outputs for and from conventional weaning (CW; 270 days of age) and early weaning (EW; 90 days of age) practices. The EW calves are moved to a sown pasture until reaching CW age. At that point, stockers in each weaning system are either sold or kept on fam as stockers-yearlings until 25 months of age to be sold for fattening purposes. Carbon footprint of both systems is estimated in terms of cattle methane (CH_4) emissions and carbon dioxide (CO_2) equivalents of CH_4 emissions.

Fig. 3. Cows’ mean liveweights at successive reproductive events (a) and time to reach them (b) during conventional (●) and early (▼) weaning farming systems in replicate 1; and over conventional (●) and early (Δ) weaning practices in replicate 2. Con, Calv, Preg, Lac, Wean and Dry represent conception, calving, pregnancy, lactation, weaning and weaning to reconception events or periods.

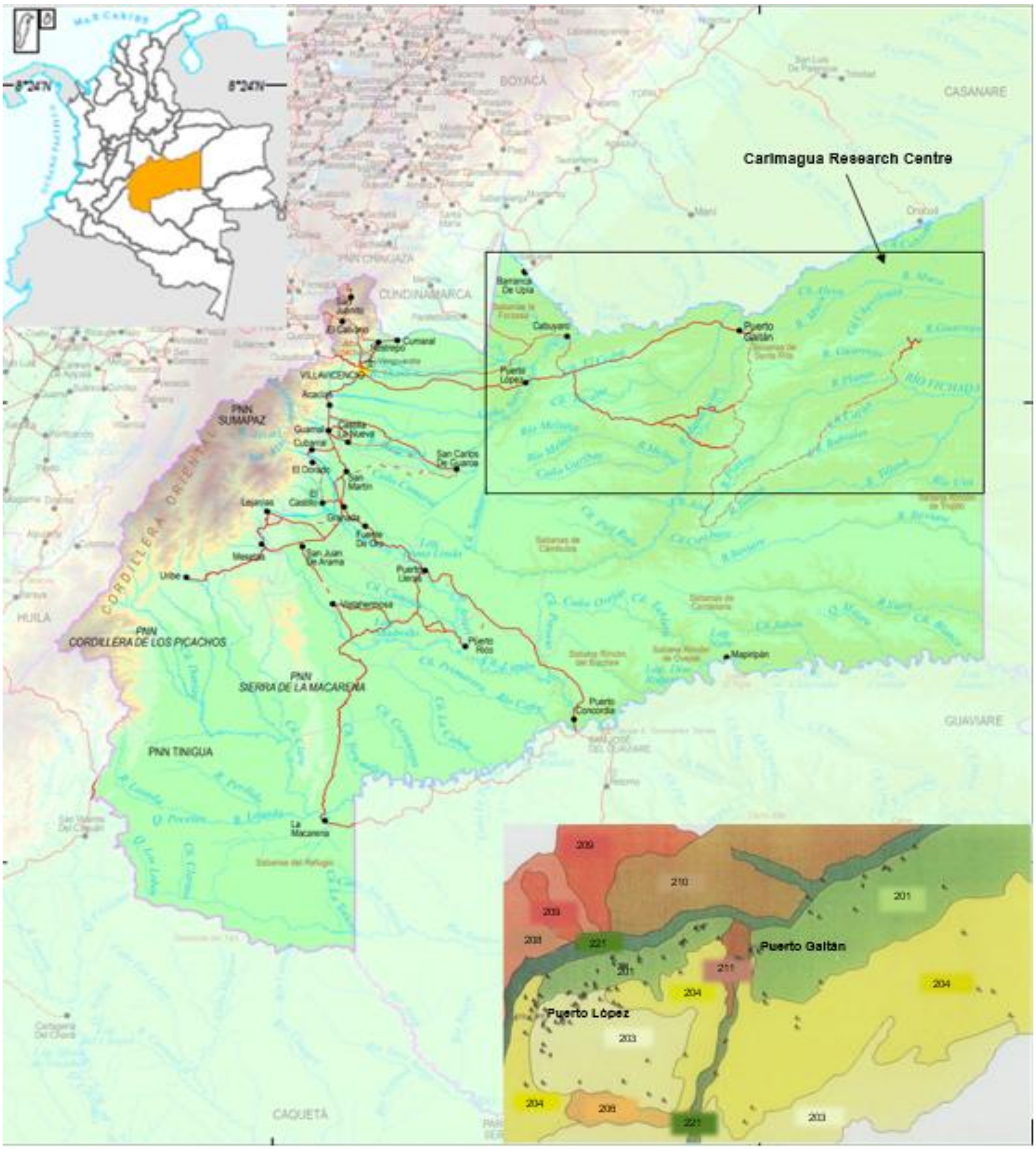
Carimagua Research Centre
BOYACA
CASANARE
CUNDINAMARCA
VILLAVICENCIO
Puerto Gaitán
Puerto López
Barranca De Upía
Cabuyaro
PNN SUMAPAZ
CORDILLERA ORIENTAL
PNN CORDILLERA DE LOS PICACHOS
PNN SIERRA DE LA MACARENA
PNN TINIGUA
HUILA
GUAVIARE
CAQUETÁ
Puerto Concordia
Mapiripán
La Macarena
Uribe
Puerto Rico
Puerto Lleras
San Juan De Arama
Granada
Mesetas
Lejanías
Vistahermosa
RÍO TICHADA
209
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Fig. 1.

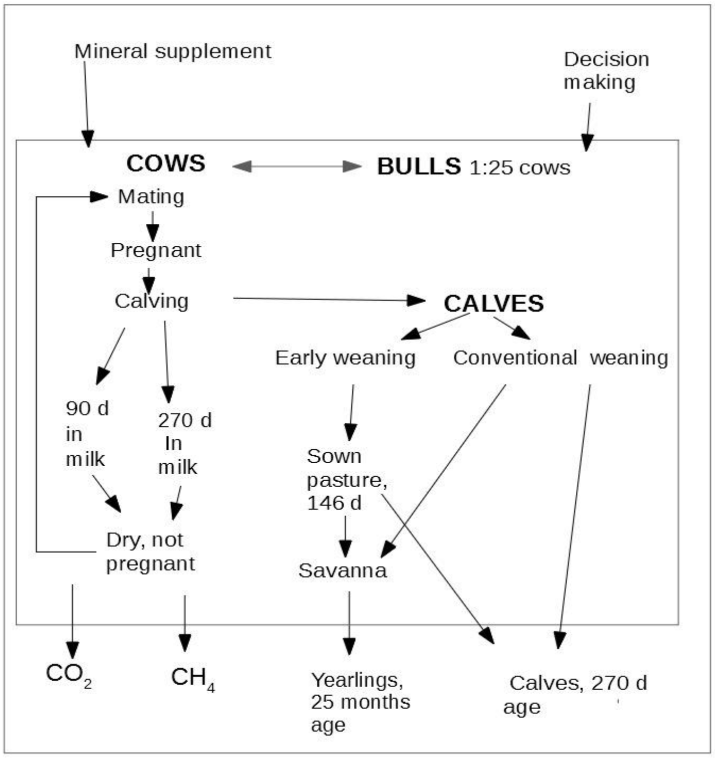
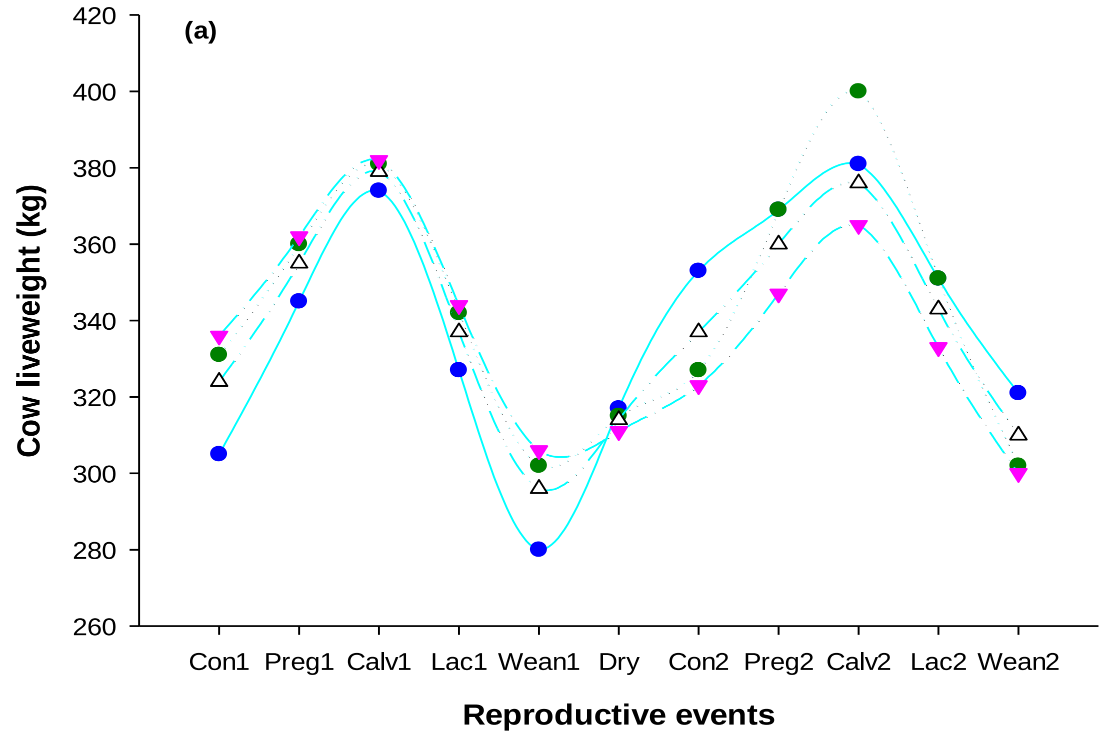

Mineral supplement
Decision making
COWS
BULLS 1:25 cows
Mating
Pregnant
Calving
CALVES
Early weaning
Conventional weaning
90 d in milk
270 d In milk
Sown pasture, 146 d
Dry, not pregnant
Savanna
CO_2
CH_4
Yearlings, 25 months age
Calves, 270 d age

Fig. 2.


(a)
Cow liveweight (kg)
420
400
380
360
340
320
300
280
260
Con1
Preg1
Calv1
Lac1
Wean1
Dry
Con2
Preg2
Calv2
Lac2
Wean2
Reproductive events

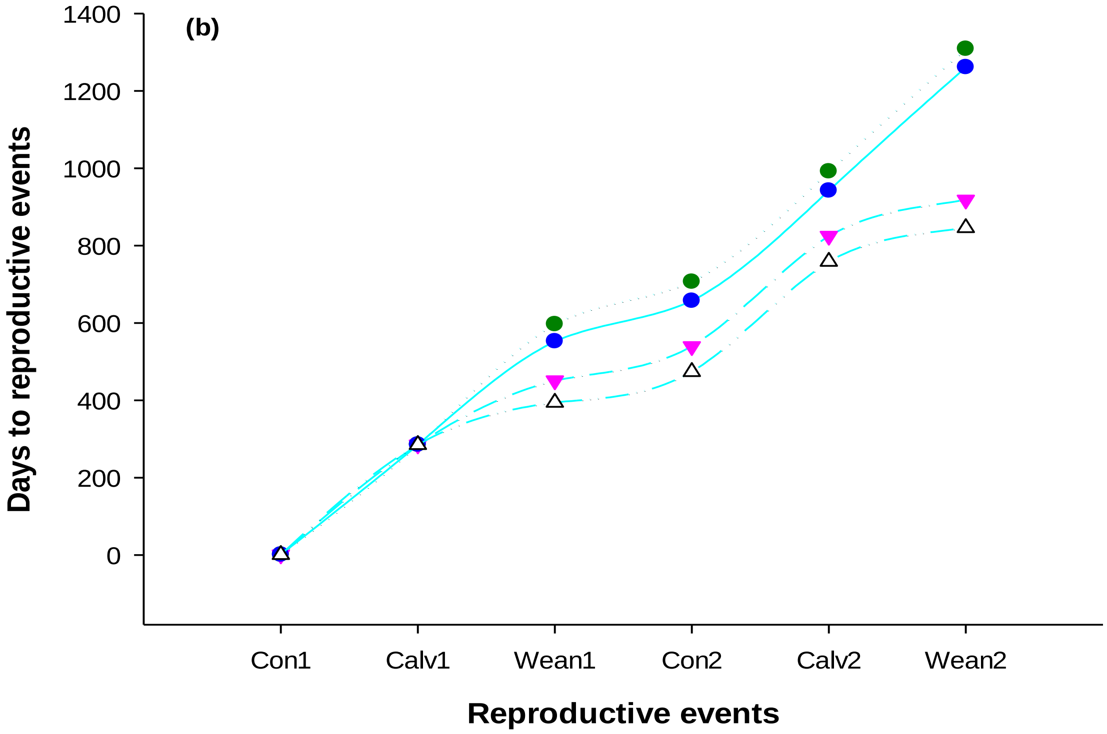

(b)
Days to reproductive events
1400
1200
1000
800
600
400
200
0
Con1
Calv1
Wean1
Con2
Calv2
Wean2
Reproductive events

Fig. 3.

Declarations

Conflict of interest

The authors declare that there are not conflicts of interest.