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The carbon footprint of beef production from cull cows finished on sown pastures in the savannas of the Colombian Orinoquía

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Abstract. Neotropical savannas of the Colombian Orinoquía are largely dedicated to year-round beef production. There is evidence of sustainable animal production in this savanna environment, but the links among animal lifetime performance, greenhouse gas emissions, and soil organic carbon (SOC) accumulation at the system level have been poorly studied to date. The objective of this study was to estimate the carbon (C) footprint of beef production from Brahman (*Bos indicus*) cull cows finished on contrasting C4-grass-based pastures in the Orinoco River Basin. Long-term individual variations of liveweights and reproductive performance were used in an Excel® dynamic model to estimate dry matter intake, methane (CH_4) emissions, carcass traits, and the C footprint at the farm gate. Values from the developed database were computed for cows born and raised on the savanna, bred on *Brachiaria decumbens*, and later finished on *B. humidicola* [Scenario (SCE) 1, SCE 2]; *B. decumbens* (SCE 3); *Andropogon gayanus* + *Melinis minutiflora* + *Stylosanthes capitata* (SCE 4); and *A. gayanus* + *S. capitata* (SCE 5) pastures. We estimated the C footprints of SCE 1, SCE 3, and SCE 5 using published values of the rates of emission of CH_4 and nitrous oxide from the soil, feces, and urine; and accumulation of SOC in the soil during the fattening period. Most of the estimated overall C footprint values at the system level were negative due to expected net SOC accumulation during the fattening period. Depending on the expected quality of management, systems ranged from near equilibrium in C balance to net increases in SOC accumulation.

Keywords: beef, methane, scenarios, soils, tropical forages

Huella de carbono en vacas de descarte cebadas en pasturas mejoradas de las sabanas de la Orinoquia de Colombia

Resumen. Las sabanas Neotropicales de la Orinoquía de Colombia están dedicadas principalmente a la producción de carne. Hay evidencias de que estos ecosistemas ganaderos pueden ser sostenibles, sin embargo, poco se conoce acerca de las relaciones entre el desempeño animal, las emisiones de gases invernadero, y la acumulación de carbono orgánico en el suelo (SOC) a nivel de sistema productivo. El objetivo del presente estudio fue estimar la huella de C de la producción de carne, utilizando vacas (*Bos indicus*) de descarte cebadas en praderas contrastantes de plantas C4. Se utilizaron variaciones reales e individuales y a largo plazo de peso y desempeño reproductivo de las vacas a través de un modelo dinámico en EXCEL® para estimar el consumo de materia seca, las emisiones entéricas de metano (CH_4), las características productivas y ambientales de las carcasas, y la huella de carbono (C) a nivel de finca. Las vacas nacidas, criadas y levantadas en sabana nativa, mantenidas en *Brachiaria decumbens* durante su vida reproductiva fueron finalizadas en los siguientes escenarios (SCEs) modelados: *Braquiaria humidicola* (SCE 1 y SCE 2), *B. decumbens* (SCE 3), pastura mixta de *Andropogon gayanus* + *Melinis minutiflora* + *Stylosanthes capitata* (SCE 4) y pastura mixta de *A. gayanus* + *S. capitata* (SCE 5). La modelación se complementó con datos publicados de tasas de emisión de CH_4 y óxido nitroso del suelo, muestras de heces y orina, así como la acumulación de SOC en el suelo durante la ceba. Las estimaciones de las huellas de C de los sistemas fueron mayoritariamente negativas debido a la acumulación neta de SOC durante el período de finalización productiva. Dependiendo de la calidad del manejo, los sistemas variaron entre equilibrio en el balance de C a aumentos netos de acumulación del SOC.

Palabras clave: carne, metano, escenarios, suelos, forrajes tropicales

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Pegada de carbono em vacas de descarte engordadas em pastagens melhoradas nas savanas da região de Orinoquia da Colômbia

Resumo. As savanas Neotropicais da Orinoquia Colombiana são principalmente dedicadas à produção de carne. Há evidências de que os ecossistemas pecuários podem ser sustentáveis, no entanto, pouco se sabe sobre as relações entre o desempenho animal, as emissões de gases de efeito estufa e o acúmulo de carbono orgânico en el suelo (SOC) no nível do sistema de produção. O objetivo do presente estudo foi estimar a pegada C da produção de carne, utilizando vacas de descarte (*Bos indicus*) terminadas em pastagens melhoradas (C4) da região de Orinoquia. Variações reais, individuais e de longo prazo para peso e desempenho reprodutivo dessas vacas foram usadas em um modelo dinâmico do EXCEL® para estimar o consumo de matéria seca, emissões de metano entérico (CH_4), características produtivas e ambientais de vacas, carcaças e pegada de carbono (C) ao nível de fazenda. Os valores da base de dados foram calculados para vacas nascidas e criadas em pastagens de *Brachiaria decumbens* e posteriormente as vacas foram terminadas em *B. humidicola* (Cenário (SCE) 1, SCE 2); *B. decumbens* (SCE 3); *Andropogon gayanus* + *Melinis minutiflora* + *Stylosanthes capitata* (SCE 4); e *A. gayanus* + *S. capitata* (SCE 5). Nós estimamos a pegada de C nos cenários SCE 1, SCE 3 e SCE 5 utilizando valores de literatura para níveis de emissão de CH_4 e óxido nitroso do solo, fezes e urina; e acumulação de SOC no solo durante o período de engorda. A maioria dos valores globais estimados para a pegada C ao nível do sistema foram negativos devido à acumulação líquida esperada de SOC durante o período de engorda. A maioria dos valores globais estimados para a pegada C ao nível do sistema foram negativos devido à acumulação líquida esperada de SOC durante o período de engorda. Dependendo da qualidade do manejo, os sistemas variaram entre equilíbrio no balanço de C a aumentos líquidos no acúmulo de SOC.

Palavras-chave: carne, metano, cenários, solos, forrageiras tropicais

Introduction

The world is facing challenges of population growth, increased hunger, malnutrition, food and feed insecurity, extreme events, and inequalities at multiple scales [Food and Agriculture Organization of the United Nations (FAO), 2009, 2015; Mora *et al.*, 2018]. These challenges apply to Colombia with its growing population, its allocation of resources, and the vulnerability of its ecosystem services to climate variability (Córdoba *et al.*, 2019). The Neotropical savannas environment of the Orinoco River Basin represents 30.4 % of continental Colombia (Andrade *et al.*, 2009), and it is generally considered a major, underutilized but fragile and biodiverse land resource (Romero-Ruiz *et al.*, 2012). This socio-cultural-rich region (Navas Ríos, 1999; Romero-Ruiz *et al.*, 2012) is also believed to have considerable potential to satisfy increased beef demand, stock turnover efficiency, and farm profitability (Ramírez-Restrepo and Vera, 2019; Ramírez-Restrepo *et al.*, 2023) based on year-round grazing on tropical pastures.

In this context, the reliability of evaluating pastoral systems' productivity and environmental impact lies in the reproducibility and replicability of raw data to refine concepts, hypotheses, and theories and assist in comparing different development views (Eckard *et al.*, 2014; Colquhoun, 2017; Ramírez-Restrepo *et al.*, 2019b, 2019c). On this basis, the preservation, reuse, and repurposing of existing databases can address new demands on science (Griffin, 2015; Murdy *et al.*, 2015; Wyborn *et al.*, 2015). This also applies to environmental metrics of cattle and their relationship with soil organic C (SOC) accumulation at the system level (Rao *et al.*, 2015; Ramírez-Restrepo *et al.*, 2019a; Ramírez-Restrepo *et al.*, 2023). To our knowledge, there are no studies using long-term individual legacy data of cull cows between birth and slaughter regarding land use, dry matter intake (DMI), methane (CH_4) emissions, and animal performance to estimate the C footprint of cull cows at the system level. Recent C footprint estimations (Ramírez-Restrepo *et al.*, 2020a) with year-round grazing of Brahman (*Bos indicus*) breeding herds suggest that cull cows fattening phase may assist in maintaining and even enhancing SOC stocks in conservatively managed improved sown pastures.

We hypothesized that the fattening of cull cows derived from tropical beef herds monitored over several reproductive cycles would allow the estimation of production efficiency and the C footprints of beef produced from cull cows grazing on contrasting tropical pastures. The objective of this study was to estimate the C footprint of beef production from Brahman cull cows finished on contrasting C4-grass-based tropical pastures in the Orinoco River Basin of Colombia.

Material and Methods

The database used for modeling

Heritage files generated from long-term grazing experiments carried out at Carimagua Research Centre (CRC: latitude 4º36′44.6″ N, longitude 74º08′42.2″ W) in the Neotropical savannas (Llanos) environment of Colombia were used as a source of animal data. The constructed large database included individual liveweight (LW), LW gains (LWG), and reproductive performance records from birth to the end of cow's reproductive performance in Brahman breeding herds over six continued reproductive cycles (RCs; conception-weaning; Vera *et al*., 2002; Ramírez-Restrepo *et al*., 2020a) lasting up to 10 ± 0.13 years. Females had two provenances, the first one consisting of animals born and raised on native savannas up to 272.6 ± 2.94 kg LW (25.87 ± 0.635 months), and the second one was born and raised on well-managed *Brachiaria decumbens* Stapf (syn. *Urochloa decumbens*) cultivar (cv) Basilisk pastures with higher LWG up to comparable initial breeding LW. In this paper, only cows initially raised on savanna were included as the production system represents the more environmentally costly path and the most common practice. Comparable shorter-term observations in several commercial ranches of the region (Vera and Seré, 1989; Astigarraga and Ingrand, 2011), although not used in the present study, further support the magnitudes and trends of the assembled dataset.

Soil properties and environmental conditions

Mean values for soil physical and chemical characteristics (0-20 cm depth) before pasture establishment (details given below) were 19.8 % sand, 40.2 % clay, 2.9 % organic matter, 4.78 pH, 90.1 % Al saturation, 1.46 µg/g available P (Bray-II), and 0.17, 0.08 and 0.06 cmol/kg of exchangeable Ca, Mg and K, respectively. These values are similar to the subgroup of farms located on relatively heavier soils monitored by Vera and Hoyos (2019) and for which animal outputs were available. Mean values of 2.202 mm of annual rainfall and 26.5 °C of ambient temperature were recorded at CRC between 1979 and 1991. The wet season occurred during the April to November period, while across the years, January and June were the driest and wettest months; and July and March were the coldest and hottest months, respectively (Figure 1).

Pastures and forage quality characteristics

The pastures used to fatten cull cows, and their botanical composition (%) on offer were as follows: *B. humidicola* cv Llanero (Rendle) Schweick (syn. *Urochloa humidicola*); *B. decumbens*; *A. gayanus* Kunth cv Carimagua + *M. minutiflora* P. Beauv + *S. capitata* Vogel cv Capica (~ 70: 20: 10); and *A. gayanus* + *S. capitata* (~ 95:5). The pastures were established with the recommended level of fertilizer application (kg/ha) of 20 P, 20 K, 48 Ca, 14 Mg and 10 S, while a third of that rate was used as maintenance fertilization every third year (Ramírez-Restrepo and Vera, 2019; Ramírez-Restrepo *et al*., 2020a; Vera-Infanzón and Ramírez-Restrepo, 2020). At the beginning of the experiments, pastures were 3-4 years old, thus largely excluding the rapid decline in animal productivity reported by Vera and Hoyos (2019) in the initial years following pasture establishment.

Pasture management during the fattening period consisted of continuous grazing during the rainy season. Cull cows were sold towards the end of the rainy season (Figure 1). All pastures were managed to conserve adequate soil cover and aboveground biomass as described by Vera and Ramírez-Restrepo (2017).

Measurements of the forage biomass and its botanical composition in the field during pre-grazing and post-grazing herbage periods were carried out approximately every two months according to the BOTANAL procedure (Jones and Tothill, 1985). Forage on offer in the *A. gayanus* pastures exceeded 6500 kg DM/ha, and at the end of the rainy season standing forage always exceeded 3000 kg DM/ha. Equivalent forage biomass values for *B. humidicol*a and *B. decumbens* pastures were 3500 and 1200 kg DM/ha, respectively.

Total crude protein (CP) and neutral detergent fiber (NDF) concentrations (g/kg DM) during the wet period were derived from the CRC grazing-forage database constructed by Ramírez-Restrepo and Vera (2019). Nutritive values (CP vs NDF) were 73-37 vs 825-785, 75-110 vs 710-650, 85-90 vs 740-746, and 101-66 vs 757-760 for the *B. humidicola*, *B. decumbens*, *A gayanus* + *M. minutiflora* + *S. capitata*, and *A. gayanus* + *S. capitata* pastures, respectively.

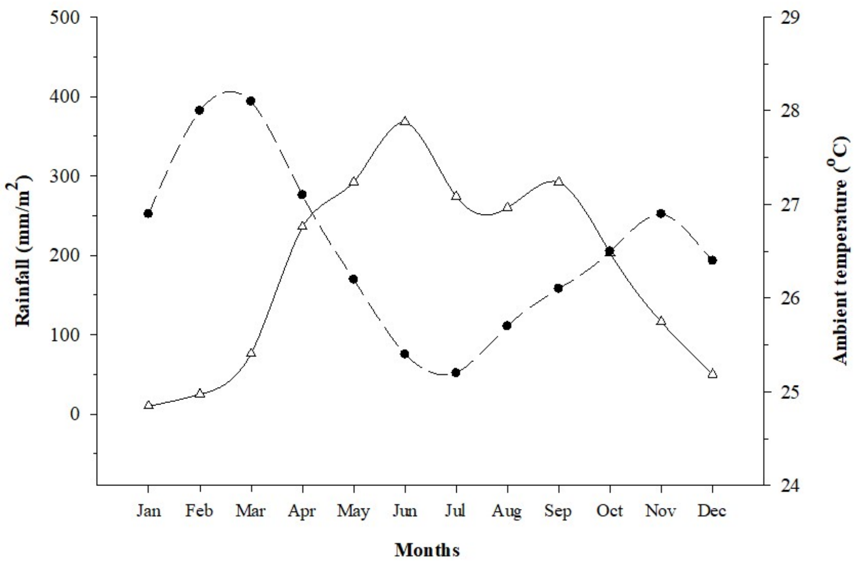

Figure 1. Average monthly precipitation (∆) and ambient air temperature (●) recorded over 12 years by the meteorological station at Carimagua Research Centre in the eastern plains of Colombia.

Modeling approach

The LWs of cull cows with different past reproductive performances were used to derive long-term trends in LWs, CH_4 emissions, and DMI, and these were expanded by using recorded cumulative LWGs (kg) over varied fattening periods (Ramírez-Restrepo and Vera, 2019). In the original field experiment, cows served as the experimental units. However, when cows were grouped in a paddock for fattening scenarios, those fattening scenarios represent the experimental units rather than individual cows themselves.

Initial and final cold carcass weights (CCW) of all animals were estimated at the start and the end of the fattening phase using a 0.4772 ratio of CW to LW (Velásquez and Ríos, 2010) to determine CCW gains (CCWG). These specifications allowed the model to estimate final LWs, carcass traits, the full cycle of production, production efficiency, and the C footprint at the system level. This study does not include any quantification from calves' data that were analyzed in detail by Ramírez-Restrepo *et al*. (2020a).

Developing scenarios

A similar stocking rate (SR; 1.3 UA/ha, 585 kg LW/ha) was used to compare five fattening scenarios (SCEs). Confidence intervals across all SCs and RCs were calculated for initial LWs (360.6-403.4 kg); daily LWGs (0.384-0.573 kg); target LWs (439-493 kg); and age (98.49-109.08 months) at slaughter. Following the methodology reported by Velásquez and Ríos (2010), carcass attributes of cull cows were calculated to estimate the interaction among LW, age and DMI dynamics, partial and lifetime CH_4 emissions, and slaughter data (Ramírez-Restrepo and Vera, 2019). To derive carcass CO_2-eq efficiency indices, for CH_4 estimation, the century horizon global warming potential (GWP) of 34 with the inclusion of climate-C feedback was used (Gasser *et al*., 2017; Mueller and Mueller, 2017; Allen *et al*., 2018) to allow for compatibility with authors' previously published work (Ramírez-Restrepo and Vera-Infanzón, 2019; Ramírez-Restrepo *et al*., 2019a, 2020a, 2023).

The first and second scenarios (SCE 1, SCE 2) represent the performance of cull cows on an overgrazed versus a well-managed *B. humidicola* pasture to yield low and high daily LWGs, respectively as reported by Vera-Infanzón and Ramírez-Restrepo (2020). Scenario 3 refers to the performance of cull cows on *B. decumbens* pasture that serves as local control and was initially reported by Ramírez-Restrepo *et al.* (2020a). Based on Ramírez-Restrepo and Vera (2019), SCE 4 and SCE 5 represented the performance of cull cows grazed on grass-legume associations of *A. gayanus* + *M. minutiflora* + *S. capitata*, and *A. gayanus* + *S. capitata* pastures, respectively. All sown pastures were 5 to 9 years old when the cows were culled.

Animals

As indicated before, females were monitored from birth (26.2 ± 0.12 kg) and were weaned (157 ± 2.82 kg; Rivera, 1988), and raised on savanna until mating (241 ± 9.76 g/day; Vera and Hoyos, 2019). Cows were offered *ad libitum* access to fresh water and a standard mineral formulation of 175 Na, 269 Cl, 137 Ca, 80 P, 20 S, 1.04 Cu, 3.5 Zn, and mg of 10 Co and 76 I g/kg of a commercial product. Registered Colombian Doctors of Veterinary Medicine ensured animal welfare regulations across all livestock manipulations in the field (Law 73, MINEDUCATION, 1985).

Calculating intakes

Dry matter intake was calculated as an LW function of feeding daily *ad libitum* on a DMI basis (i.e., 2.1 % of total LW; Fisher *et al*., 1987) from measurements in open-circuit chambers in tropical Australia (Ramírez-Restrepo and Vera, 2019) using a least-squares intercept-slope regression (Equation 1) specified as: $y = a + bx$

DMI kg/day = 2.216 (± 1.315) + 0.014 (± 0.003) LW (kg)

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

Predictions of DMI with Equation 1 fall within the range of field measurements by Hess (1995), and Pereira *et al*. (2009) for *B. humidicola*.

Estimating ruminant CH_4 emissions

Using the structured daily DMI regression form, individual estimations of CH_4 emissions were based on the simple relationship between LW per animal and CH_4 emissions per day in calibrated (pure CH_4 gas 0.99 recoveries) open-circuit chambers (Equation 2). This was recorded from well-cared and trained Brahman (Ramírez-Restrepo *et al*., 2016b) and Belmont Red Composite [Brahman x Africander (African Sanga) x Hereford-Shorthorn (3/4 *B. taurus*); Ramírez-Restrepo *et al*., 2014, 2016a] steers fed *ad libitum*.

CH_4 g/day = 16.176 (± 21.087) + 0.324 (± 0.057) LW (kg)

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

Thus, predicted CH_4 emissions are consistent with the estimations of Cottle and Eckard (2018) and are also consistent with recently published reports (Ramírez-Restrepo and Vera, 2019; Ramírez-Restrepo *et al*., 2019a, 2020a, 2023). As expected, this allows the present results also to be comparable with other tropical cattle system values (Ku-Vera *et al*., 2018). Lastly, we deliberately ignored issues related to CO_2-eq costs involving transportation, supply chains, the slaughterhouse, and the retail meat market.

Estimating CO_2-eq CH_4 footprint, C stocks, rate of SOC accumulation, and overall C footprint

Greenhouse gas emissions and C footprints were calculated for three contrasting scenarios (SCE 1, SCE 3, and SCE 5) that were chosen to represent a wide range of cattle fattening systems currently in use. Some required parameters were obtained from adjoining, mostly contemporary, paddocks (Rao, 1998; Fisher *et al*., 1998; Rondón *et al*., 2006). These were complemented when required with data obtained under comparable Neotropical savannas, including abundant data from the Venezuelan savannas reviewed by Castaldi *et al*. (2006). Emissions from soils, feces, and urine were estimated using the published values on emission factors from the literature, and in all cases, we used the maximum positive values reported. Soil emission factors used for CH_4 and nitrous oxide (N_2O) were adopted from Castaldi *et al*. (2006) of the Venezuelan savannas. Although acid savanna soils have been reported to act as a seasonal sink, rather than a source, particularly for CH_4, this was not considered in the present estimations. Values on N intake by animals were calculated from the predicted DMI as explained above, and forage N contents were reported in several grazing experiments by Lascano and Thomas (1990), Lascano and Euclides (1996), and from our data. Nitrogen digestibility was calculated as in Glover *et al*. (1957), and urinary N output as per Equation 1 reported by Waldrip *et al*. (2013). The resulting animal N balance was checked for compatibility with the observed LWG against the requirements suggested by Rotta *et al*. (2016) for tropical cattle in Brazil. Maximal fecal emissions were estimated from the emission factors derived by Zhu *et al* (2018), whereas those for fecal and urinary N_2O emissions were derived from Lessa *et al*. (2014).

Conversion of native savanna to sown pastures slightly modifies soil emissions as reviewed by Castaldi *et al*. (2006) for the seasonally dry Neotropical savannas. Data from García-Montiel *et al*. (2001) and Castaldi *et al*. (2006) showed an average value of soil CH_4 emissions during the wet season as 1.18 mg/m^2 day, but it is noted that soils under these conditions may also be a net CH_4 sink (Sanhueza *et al*., 1994a, 1994b). Similarly, soil N_2O emissions averaged 0.32 mg/ m^2 per day, but the range of values includes negative values as well. However, we followed a conservative approach and used relatively high values for soil emissions. Pasture establishment and maintenance incur in GHG emission costs related to machinery use, and the use of fertilizers, and these were calculated as in Ramírez-Restrepo *et al*. (2020a). Pasture establishment costs were prorated over the assumed persistence of well-managed pastures for 15 years, as it was documented for on-farm pastures by Vera and Hoyos (2019) for similarly managed on-farm sown grasslands.

The aboveground and belowground C stocks and SOC accumulation rates from improved pastures were estimated for the three contrasting SCEs to reflect differences that are not usually captured by animal performance variables and static characteristics. Values on SOC accumulation derived from contemporaneous experiments at CRC and nearby to the current study area were used (Fisher *et al*., 1994; Rao, 1998; Trujillo *et al*., 2006; Costa *et al., 2022; Hyman et al*., 2022). The methods used to determine SOC stocks in different pastures were described by Fisher *et al.* (1994). Values used to show the range of pasture biomass production of both aboveground (Fisher *et al*., 1998; Rao, 1998; Grace *et al*., 2006) and belowground (Fisher *et al*., 1998; Rao, 1998; Trujillo *et al*., 2006) are summarized in Table 3.

Statistical analyses

Data were analyzed with the GLM procedure of the Statistical Analysis System (SAS, 2016; version 3.5) including the upper and lower confidence limits (CLM) for each mean observation and CL for the parameter estimates (CLPARM) methods. Models for LW and age dynamics, DMI, CH_4 emissions, carcass features, and carcass-related indices considered the fixed effects of breeding-herd RCs and animal-fattening SCEs and their interaction. The relationships between total LWG and CH_4 emissions per kg LWG during the fattening process were performed using the CORR and REG procedures. Significant differences between least-squares means ± standard errors of the mean were declared when P ≤ 0.05.

Results

Animal performance and CH_4 emission metrics

The effects of SCEs on calculated DMI, LWGs, slaughter age, carcass traits, daily CH_4, CH_4 yield (CH_4 g/kg DMI), period-CH_4 emissions, and CO_2-eq CH_4 concentration in carcass yields are shown in Table 1. Compared to cull cows on the mixed *A. gayanus* + *S. capitata* pasture (SCE 5), cows on the first *B. humidicola* pasture (SCE 1) had the lowest DMI, however, cows grazed on the second *B. humidicola* (SCE 2), the *B. decumbens* (SCE 3), and the *A. gayanus* + *M. minutiflora* + *S. capitata* pasture (SCE 4) performed similarly to cull cows in the SCE 5. Accordingly, the model yielded total DMIs of 1.20, 1.51, 1.46, 1.39, and 1.65 ± 0.026 t of DMI from the first to the fifth fattening SCEs.

Relative to the *B. humidicola* low LWG scenario (SCE 1), the remaining SCEs had higher numerical LWGs and CCWGs of 19, 27, 46, and 49 %, and 46, 50, 63, and 95 %, respectively. This trend was repeated in terms of lean meat and edible protein carcass gain (LMCG, EPCG, Table 1).

Daily CH_4 and CH_4 yield emissions per animal for the *B. humidicola* (SCE 1) were significantly (P ≤ 0.05) lower than those of the *A. gayanus* + *S. capitata* (SCE 5), but enteric emissions were similar among the other SCEs (Table 1). Furthermore, the emission of CH_4/kg LWG decreased linearly from SCE 1 to SCE 5 (r^2 = 0.88, P = 0.02, r = -0.93), amounting to a difference of 28 % between the two extreme SCEs. Hence, the magnitude of CH_4 emissions for the finishing period in terms of kg CO_2-eq/kg CCWG, LMCG, and EPCG decreased (P ≤ 0.0001) between SCE 1 and SCE 5 by 29 % (Table 1).

The effect of successive RCs on systems performance is given in Table 2. There were significant differences in DMI values between some RCs (P ≤ 0.0001). Lifetime DMIs (t DM) differed (P ≤ 0.0001) among the consecutive RCs evaluated (12.19 ± 0.884 vs 17.65 ± 0.395 vs 23.38 ± 0.316 vs 25.10 ± 0.334 vs 27.39 ± 0.266). Emissions between RCs during the fattening practice differed when expressed in kg CO_2-eq/kg CCWG, with the largest difference amounting to 18 % between RC 4 and RC 6 (P ≤ 0.0001). However, over the lifetime of the animals, there was at most an 11 % difference (P ≤ 0.0001) between RC 1 and RC 6, such that the ranking of the RCs depends on the carcass parameter used for the comparisons.

Estimated C footprint of beef production of cull cows

Enteric emissions increased 30 % from SCE 1 to SCE 5 (Table 3), but the magnitude of the changes in fecal CH_4 production was less. On the contrary and associated with the increased N intake of SCE 5, urinary N_2O emission rose considerably. Gains in the carcass, lean meat, and edible protein weights (Table 1) differed between SCEs, with SCE 5 nearly doubling the gains in SCE 1, and emissions per kg of gain in carcass parameters diminished from SCE 1 to SCE 5 by 29 %. Over the lifetime of the animals, differences between SCEs in emissions per kg of the final carcass, lean meat and edible protein weights were less pronounced, with at most 12 % higher emissions in SCE 1 than in SCE 5 (Table 2). As before, the remaining SCEs showed intermediate values between the two extremes. Thus, the magnitude of the differences between SCEs depended very much on the denominator used for the comparisons, while LW determined the final point for sales of cows.

The estimated CO_2-eq CH_4 emission values from the feces of SCE 3 were 9.2 % higher while SCE 5 was 13.7 % larger compared to SCE 1. Estimated CO_2-eq N_2O emission values from the feces of SCE 3 were 30 % higher, while SCE 5 was 44 % higher compared to SCE 1. The CO_2-eq N_2O emission values estimated from the urine of SCE 3 were 2.11-fold greater, while SCE 5 was 2.87-fold greater compared to SCE 1. The contribution of the mineral supplement consumed by cows to CO_2-eq GHG emission was also greater for SCE 5 than SCE 3 and SCE 1. The estimated values of total CO_2-eq GHG emissions (kg/ha) during the grazing period, including CH_4 from animals, CH_4 and N_2O from feces, and N_2O from urine together with the mineral supplement consumed were 1.232; 1.483 and 1.640 for SCE 1, SCE 3, and SCE 5, respectively. Total values of CO_2-eq GHG emissions (kg/ha) during the grazing period at the system level were 1.345; 1.613 and 1.781 for SCE 1, SCE 3, and SCE 5, respectively (Table 3).

Nevertheless, differences between SCEs are confounded with the different final LWs (Table 1) and consequently different lengths of the fattening period, and these differences disappear if expressed per day, with an average for total GHG emissions of 8.4 kg CO_2-eq/ha day.

The stocks of SOC to 1 m soil depth for the medium textured soils of all three scenarios (SCE 1, SCE 3, and SCE 5) were estimated to be in the range of 130 to 160 Mg/ha based on the published reports cited in Table 3. The range of values of the standing aboveground biomass estimated from published reports of SCE 1 was 1.2 to 3.5 Mg/ha and this was markedly lower than those of SCE 3 (5.15 to 9.07) and SCE 5 (3.0 to 6.5). Standing below-ground biomass values (Mg/ha) estimated from published reports ranged from 2.8 to 9.3, 8.3 to 10.5, and 6.0 to 9.0 for SCE 1, SCE 3, and SCE 5, respectively. We assumed the same values for CO_2-eq CH_4 (3.2 x 34 kg/ha/year) and N_2O (1.05 x 298 kg/ha/year) emission from the soil for all three SCEs to estimate differences among the three SCEs based on the number of days of the grazing period.

The estimated emission values from fertilizers and tillage were the same among the three SCEs since pasture establishment methods were the same. Using the published values of above- and below-ground biomass and their contribution to the SOC accumulation, we estimated a range of rate of SOC accumulation from 1.0 to 3.0 Mg/ha/year (Table 3).

The estimated overall C footprint values at the system level in CO_2-eq in Mg/ha were -0.140 to -3.110; -0.154 to -3.688; and -0.167 to -4.059 for SCE 1, SCE 3, and SCE 5, respectively. These negative values imply that all three systems showed small to high values of net SOC accumulation after correcting for GHG emissions from animals, soil, and external inputs to the system.

Table 1. Dry matter intake (DMI), liveweight (LW) gain, slaughter age, carcass attributes, methane (CH_4) emissions, and carbon dioxide equivalent (CO_2-eq)-CH_4 carcass efficiency indices of commercial Brahman (*Bos indicus*) cull cows continuously mated on *B. decumbens* pastures‡ and fattened on grass alone *Brachiaria humidicola* (SCE 1, SCE 2), *B. decumbens* (SCE 3), and grass-legume association pastures of *Andropogon gayanus* + *Melinis minutiflora* + *Stylosanthes capitata* (SCE 4) and *A. gayanus* + S. capitata (SCE 5)

	SCE 1	SCE 2	SCE 3	SCE 4	SCE 5	Pooled s.e.m.
Number of animals	30	30	30	30	30	
DMI, kg/head day	8.093^{b}	8.337^{ab}	8.342^{ab}	8.419^{ab}	8.551^{a}	0.153
LW gain, kg/day †	0.384	0.457	0.486	0.561	0.573	0.014
Final LW, kg	439^{c}	465^{b}	467^{b}	475^{a}	493^{a}	10.8
Age at slaughter, months	103.0	103.0	103.9	103.6	104.5	2.30
Cold carcass weight gain (CCWG, kg)^{T}	27.20	39.60	40.84	44.37	52.96	4.164
Lean meat carcass gain (LMCG, kg)	16.52	24.06	24.82	26.96	32.18	2.885
Edible protein carcass gain (EPCG, kg)	4.29	6.25	6.45	7.01	8.36	0.658
			CH_4 emission metrics			
CH_4, g/head day	150.6^{b}	156.0^{ab}	156.2^{ab}	157.9^{ab}	160.9^{a}	3.50
CH_4, g/kg DMI	18.57^{b}	18.68^{ab}	18.69^{ab}	18.72^{ab}	18.78^{a}	0.077
Period CH_4, kg/head	22.34^{e}	28.35^{bc}	27.50c	26.17^{d}	31.20^{a}	0.610
kg CO_2-eq/kg CCWG	27.98^{a}	24.33^{b}	22.88^{c}	20.04^{de}	19.99^{e}	0.526
kg CO_2-eq/kg LMCG	46.05^{a}	40.04^{b}	37.66^{c}	32.98^{de}	32.90^{e}	0.886
kg CO_2-eq/kg EPCG	177.12^{a}	154.03^{b}	144.85^{c}	126.85^{de}	126.55^{e}	3.332

Adapted from [T]Velásquez and Ríos (2010), [†]Ramírez-Restrepo and Vera (2019), and [‡]Vera *et al*. (2002) and Ramírez-Restrepo *et al*. (2020a).
The least-squares means values in the same row bearing different letters between SCEs are significantly different (a,e: P ≤ 0.05). Standard error of the mean (s.e.m.).

Table 2. Influence of computed finishing scenarios (SCEs)† on dry matter intake (DMI), methane (CH_4) emissions, and carbon dioxide equivalent (CO_2-eq)-CH_4 carcass efficiency indices of consecutive reproductive cycles (RCs), and on CO_2-eq-CH_4 lifetime emissions of carcass traits in multiparous commercial Brahman (*Bos indicus*) cull cows‡

	2-RC	3-RC	4-RC	5-RC	6-RC
Fattening phase					
Number of animals	30	29	24	18	11
DMI, kg/head/day	8.469 ± 0.345^{ab}	8.727 ± 0.154^{a}	7.717 ± 0.140^{c}	7.981 ± 0.130b^{c}	8.848 ± 0.104^{a}
CH_4, g/head/day	159.1 ± 7.88^{ab}	165.0 ± 3.52^{a}	141.9 ± 3.21^{c}	147.9 ± 2.97^{bc}	167.2 ± 2.37^{a}
CH_4, g/kg DMI	18.78 ± 0.173^{ab}	18.89 ± 0.077^{a}	18.33 ± 0.070^{c}	18.50 ± 0.065^{b}	18.91 ± 0.052^{a}
Period CH_4, kg/head	27.59 ± 1.374^{ab}	28.61 ± 0.614^{a}	24.61 ± 0.561^{c}	25.66 ± 0.519^{bc}	29.09 ± 0.414^{a}
kg CO_2-eq/kg CCWG	23.48 ± 1.185^{ab}	24.32 ± 0.530^{a}	20.91 ± 0.483^{c}	21.80 ± 0.447^{bc}	24.73 ± 0.357^{a}
kg CO_2-eq/kg LMCG	38.60 ± 1.950^{ab}	40.03 ± 0.872^{a}	34.41 ± 0.796^{c}	35.88 ± 0.737^{bc}	40.70 ± 0.588^{a}
kg CO_2-eq/kg EPCG	148.46 ± 7.500^{ab}	153.98 ± 3.354^{a}	132.37 ± 3.062^{c}	138.02 ± 2.835^{bc}	156.57 ± 2.261^{a}
	SCE 1	SCE 2	SCE 3	SCE 4	SCE 5
Lifetime emissions					
Number of animals	30	30	30	30	30
kg CO_2-eq/kg CCW	65.06 ±1.851^{a}	61.82 ± 1.851^{ab}	61.30 ± 1.851^{ab}	60.01 ± 1.851^{b}	58.22 ± 1.851^{b}
kg CO_2-eq/kg LM	107.05 ± 3.046^{a}	101.73 ± 3.046^{ab}	100.87 ± 3.046^{ab}	98.75 ± 3.046^{b}	95.81 ± 3.046^{b}
kg CO_2-eq/kg EP	411.76 ± 11.715^{a}	391.29 ± 11.715^{ab}	387.99 ± 11.715^{ab}	379.82 ± 11.715^{b}	368.50 ± 11.715^{b}

[†]*Brachiaria humidicola* (SCE 1, SCE 2), *B. decumbens* (SCE 3), *Andropogon gayanus* + *Melinis minutiflora* + *Stylosanthes capitata* (SCE 4) and *A. gayanus* + *S. capitata* (SCE 5) pastures.
Adapted from † Ramírez-Restrepo and Vera (2019), and ‡ Vera *et al.* (2002) and Ramírez-Restrepo *et al.* (2020a). EPCG: Edible protein carcass gain. CCWG: Cold carcass weight gain. LMCG: lean meat carcass gain. The least-squares means (LSM) ± standard error of the mean in the same row bearing different letters are significantly different (a-d: P ≤ 0.05).

Table 3. Estimated greenhouse gas (GHG) emissions and overall carbon (C) footprint of commercial Brahman (*Bos indicus*) cull cows fattened on *B. humidicola* (SCE 1), *B. decumbens* (SCE 3), and *Andropogon gayanu*s + *Stylosanthes capitata* (SCE 5) pastures

	Scenarios			Observations, data sources, and emission factors
Parameters	SCE 1	SCE 3	SCE 5	
Days on a grazing system	148	176	194	
Cows	30	30	30	
SR, cows/ha	1.42	1.38	1.34	Average on-ranch and on-station SR values on MTAC
Mean final LW, kg/head	439	467	493	Table 1 of this paper
CO_2-eq enteric CH_4, kg/ha	1082	1289	1418	
CO_2-eq CH_4 from feces, kg/ha	113.8	124.3	129.4	Zhu *et al*. (2018): EF dry season = 0.001, rainy = 0.003
CO_2-eq N_2O from feces, kg/ha	6.17	8.02	8.87	Lessa *et al*. (2014): EF = 0.0014
CO_2-eq N_2O from urine, kg/ha	28.44	59.96	81.71	Chirinda *et al*. (2019): EF = 0.016; Lessa *et al*. (2014): EF = 0.0193
CO_2-eq of mineral supplement consumed, kg/ha	1.52	1.75	1.87	Cardoso *et al*. (2010) cited by Cerri *et al*. (2016)
Total CO_2-eq GHG emissions, kg/ha	1232	1483	1640	
Estimation of overall C balance				
SOC to 1 m depth, medium texture soil, Mg/ha	130 - 160	130 - 160	130 - 160	Fisher *et al*. (1994); Rondón *et al*. (2006); Ramírez Restrepo *et al*. (2019a)
Standing aboveground (shoot) biomass, DM Mg/ha	1.2 - 3.5	5.1 - 9.1	3.0 - 7.0	Fisher *et al*. (1998); Kanno *et al*. (1999); Rao *et al*. (2001a); Grace *et al*. (2006)
Standing belowground (root) biomass, DM Mg/ha	2.8 - 9.3	8.3 - 10.5	6.0 - 9.0	Fisher *et al*. (1998); Rao (1998); Kanno *et al*. (1999); Rao *et al*. (2001b); Trujillo *et al*. (2006)
Total aboveground and belowground biomass, DM Mg/ha	4.0 - 12.8	13.4 - 19.6	9.0 - 15.0	
CO_2-eq CH_4 emission from the soil, kg/ha	-2.74	-3.20	-3.59	Castaldi *et al*. (2006)
CO_2-eq N_2O emission from the soil, kg/ha	91.23	108.49	119.59	Castaldi *et al*. (2006)
CO_2-eq emission from fertilizer inputs and tillage, kg/ha	24.64	24.64	24.64	Edwards-Jones *et al*. (2009); Kim *et al*. (2011); University of Arkansas (2019)
CO_2-eq total GHG emissions at the system level, kg/ha	1345	1613	1781	
SOC accumulation rate, Mg/ha/year	1.0 to 3.0	1.0 to 3.0	1.0 to 3.0	Fisher *et al*. (1994); Rao *et al*. (1998); Fisher *et al*. (1998); Rondón *et al*. (2006); Fisher *et al*. (2007); Costa *et al*. (2022); Hyman *et al*. (2022)
SOC accumulation, kg/ha	405 to1215	482 to 1446	531 to 1593	SOC accumulation during the grazing period
CO_2-eq soil C accumulation, kg/ha	1485 to 4445	1767 to 5301	1948 to 5840	SOC accumulation in CO_2-eq during the grazing period
Overall C footprint at the system level in CO_2-eq, Mg/ha	-0.140 to -3110	-0.154 to -3688	-0.167 to -4059	Estimated from the difference between GHG emissions and the soil C accumulation during the grazing period

CH_4: Methane. CO_2-eq: Carbon dioxide equivalent. EF: Emission factor. Mg: megagram. LW: Liveweight. N_2O: Nitrous oxide. MTAC: Medium texture acid soils. SOC: Soil organic carbon. SR: Stocking rate. Negative CO_2-eq values for soil C for overall C footprint imply SOC accumulation. CO_2-eq emission values are expressed for the total duration of the grazing period.

Discussion

The use of legacy data in the present paper aligns well with the views of many authors that reviewed the issue by taking into consideration of reduced funding and the need to take a fresher, and more comprehensive view of long-term results from studies on grazing systems (Rouquette *et al*., 2009; Black 2014, 2018). Some authors have even questioned the occasional excess of collecting "futile data" (Tedeschi, 2019), rather than making fuller and more innovative use of existing information. The present inclusion of cull cows' emissions adds to the need to consider full cattle production cycles as discussed by Eckard *et al*. (2014). Lastly, current cattle systems in the region continue to be dominated by breeding herds grazed on traditional low-input *Brachiaria* spp. pastures [Romero *et al*., 2018; AGROSAVIA, 2019; Encuesta Nacional Agropecuaria (ENA), 2019].

Grazing systems and animal production

Early on-farm studies (Vera and Seré, 1989) noted that the fattening of cull cows in extensive ranches constitutes an opportunistic use of recently established sown pastures and provides a quick and profitable return on investments. Fat cull cows constitute 32 % of the cattle market in the study region (Romero *et al*., 2018), whereas males account for 53 % of the total, and all of them are mostly raised and fattened on sown tropical grass pastures. A recent survey (Romero *et al*., 2018) revealed that the most important grasses during the study were *B. dictyoneura*, *B. humidicola*, and *B. decumbens.* Another survey (Díaz *et al*., 2018) carried out in both the Orinoco River Basin and the Atlantic coast of Colombia, verified the continued popularity of those three grass species. The present study, therefore, includes pastures that represent a range of current alternatives for grass pastures differing in quality and management demands. *B. humidicola* (SCE 1) constitutes the lowest limit of that range, while the *A. gayanus* + *S. capitata* (SCE 5) represents a higher quality pasture that is admittedly more demanding of management, particularly under conditions of extensive production.

In this study, we used a combination of on-station mid to long-term grazing data to estimate the C footprint of beef production from cull cows finished on contrasting C4-grass-based pastures. To our knowledge, this is the first such integrated analysis in the Orinoco River Basin. In this context, the results presented in Tables 2 and 3 show evidence for the varying links between CH_4 emissions, LWs, carcass metrics, and SOC accumulation. Scenario 1 relied on an intensively grazed *B. humidicola* pasture, a management technique that is most frequently observed on commercial ranches, whereas SCE 3 represents a traditional approach to fattening, and SCE 5 indicates the potential of a stable grass-legume pasture which could be feasible under much-improved management and production conditions.

Animal performance, CH_4 emissions, and carcass measures

The cumulative emissions (Table 2) would justify culling cows after the third weaning as emissions subsequently increase again. The effects of this practice might be an increased number of heifers (Vera-Infanzón and Ramírez-Restrepo, 2020) for earlier breeder replacement and specialized farming systems (Ramírez-Restrepo, *et al*., 2023) resulting in more stable temporal emissions. Culling of older mature breeding dams should result in more efficient cow-calf operations with lower environmental impact. In contrast, Roberts *et al*. (2015) suggested the opposite view when applied to temperate, more intensive, breeding systems. Nevertheless, given the diversity of pastoral-beef farming systems in the Llanos (CORPOICA, 2010; Vera and Hoyos, 2019), further data and ruminant model-mediated predictions would be desirable. A small further refinement of the carcass analyses could be made if additional estimates of the carcass: LW ratio, as opposed to the fixed 0.4772 value, become available for cull cows in the study region.

Our results suggest a need to strategically switch fertile heifers from grazing on native savanna or low-quality *B. humidicola* pastures to superior nutritive value *B. decumbens* pastures and other types of grass pastures in the mid to long-term (Vera *et al*., 2002; Ramírez-Restrepo *et al*., 2020a). Previous Australian studies (Marshall, 2010; Marshall and Smajgl, 2013; Marshall *et al*., 2014) indicated that delaying emissions would facilitate adaptation to climate-driven changes. Furthermore, there is evidence from consumer research in Colombia (Charry *et al*., 2019) that buyers have preferences for beef welfare and eco-friendly certified beef production. This means that some consumer segments would pay about 52 % more when in addition to welfare and eco-friendly labels, certified reduction in GHG emissions of the marketed beef is available (Charry *et al*., 2019).

The analysis of the present C balance at the system level is conservative, and we avoided dealing with current controversies on the biogenic C cycle in grazing systems that have been previously addressed by Adegosan *et al*. (2015) and Wiloso *et al*. (2016). This also includes the possible short-life effect of emitted enteric CH_4 (GWP 0-20-year average vs GWP 0-100-year average; Mueller and Mueller, 2017; Allen *et al*., 2018) from animals. Consistent with these views, we have reported the actual amounts of CH_4 and discussed our calculations based on the CO_2-eq values at 100 years' average horizon that we consider to be a conservative approach to emissions.

Cull cows in the present study, raised on savanna as heifers, and bred and fattened on *B. decumbens* showed average carcass CO_2-eq stores 1.1 times the amount of CO_2-eq accumulated in their counterparts grazing lifetime on only *B. decumbens* pastures (detailed data not shown). These estimated values indicated that although the same beef product is produced, the CO_2-eq overhead of cull cows across their lives varies considerably according to management in early life. This differs from FAO (2013)'s beef production data that showed a global life cycle analysis (LCA) value of 67.8 kg CO_2-eq/kg CW), or the LCA annual estimations of Cardoso *et al*. (2016) on degraded *Brachiaria* pastures (51.66 kg CO_2-eq/kg CW). These contrasting differences suggest the need to evaluate beef systems relative to culling strategies since the present results showed that culling over the second or third weaning is a practical farming management response to mitigate climate change. Open-circuit respiration chamber studies (Grandl *et al*., 2016) with Brown Swiss cattle (*B. taurus*) have shown that CH_4 production in heifers increases with age, while in multiparous cows the highest emissions are linked to their second and third lactations (4 to 6.5 years). This was followed by slightly lower CH_4 production in older cows. In parallel, the highest magnitude of that CH_4 emission response from *B. indicus* cows in lactation (1 to 6) was found by Ramírez-Restrepo *et al*. (2020a) during the fourth lactation (9 years).

Estimated C footprints

Extensive grazing systems can accumulate SOC under different soil, climate, and management systems, as shown by meta-analysis and synthesis of published results (Conant *et al*., 2017; Viglizzo *et al*., 2019). Several practices, including proper grazing management, fertilization, sowing of improved grass and/or legume species, irrigation, and conversion from cultivation, could contribute to an increase in SOC accumulation to a range of 0.105 to more than 1 Mg C/ha/year (Conant *et al*., 2017) over the longer time but as yet the undefined length of years. Results from long-term grazing experiments conducted in well-watered tropical areas, using well-managed *Brachiaria* grass-based pastures indicated that it is possible to not only improve animal production but also increase SOC stocks (da Silva *et al., 2017; Segnini et al*., 2017; dos Santos *et al*., 2019) over the medium term.

Tropical pastures with sown grasses with deep root systems, such as *B. humidicola* and *A. gayanus* when well-managed (Fisher *et al*., 2007) with proper grazing and maintenance fertilizer application (Braz *et al*., 2013; Saravia *et al*., 2014) can increase SOC stocks in deep soil layers up to 1 m depth, while soils under poorly managed or degraded pastures may lose SOC over time (Boddey *et al*., 2010). In this study, our assumed values of SOC accumulation rates of 1 to 3 Mg/ha/year were based on the published reports on above- and below-ground net primary productivity (NPP; Fisher *et al*., 1998; Kanno *et al*., 1999; Rao *et al*., 2001a; Trujillo *et al*., 2006) and SOC accumulation in long-term pastures in Colombia and Brazil (Fisher *et al*., 1994, 2007; Bustamante *et al*., 2006; Braz *et al*., 2013; Saravia *et al*., 2014; Baptistella *et al*., 2020; Hyman *et al*., 2022).

Pasture utilization by grazing cattle under tropical conditions is in the range of 20 to 30 % and 40-50 % of the consumed DM is returned as feces, so that the annual amount of litter and feces returned to the soil surface is in the range of 33.5 to 40.5 Mg/ha/year (Fisher *et al*., 1998, 2007). This C return to soil depends on the level of pasture utilization in the range of 13 to 16 Mg C/ha/year, assuming a value of 40 % C in DM. The NPP of the aboveground biomass of *A. gayanus* pastures in the eastern plains was estimated to be as much as 43 Mg/ha/year (Fisher *et al*., 1998). Trujillo *et al*. (2006) found that the NPP of belowground biomass of well-managed grass alone (*B. dictyoneura*) pasture was 30.0 Mg/ha/year, while the grass-legume (*B. dictyoneura* + *S. capitata*) association was 31.34 Mg/ha year. *Brachiaria dictyoneura* grass has been recently classified as *B. humidicola* and it is similar in growth habits to the *B. humidicola* grass used in this study. Kanno *et al*. (1999) compared five different tropical grasses in their differences in root distribution under continuous grazing with low amounts of fertilizer application in the Cerrados of Brazil. Although they measured the total root biomass only up to 40 cm soil depth, the values of different grasses ranged between 6 to 16 Mg/ha. Urquiaga *et al*. (1998) estimated that 54 % and 62 % of root C from *A. gayanus* and *B. decumbens* pastures, respectively will be non-decomposable thereby contributing to an increase in SOC accumulation. The belowground root biomass and its functional activity in tropical pastures result from root production, growth, mortality, and decomposition processes (i.e., root turnover), which occur simultaneously and fluctuate widely under grazing conditions and the age of the pasture (Rao, 1998; Fisher *et al*., 2007; Siqueira da Silva *et al*., 2019).

Root turnover in the grass was estimated to be 2.2 times in both grass alone (*B. dictyoneura*) and grass + legume (*B. dictyoneura* + *Arachis pintoi*) pastures (Rao *et al*., 2001b). If one assumes that the NPP of belowground DM is similar to aboveground DM, the total C inputs to a grazed pasture are estimated to be in the range of 26 to 32 Mg/ha/year (Fisher *et al*., 1998). Improved grasses used in this study differ in their growth habits and values for both above- and belowground DM production as well as in litter decomposition. *Andropogon gayanus* is an erect, tussock-forming tall grass, *B. decumbens* is low-growing, erect or decumbent, rhizomatous and stoloniferous grass while *B. humidicola* is a strongly stoloniferous and rhizomatous grass. The rate of litter decomposition reported was lower for *B. humidicola* and *A. gayanus* compared to *B. decumbens.* The legume litter of *S. capitata* decomposes much faster than that of the three grasses (Thomas and Asakawa, 1993). Boddey *et al*. (2020) indicated that the amount of N being recycled through aboveground plant litter could be over 100 kg N/ha/year for the grass-legume association; and they also pointed out that belowground N recycling may be of the same magnitude as the aboveground N (Trujillo *et al*., 2006). Root tissue of higher C: N ratios in tropical grasses (109-224) could lead to slower decomposition and formation of fewer microbial by-products (Rao, 1998, Trujillo *et al*., 2006; Dietzel *et al*., 2017). Root C: N ratios could play a key role in contributing to a larger proportion of SOC that is found in deeper soil layers below 20 cm soil depth (Fisher *et al*., 2007). Under pasture (*B. brizantha*) land use treatment, de Figueiredo *et al*. (2010) reported that 48 % of the total SOC was in the form of particulate organic carbon (POC), and a high value of C: N ratio of 47.8 was observed with this POC by these authors. Clearly, all of the above factors may influence the range of the assumed values of SOC accumulation.

The amount of SOC accumulation in long-term (up to 9 years old) pure grass pastures in the eastern plains of Colombia was about 3.0 Mg/ha/year but it was markedly increased with a legume component in the pasture (Fisher *et al*., 1994). The use of legume components in association with grasses can not only improve N supply to the grass but also considerably enhance soil biological activity. This is through an increase not only in terms of earthworm biomass and soil aggregation (Lavelle *et al*., 2014) but also in the rate of N mineralization (Rao *et al*., 1994). Proper grazing management together with maintenance fertilizer application every two to three years could sustain both aboveground- and belowground NPP leading to significant amounts of SOC accumulation in improved pastures in the eastern plains of Colombia.

We do not assume that SOC accumulation in introduced pastures will either be constant or be continued indefinitely. But two recent studies from the Brazilian agroecosystems presented some interesting observations. Durrer *et al*. (2021) used a 100-year observational chrono-sequence spanning primary forest-to-pasture conversion and subsequent secondary forest succession in the Amazon region and observed a surprising increase in topsoil SOC concentrations in pastures at 60 years following conversion. To predict long-term changes in SOC stocks after pasture intensification and diversification, Damian *et al*. (2021) used the DayCent model and simulated the effects of converting poorly managed pastures (PMP) to more intensive and diversified systems of pasture management, including fertilized pasture (FP). They used field data collected from three regions with contrasting climatic conditions. The DayCent model estimated that the conversion of PMP to FP increases the soil C stocks by 0.95 Mg/ha/year. The model also estimated that the fertilization of the pasture every year (FP) could result into higher SOC stocks.

The differences in overall C footprint estimates among SCE1, SCE 3, and SCE 5 were not that marked at the lower range, but at the higher range, those were larger due to a greater number of grazing days and the resultant SOC accumulation. The overall C footprint values shown in Table 3 include an interval of possible values that range from near neutrality to high net soil C accumulation (negative values). They reflect the natural variability encountered due to soils, management strategies, between-years variability, and variation in the potential growth of different species.

The three different tropical grasses included in the SCEs generally exhibit high belowground productivity, thus accumulating large amounts of organic C in depths up to 2 meters, a contribution frequently underestimated in the past due to only superficial soil measurements (Qi *et al*., 2019). The values estimated for *B. humidicola* in SCE 1 are particularly interesting since this germplasm accession CIAT 679 has been consistently demonstrated to have a high root growth rate, and very slow decay rate of stored biomass, even in visually degraded, overgrazed pastures (Chirinda *et a*l., 2019). This greater ability of *B. humidicola* pastures with lower values of digestibility and N content may be associated with the ability of biological nitrification inhibition (BNI), a trait that even extends to inhibition of N release from urine patches (Byrnes *et al*., 2017). These BNI effects were not accounted for in our calculations, so the corresponding overall C footprint values may be a conservative estimate. On the contrary, generalizations of results for SCE 5 based on *A. gayanus* grass are narrower, as there is limited information on its environmental impact, this species has a smaller niche, and it is more demanding of adequate grazing management than generally practiced in extensive systems. Nevertheless, SCE 5 constitutes a prototype of a productive grass-legume pasture that has persisted well under good management in on-station trials and a small number of commercial ranches.

Conclusions

This study elaborates on realistic simulated SCEs of beef production by culling cows in the Llanos of the Colombian Orinoquía. It was made possible by the intensive use of long-term on-station legacy data of animal production and studies related to animal GHG emissions and dynamics of plant biomass, both above- and below-ground, complemented with data on soil emissions and SOC accumulation. Large and practically important differences were found in emissions and footprints between the tropical pasture systems studied. These differences were particularly notable during the fattening phase of cull cows on the three systems chosen to represent two widely used production practices with grass-alone pastures, compared to one promising grass-legume pasture. The results clearly demonstrated that given a fixed fattening period during the wet season, system performance depends very much on the daily weight gains allowed for by the pastures used. Furthermore, the present estimates of emissions and footprints suggest that cows' age at culling may significantly impact system performance, an issue that deserves further long-term research. The estimates of C footprints based on substantiated rates of SOC accumulation over the medium-term show that the tested system may compensate for animal and soil GHG emissions. However, the net values may vary over a relatively wide range and demand above-average grazing management strategies relative to current practices.

Conflicts of interest: The authors declare that there has been no interest(s) that might raise the question of bias in the reported research or the manuscript's inferences, opinions, or conclusions.

Ethics statement: The research did not require ethical review and approval because the animal data that were used in the study were repurposed from legacy files recorded ethically at the Carimagua Research Station (CRC).

Author contributions: CAR-R: Investigation, Data curation, Conceptualization, Methodology, Model development, Writing, Review, and Editing. RRV-I: Investigation, Data curation, Conceptualization, Methodology, Model development, Writing, Review, and Editing. IMR: Methodology, Writing, Review, and Editing.

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