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# The carbon footprint of young-beef cattle finishing systems in the Eastern Plains of the Orinoco River Basin of Colombia

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**Introduction:** Previous research has shown increased productivity amongst sown grass pastures compared to native savanna pastures by year-round grazing for fattening of adult and young Brahman (*Bos indicus*)-bred cattle in the well-drained native savanna ecosystem of the Colombian Orinoquía. But there is limited information on the carbon footprint (CF) of commercial young-Brahman heifers and steers reared throughout life on well-managed *Brachiaria decumbens* Stapf pastures.

**Methods:** The present study characterized growth, lifetime enteric methane (CH<sub>4</sub>) emissions, carcass carbon dioxide equivalent (CO<sub>2</sub>-eq) CH<sub>4</sub> efficiency intensities (i.e., emissions per kg of product), and estimated the overall CF of young cattle grazing *B. decumbens* pastures subject to a range of daily liveweight gains (DLWGs; 0.428 – 0.516 kg) and fattening framework (405 – 574 kg). Weaning data from seven consecutive calving seasons in a commercial Brahman breeding herd continuously grazed on *B. decumbens* were integrated with a Microsoft Excel<sup>®</sup> dynamic greenhouse gas emission (GHGE) simulation of stockers-yearlings, and seven fattening, and processing scenarios.

**Results:** The model predicted that heifers subject to low and high DLWGs (0.428 vs 0.516 kg) and steers (0.516 kg) may be successfully fattened without supplementation assuming that animals had access to a well-managed grass pasture. Depending on the fattening strategy, kg CO<sub>2</sub>-eq CH<sub>4</sub>/kg edible protein values ranged from 66.843 to 87.488 ± 0.497 for heifers and from 69.689 to 91.291 ± 0.446 for steers.

**Discussion:** Assuming that forage on offer is at least 1,500–2,000 kg of dry matter/ha during the rainy season, all the simulated systems showed potential for C neutrality and net-zero C emission when considering GHGEs from the soil, pasture, and animal components vs the estimated soil C capture over seven seasons. However, under a more optimistic scenario, these beef systems could

accomplish substantial net gains of soil C, over the period for which field data are available. Overall, this study projects the positive impact of the design of plausible fattening strategies on grasslands for improving cattle productivity and reducing emission intensities with concomitant increases in technical efficiency.

#### KEYWORDS

beef farming systems, cow-calf operations, improved pastures, methane emission, soil carbon capture

## Introduction

Emerging agri-food production systems aim to achieve food security and environmental sustainability while reducing poverty through technological innovations, alternative food sources, safe supply chains, affordable diets, food preferences, and lifestyle shifting, among other factors (Food and Agriculture Organization (FAO), 2022). However, it is still unclear how the new agri-food systems will meet regulatory pathways, consumer perspectives, planetary health expectations, and multidimensional livelihoods (Stephens et al., 2018; FAO, 2022). For example, when available, lab-cellular meat could have a larger detrimental carbon footprint (CF) impact than the environmental imprint from conventional beef farming systems (BFS) (Lynch and Pierrehumbert, 2019; Chriki and Hocquette, 2020).

In Latin America and the Caribbean, livestock systems operated by 60 million people generate 41.5% of the agricultural gross domestic product in the region and supply 11% and 23% of the milk and beef global market, respectively (FAO, 2021). In the specific case of cattle farming systems, their sustainability scales depend on several factors. These include (i) animal metabolism and animal farm exchanges (Vera and Ramírez-Restrepo, 2017; De Rosa et al., 2021); (ii) generation of ecosystem services (Rao et al., 2015); (iii) animal nutrition based on the adequacy of concentrates, crop-based biomass, industrial-scale by-products, and forage resources (Ramírez-Restrepo et al., 2017; Cumbe et al., 2021; Marín-López et al., 2022); (iv) participatory adaptation to climate variability (Marshall and Smajgl, 2013; Sen et al., 2022); and (v) socio-cultural and livelihoods functions (Marshall et al., 2014; Sen et al., 2021).

The Orinoco River Basin extends over 1.1 million km<sup>2</sup> encompassing the Pre-Cambrian Guyana Shield, Colombia, and Venezuela (Frappart et al., 2015). In this context, from a resource-use perspective (Greenwood, 2021), the 170,000 km<sup>2</sup> of grassland savannas (i.e., Llanos; Romero-Ruiz et al., 2011) within the biodiversity and natural transitions of 205 ecosystems of the Colombian Orinoquía (347,208 km<sup>2</sup>; Instituto de Investigación de Recursos Biológicos Alexander von Humboldt and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, 2020) constitute a good example of some of the challenges faced by the BFS. This grassland savanna is a fragile and complex riverine ecosystem encompassing Amerindian groups, cultural history, socio-political dynamics, traditional ecological knowledge, and biodiversity (Navas Ríos, 1999; Gassón, 2002).

Biodiversity dynamics in the Colombian Orinoquía encompass 191 amphibians, 1,043 birds, 663 fish, 254 mammals, 155 reptiles, 5,411 plants, and 680 insect species (Instituto de Investigación de Recursos Biológicos Alexander von Humboldt and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, 2020). To the authors' knowledge, there are no inventories that describe the details of insect fauna, distribution, biological and ecological differences, habitats, host plants, and plant-herbivore interactions in the Llanos dealing with the effects of grassland savanna conversion to improved grass monocultures or grass-legume pastures.

Previous work indicated that there are opportunities for the intensification of beef farming through the careful use of natural resources including the well-drained native savanna ecosystem (WNSE) landscape, limited external inputs, newer technical knowledge, and enhanced management expertise (Ramírez-Restrepo et al., 2019a; Vera-Infanzón et al., 2023). Lavelle et al. (2014) evaluated soil macroinvertebrate communities and soil-based ecosystem services (climate regulation, hydrologic functions, soil stability provided by macro aggregation, and nutrient provision potential) in four major production systems of the Orinoco River Basin of Colombia that includes improved pastures, annual crops, oil palm, and rubber plantations, and compared them to the original savanna. They found that indicators for macroinvertebrate biodiversity and activity and soil macro aggregation were highest within improved pastures. According to Decaëns et al. (2001), termites and earthworms are the dominant components of macrofauna communities in the WNSE while the abundance and diversity of macroinvertebrate communities are determined by the structure and the nature of the vegetation. Therefore, the conversion of the native savanna into an improved pasture, either grass alone or mixed with legumes, maintains the macrofauna taxonomy richness and increases up to almost 13 times the macrofauna biomass (Decaëns et al., 2001). This is mainly due to the use of the *Brachiaria decumbens* Stapf cultivar Basilisk in association with the herbaceous *Pueraria phaseoloides* (accession CIAT 9900 - kudzu) legume and the increase of organic matter from leaf litter and cattle manure (Jiménez et al., 1998).

Recent studies on cow-calf Brahman (*Bos indicus*) herds grazing on WNSE (Ramírez-Restrepo et al., 2019b) and *B. decumbens* (syn. *Urochloa decumbens*; Ramírez-Restrepo et al., 2020) pastures, and cull cow-fattening systems on *B. decumbens* pastures (Ramírez-Restrepo et al., 2023) showed that BFS on the WNSE not only reduce environmental impacts by operating from near equilibrium in

overall CF balance to net increases in soil organic C (SOC) accumulation but may also contribute toward the United Nation's Sustainable Development Goals (UN, 2015). In parallel, increased productivity of grass-legume pastures in the WNS ecosystem has been demonstrated by the fattening of adult (Ramírez-Restrepo and Vera, 2019) and young Brahman-influenced cattle (Rincón et al., 2018; Rincón and Villalobos, 2021). Nevertheless, to the authors' knowledge, no study has assessed the CF of suckler Brahman heifers and steers and their interconnected postweaning growth and finishing systems at pasture level in the WNSE of the Colombian Orinoquia.

In this view, the present study aims to characterize growth, lifetime CH<sub>4</sub> emissions, the environmental efficiency of carcass characteristics, and the overall CF of young cattle subject to lifespan-grazing on *B. decumbens* pastures. It is focused on testing the underlying relationships through scenario (SCE) analysis of forage management and consumption, greenhouse gas emissions (GHGE), SOC stocks, and potential C-holding capacity as the components of CF in a single-issue life cycle assessment of a functional farming system (Weiler et al., 2014; Ramírez-Restrepo et al., 2020; González-Quintero et al., 2022; Ramírez-Restrepo et al., 2023). Possible outcomes from SCE analyses are likely to assist the investigation of sustainable circularity of BFS (Mehrabi et al., 2020; Broom, 2021), land-based GHGE removal projects and climate finance research (Costa et al., 2022), and law and policy recommendations (Bowman et al., 2012; Ayarza et al., 2022).

Thus, the present study integrated WNSE weaning data from seven continued calving-weaning seasons in a commercial Brahman breeding herd continuously grazed on *B. decumbens* using a dynamic Microsoft Excel<sup>®</sup> GHGE simulation of stockers-yearlings, fattening, and processing phases, and GHG dynamics. We tested the hypothesis that in a WNSE, suckling growth paths would affect lifetime production and the sustainable efficiency of carcass yields in commercial young-Brahman heifers and steers reared throughout life on well-managed *B. decumbens* pastures. This hypothesis was tested to better understand the GHGE environmental impact of WNSE beef-herd farming systems equated through the life cycle as an integral part of current and future agri-food systems.

## Methods

### Database

The breeding herd dataset (Vera et al., 2002) extended by Ramírez-Restrepo et al. (2023) was integrated with the herd's unpublished seventh reproductive cycle (RC; i.e., conception-weaning) at Carimagua Research Centre (latitude 4°36'44.6" N, longitude 74°08'42.2" W) in the Colombian WNSE. Data from 30 cows provided individual liveweight (LW) and age fluctuations across male (n = 55) and heifer (n = 75) calves from birth [28.6 ± 0.50 vs 27.8 ± 0.42 kg (least-squares means ± SEM)] to weaning (183.9 ± 4.80 vs 162.5 ± 4.10 kg and 8.5 ± 0.18 vs 8.4 ± 0.15 months) up to 10.3 ± 0.49 years. Details of the breeding herd on year-round grazing of *B. decumbens* cultivar Basilisk pastures outlining long-term reproductive efficiency and the allocation of GHG costs to cows and cow-calf pairs were described by Ramírez-Restrepo et al. (2020).

## Animal management

Calving events were daily recorded on the paddock while at approximately 4 month intervals, cow's rectal palpation, and visual body condition score [on a scale of 1 (poor) to 5 (fat)], LWs, branding, and castration of males (steers) at weaning were performed in the yard. Briefly, animals were adequately restrained in cattle crushes to minimize the risk to the welfare of cattle, particularly stress while also ensuring the field staff's well-being. Branding irons were well maintained and heated correctly to perform a 2-3 seconds blue-hot-iron branding [CIAT's symbol, and two and three numbers to identify the year of birth and stock sequence, respectively] on a dry hide (near the left side rump) of the animal. Surgical removal of testicles involving enough twist of the spermatic cord and the severed scraping of it to allow quick blood clotting was performed through the implementation of good hygiene practices related to the use of an antiseptic solution in a bucket for hands, scrotum disinfection handling, and instruments (scalpel handles-No 3 and sterile disposable scalpel blades-No 10 changed regularly). Post-surgical healing was also facilitated by the use of antibacterial fly powder and antiseptic spray on the incision before releasing weaners from the yard, monitoring on a clean paddock for 14 days, the use of anti-inflammatory drugs, and previous tetanus (*Clostridium tetani*) vaccination. In both, branding and castration practices pain minimization strategies were followed.

Weaners from different provenance at Carimagua became stockers and yearlings (i.e., backgrounding) on native savanna (Ramírez-Restrepo and Vera-Infanzón, 2019) and experimental pastures (Lascano and Estrada, 1989; Lascano, 1991) whereas surplus heifers and yearling steers were sold to regional farms. Among the livestock categories, pooled stockers-yearlings extended the efficient utilization of low-input pastures based on the relevance of replacement heifers (Vera-Infanzón and Ramírez-Restrepo, 2020; Vera-Infanzón and Ramírez-Restrepo, 2022) and the association of mixed ages and stock classes (Ramírez-Restrepo and Vera, 2019) of farming systems.

In all cases, cattle had always free access to fresh water plus a commercial mineral supplement containing as-kg fed 137 g Ca, 269 g Cl, 0.01 g Co, 1.038 Cu, 0.076 g I, 175 g Na, 80 g P, 20 g S, and 3.5 g Zn. Supplement intake was recorded on a fortnightly basis. Trial design and implementation were done by accredited Colombian Doctors of Veterinary Medicine according to Colombian husbandry and animal welfare standards and guidelines (MINEDUCATION, 1985).

## Climatic factors and soil properties

The climate recorded during the research period at Carimagua's weather station was humid-very humid (April-November) and dry (December-March) with annual precipitation of 3,300 mm in 1986, dropping to an average of 2,202 mm between 1979 and 1991. Thirteen-year minimum and maximum ambient temperatures were 25.2°C to 28.1°C, respectively (Vera and Ramírez-Restrepo, 2017).

Soils at the site were well-drained clay loam Oxisols (tropheptic haplustox isohyperthermic) with 4.78 pH and 90.1% Al saturation. The 0-20 cm soil layer contained 2.9% organic matter, 40.2% clay,

19.8% sand, 1.46 µg/g available P (Bray-II), and exchangeable (cmol/kg) Ca (0.17), Mg (0.08), and K (0.06; Ramírez-Restrepo et al., 2020).

## Pastures and grazing management

*Brachiaria decumbens* cultivar Basilisk pastures were established 2-3 years before cow-calf grazing following the recommended application (kg/ha) of Ca (48), P (20), K (20) Mg (14), and S (10) (Ramírez-Restrepo et al., 2020). Every 3 years and for ~60 days, cattle were shifted to identical *B. decumbens* pastures that were used strategically for adult steers fattening to allow pasture renewal practices including two light disking plus the spread of a third of the establishment fertilization (Vera et al., 2002).

The field experiment used a stocking rate of 1.5 head/ha to ensure conservative grazing management that balanced forage growth and use and maintained full soil cover and land conditions to minimize erosion. Pasture performance was monitored six times per year following the BOTANAL procedure (Jones and Tothill, 1985). Forage mass was between 1,500 and 3,500 kg dry matter (DM)/ha with contents (g/100 g DM) of crude protein (CP, 7.1-11.0), neutral detergent fiber (65.0-71.0), ash (8.5-10.0), and fat (1.0) while *in vitro* DM digestibility (IVDMD; g/100 g) of the whole plant was 63.7 and 55.0, in the wet and dry season, respectively. (Values derived from a Carimagua grazing-forage database assembled by Ramírez-Restrepo and Vera, 2019).

## Modeling approach

The basic structure of the modeling framework is one of beef production in which the benefits of plausible growth (Ramírez-Restrepo and Vera-Infanzón, 2019) and fattening (Ramírez-Restrepo et al., 2023) practices were estimated using least-squares regressions concerning LW-derived CH<sub>4</sub> emissions (Eq. 1) and DM intake (DMI; Eq. 2) from 56 days of age. These functional relationships ( $y = a + bx$ ) are derived from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) calibrated (0.99 pure CH<sub>4</sub> gas recovery) open-circuit chambers measurements using Brahman (Ramírez-Restrepo et al., 2016a) and Belmont Red Composite [Africander (African Sanga) x Brahman x Hereford-

Shorthorn (3/4 *B. taurus*; Ramírez-Restrepo et al., 2014; Ramírez-Restrepo et al., 2016b) steers fed ad libitum on a daily DM basis (2.1% of total LW; Fisher et al., 1987).

$$\text{CH}_4 \text{ (g/d)} = 16.176 (\pm 21.087) + 0.324 (\pm 0.057) \text{ LW (kg)} \quad (1)$$

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

$$\text{DMI (kg/d)} = 2.216 (\pm 1.315) + 0.014 (\pm 0.003) \text{ LW(kg)} \quad (2)$$

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

The second strategy in the model was to link weaning LW differences ( $P < 0.0001$ ) between heifers and steers with on-farm low (0.428 kg) and high (0.516 kg) post-weaning on-farm daily LW gains (DLWGs) in heifers and steers (0.516 kg) on *B. decumbens* pastures (Vera and Hoyos, 2019), respectively to reach target slaughter LW SCEs that are representative of those used in the industry (Wiedemann et al., 2015; Ramírez-Restrepo and Vera, 2019). Under this rationale, the model is implicitly ensuring that individual preweaning LW variations within each sex category are maintained up to slaughter at variable ages and grazing times to capture temporal and spatial beef-herd transactions, and existing regional land uses (Vera-Infanzón et al., 2023). The third strategy paired the slaughterhouse LWs with hot (0.4992) and chilled (0.4772) carcass dressing-outs (Velásquez and Ríos, 2010), accumulated CH<sub>4</sub> emissions, and DMIs.

## Functional scenarios and system boundaries

The post-weaning combination in heifers [confidence limits for weaning 154.4-170.6 kg] of non-feed supplemented low and high DLWGs allowed them to simultaneously reach an early breeding status (272.7 ± 0.01 kg) and the simulation of four target LW SCEs (i.e., 405, 414, 438, and 453 kg representing SCE 1, SCE 2, SCE 3, and SCE 4, respectively (Figure 1). In parallel, assuming a single DLWG, the backgrounding-fattening period of steers (weaning confidence limits 174.4-193.5 kg) to achieve butcher LWs of 435, 474, and 574 kg was represented by SCEs 5, 6, and 7, respectively (Figure 1). Hence, derived carcass carbon dioxide equivalent (CO<sub>2</sub>-eq) efficiency intensities constituted the specific system's boundary cut-off criteria

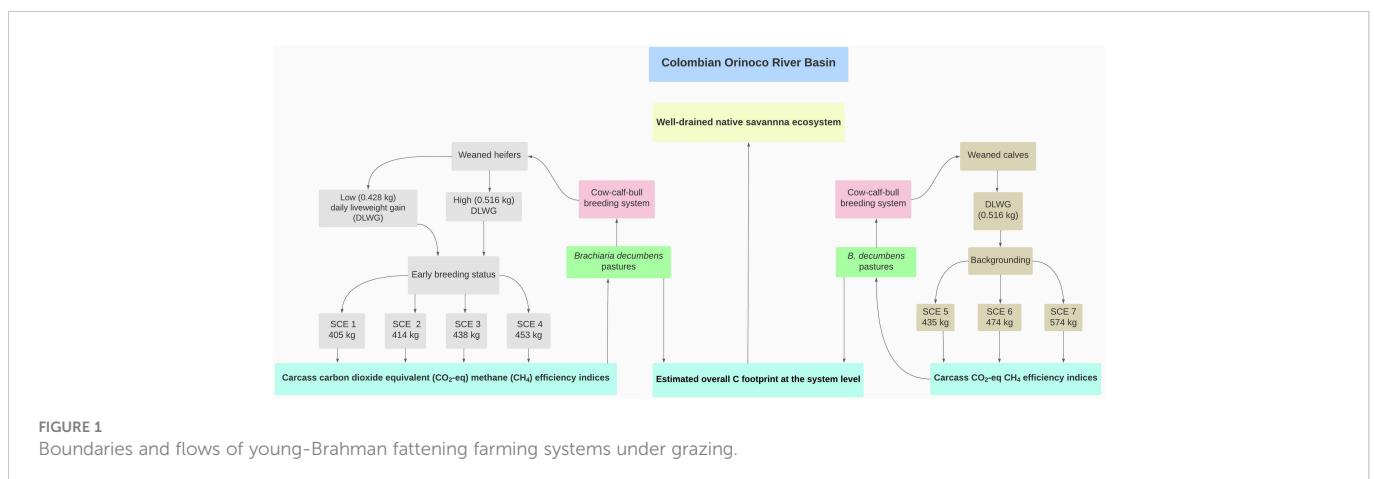


FIGURE 1  
Boundaries and flows of young-Brahman fattening farming systems under grazing.

(Figure 1). An underlying assumption in using a post-weaning dataset partitioned into male and female sets is that LWGs of young steers are larger than in heifers grazing the same tropical pastures year-round (Ramírez-Restrepo and Vera, 2019). Thus, in the suckling herd, this study considered calves and heifers as experimental units while post-weaning sex-grouped animals represented the experimental units over the simulated fattening SCEs.

## Animal GHG footprint, soil C stocks, and C footprint calculation

The scope of this computation considered the interconnected CF of GHG dynamics on *B. decumbens* portrayed by Ramírez-Restrepo et al. (2020); Ramírez-Restrepo et al. (2023), and to the extent possible, parameters used in this study have been reviewed. Briefly, fecal CH<sub>4</sub> assumed the predicted DMI, IVDMD (55 g/100 g), and the 0.112 emission factor (EF; Zhu et al., 2018). Nitrogen excretion assumed DMI, N concentration (1.488 g/100 g), nutrient digestibility (71.62 g/100 g; Vercoe and Frisch, 1970), and the kg N<sub>2</sub>O/kg N EF of 0.0014 (Lessa et al., 2014) and 0.016 (Chirinda et al., 2019) for feces and urine, respectively. Intakes of DM and CP met the LW-related requirements of female and male *B. indicus* cattle raised on pasture in Brazil (Rotta et al., 2016). The factor used for a kg of the mineralized supplement was 0.800 kg CO<sub>2</sub>-eq (C-equivalent; KLIMATMÄRKING FÖR MAT, 2009) while supplement intake assumed the 0.124 g/kg LW factor derived from the expected consumption of 60 g/day by a 500 kg Brahman in the foothills region of the Colombian Llanos (Rincón et al., 2018).

The estimation of the overall C balance was mainly adapted from contemporary studies on soil-plant relations conducted at Carimagua (Fisher et al., 1994; Rondón et al., 2006; Trujillo et al., 2006). Soil organic C values to 1 m depth considered data from Fisher et al. (1994); Rondón et al. (2006), and Fisher et al. (2007). The standing above and belowground DM biomass values used were from published reports (Fisher et al., 1998; Rao, 1998; Kanno et al., 1999; Rao et al., 2001a, b; Grace et al., 2006; Trujillo et al., 2006). Soil CH<sub>4</sub> and N<sub>2</sub>O emissions were estimated from the review studies done by Castaldi et al. (2006) and Rondón et al. (2006). The CO<sub>2</sub>-eq footprint from pasture establishment and maintenance was assumed on a prorated basis considering 15 years of on-farm productive grazing (Vera and Hoyos, 2019). Fertilizer and tillage imprints were computed from Edwards-Jones et al. (2009); Kim et al. (2011), and the University of Arkansas (2019) while the estimated range of CO<sub>2</sub>-eq SOC accumulation rate was based on published reports (Fisher et al., 1994; Rao, 1998; Fisher et al., 1998; Rondón et al., 2006; Fisher et al., 2007; Costa et al., 2022; Hyman et al., 2022).

The study used the horizon global warming potential (GWP)<sub>100-34</sub> value for CH<sub>4</sub> that includes climate-C feedbacks (Gasser et al., 2017; Mueller and Mueller, 2017; Allen et al., 2018) whilst the GWP<sub>100-298</sub> value for N<sub>2</sub>O (Ramírez-Restrepo et al., 2019b). This is consistent with previous studies on GHGE conducted by Vera et al. (2023) that were aimed to assist possible BFS intensification on the WNSE, as well as discussions, and policy-making efforts focusing on environmental trade-offs, planning, natural resources management, rural livelihoods, market chains, and research for development (Latawiec et al., 2014; Cunha Malafaia et al., 2021).

## Statistical analyses

The variances associated with age and LW fluctuations, CH<sub>4</sub> emissions, dynamics of the relationships between LWs and CH<sub>4</sub> emissions, DMI, and carcass measurements were tested using the GLM procedure within the Statistical Analysis System (SAS<sup>®</sup>, 2021) including the upper and lower confidence limits for each mean observation and the confidence level for the parameter estimation methods. The model considered the fixed effects of breeding-herd RCs (i.e., 1 to 7) and fattening-slaughter SCEs (i.e., 1 to 7), and their interaction. Results are presented as least-squares means ± standard errors of the mean (SEM) while differences between the main factors were reported if significant at  $P \leq 0.05$ .

## Results

Heifers' differences among SCEs in low and high DLWGs from the early breeding status to slaughter were significant (Table 1). The slaughter age increased from SCE 1 to SCE 4 by 12% and 11% for the low and high DLWGs, respectively, while in parallel, a 5% and 4% increase in DMI between the first and fourth fattening SCEs was compensated by the improvements in LWGs. The estimates of CH<sub>4</sub> emissions per day, DMI, and during the fattening phase were consistently higher for both DLWGs in SCE 4 than across other SCEs. As expected, CH<sub>4</sub> emissions during the fattening period increased up to 45% with increasing slaughter LW.

The effect of SCEs on CO<sub>2</sub>-eq CH<sub>4</sub> emission profiles during the fattening period and lifespan of heifers are presented in Table 2. Compared to SCE 4, fattening emissions per kg LWG and FLW were significantly lower in the low and high DLWGs of SCE 1 by 6.1% and 29.1%, respectively. However, lifespan emissions in SCE 4 were significantly higher than in SCE 1 for the low and high DLWGs in terms of the LWG (10.9% vs 10.4%), slaughter LW (11.8% vs 11.3%), and birth LW (25.0% vs 24.4%) efficiency indicators.

Final age, total LWG, daily DMI, CH<sub>4</sub> emissions, and CH<sub>4</sub> yield (g/kg/DMI) of steers in the backgrounding phase were significantly lower than for steers in SCE 5 (10%, 16%, 5%, 6%, 1%, and 20%), SCE 6 (20%, 31%, 9%, 12%, 2%, and 41%), and SCE 7 (46%, 70%, 19%, 25%, 5%, 104%; Table 3). Fattening and lifespan CO<sub>2</sub>-eq CH<sub>4</sub> emission metrics from steers are shown in Table 4. Differences in LWG estimations between SCEs were larger during the animals' lifespan than during the fattening period while the final LW indices were larger over the fattening period than during the lifetime frame. In heifers and steers, CO<sub>2</sub>-eq CH<sub>4</sub> EFs related to carcass characteristics increased linearly and significantly across their respective DLWGs and SCEs (Table 5).

Table 6 shows estimated GHGE, observed ranges for important variables, and estimated overall C balance for SCEs 1 and 4 and SCEs 5 and 7. Relative to high DLWGs, the estimated enteric CO<sub>2</sub>-eq CH<sub>4</sub> emissions in heifers were lower in the low DLWG group of SCEs 1 and 4 by 6.6% and 6.8%, respectively, while steers' emissions were 18.9% higher in SCE 7 than in SCE 5. The estimated CO<sub>2</sub>-eq CH<sub>4</sub> emission from heifers' feces was 5.4% higher in the low DLWG SCE 4 than in the counterpart SCE 1 while in steers, 268 extra days of grazing between SCE 5 and SCE 7 were associated with 14.1% increase in emissions. In heifers, differences in CO<sub>2</sub>-eq N<sub>2</sub>O emission from

TABLE 1 Estimated fattening performance, dry matter intake (DMI), and methane (CH<sub>4</sub>) emissions from <sup>†</sup>early-breeding (EB) Brahman (*Bos indicus*) heifers gaining daily either low or high liveweight (LW) on *Brachiaria decumbens* pastures <sup>‡</sup> in relation to slaughterhouse LW scenarios (SCEs)<sup>†</sup>.

	SCE 1		SCE 2		SCE 3		SCE 4	
	Low	High	Low	High	Low	High	Low	High
Number of animals	75	75	75	75	75	75	75	75
EB-fattening phase (days)	309 ± 0.06d	256 ± 0.06d	330 ± 0.06c	273 ± 0.06c	386 ± 0.06b	330 ± 0.06b	421 ± 0.06a	349 ± 0.06a
Slaughter age (months)	27.08 ± 0.26d	23.92 ± 0.26d	27.77 ± 0.26cd	24.49 ± 0.26cd	29.61 ± 0.26b	26.02 ± 0.26b	30.76 ± 0.26a	26.97 ± 0.26a
DMI (kg/head/day)	7.050 ± 0.001d	7.084 ± 0.001d	7.113 ± 0.001c	7.130 ± 0.001c	7.279 ± 0.001b	7.295 ± 0.001b	7.384 ± 0.001a	7.401 ± 0.001a
CH <sub>4</sub> (g/head/day)	128.1 ± 0.02d	128.4 ± 0.02d	129.6 ± 0.02c	129.9 ± 0.02c	133.4 ± 0.02b	133.8 ± 0.02b	135.8 ± 0.02a	136.2 ± 0.02a
CH <sub>4</sub> (g/kg DMI/day)	18.17 ± 0.002d	18.12 ± 0.002d	18.22 ± 0.002c	18.23 ± 0.002c	18.33 ± 0.002b	18.34 ± 0.002b	18.40 ± 0.002a	18.40 ± 0.002a
CH <sub>4</sub> (kg/head/fattening) <sup>‡</sup>	39.59 ± 0.008d	32.92 ± 0.008d	42.78 ± 0.008c	35.59 ± 0.008c	51.53 ± 0.008b	42.86 ± 0.008b	57.23 ± 0.008a	47.60 ± 0.008a

<sup>†</sup> Vera et al. (2002)'s threshold early breeding (EB) LW of 272.7 ± 0.01 kg.

<sup>‡</sup> Corresponded to Wiedemann et al. (2015)'s processing LWs of 405 kg (SCE 1), 414 kg (SCE 2), 438 kg (SCE 3), and 453 kg (SCE 4) achieved by daily low (0.428 kg) and high (0.516 kg) fattening LW gains (LWGs) across SCEs. <sup>‡</sup>Adapted from Vera et al. (2002) and Ramírez-Restrepo et al. (2020).

<sup>‡</sup> Depicted fattening phase begins as the heifers reach the EB-LW, at between 15.52 ± 0.26 months (High) and 16.95 ± 0.26 months (Low), and ends when heifers are slaughtered when they reach the targeted slaughter LWs.

Least-squares mean values (± SEM) in the same row within the same LWGs columns bearing different letters through SCEs are significantly different at P ≤ 0.05.

feces, urine, and mineral supplement intake were small between low and high DLWGs and between SCEs, but emissions from steers were 14.1% lower in SCE 5 than in SCE 7. From comparable days of grazing, total animal CO<sub>2</sub>-eq GHGE (kg/ha/year) were 7.1% lower in the low DLWG SCE 1 than in the high DLWG SCE 4 whilst averaged GWP GHGE in heifers and steers amounted to 2,531 and 2,877 CO<sub>2</sub>-eq GHGE (kg/ha/year) from 568 and 622 grazing days, respectively.

Stocks of SOC to 1 m soil depth for the clay loam soil texture and well-drained Oxisols of SCEs 1, 4, 5, and 7 were estimated to be in the range of 130 to 160 t/ha while the range of standing shoot and root DM biomass values represented the 38% and 46% and the 62% and 54% of the total range of DM biomass, respectively. In parallel, using the CO<sub>2</sub>-eq CH<sub>4</sub> (-6.6; 3.2 x 34 kg/ha/year) and CO<sub>2</sub>-eq N<sub>2</sub>O (225; 1.05 x 298 kg/ha/year) emissions (Ramírez-Restrepo et al., 2020) and compared to the total GWP of GHG at the system level in SC1 low DLWG, there was an increase of 6.1% in the counterpart treatment in SCE 4, which in turn, was 17.6% lower than the value from most productive steer SCE. Across groups, heifers and steers subject to the same DLWG (i.e., 0.516 kg) in SCEs 4 and 7 showed the lowest overall level of SOC capture.

## Discussion

This study complements our previous efforts that dealt with the estimation of the carbon footprint (CF) of various beef farming systems in the Colombian Orinoquía Llanos. Earlier studies were focused on (i) breeding herds maintained on diverse native and sown tropical grasslands (Ramírez-Restrepo et al., 2019b; Ramírez-Restrepo et al., 2020); (ii) fattening of cull cows from the breeding herd (Ramírez-Restrepo et al., 2023); and (iii) finishing cull cows on contrasting sown pastures, and raising heifers intended as replacement breeders also on sown vs native grasslands (Vera et al., 2023). With this study's results on CF estimates for fattening young females and males, we complete the production life cycle of cattle raised on grazed pastures.

This research has considered the possible greenhouse gas emission (GHGE) and the CF implications of young fattening BFS, and it particularly focused on the link between individual growth records, *B. decumbens* pastures, grazing management, and the environmental efficiency of carcass characteristics. In this study, we repurpose a unique long-term Brahman breeding herd data set recorded on the field from 1979 when the breeding herd was born together with enteric CH<sub>4</sub> calculations that included the findings from pooled *B. indicus* and *B. indicus* x *B. taurus* breeds open-circuit chamber measurements. By doing this in the absence of recently collected, rigorous field data from the region, we were able to map and share knowledge about common as well as commercial cattle farming systems that are recognized worldwide that may be subjected to human intervention with the use of new technologies and innovation to ensure a significant positive impact on the industry, climate, food systems, and society.

This study's outcome is considered to be a piece of baseline information that is not readily available in the Colombian cattle industry. The presented model predicted that heifers and steers may be successfully fattened without supplementation assuming that animals had access to a nutritive forage grass as a sole feed after extended periods of conventional farm management. Production issues are known to influence farmers' acceptance of *Brachiaria* spp. pastures and these include soil constraints as one of the major factors influencing the decline in tropical forage species' vigor, density, and productivity over time (Vera and Hoyos, 2019).

## Cattle performance improved on grazing lands

The predicted chilled carcass weights (CCWs) in the range of 193-210 kg for heifers and 208-274 kg for steers at 24-31 and 24-33 months of age, respectively, can be compared with the results of León-Llanos et al. (2022) who reported in the Llanos a range of 259-269 kg CCWs at 34-35 months from seven commercial Brahman crosses

TABLE 2 Comparison of fattening and lifespan periods in terms of farm-gate carbon dioxide equivalent (CO<sub>2</sub>-eq) methane emission metrics of surplus early-breeding (EB) Brahman (*Bos indicus*) heifers born and raised on *Brachiaria decumbens* pastures † making either low (0.428 kg) or high (0.516 kg) daily gains to achieve commercial slaughterhouse LW scenarios (SCEs) †.

	SCE 1		SCE 2		SCE 3		SCE 4	
	Low	High	Low	High	Low	High	Low	High
Number of heifers	75	75	75	75	75	75	75	75
<b>EB-fattening period</b>								
kg CO <sub>2</sub> -eq/kg LWG	10.178 ± 0.001d	8.462 ± 0.001d	10.295 ± 0.001c	8.565 ± 0.001c	10.601 ± 0.001b	8.817 ± 0.001b	10.794 ± 0.001a	8.977 ± 0.001a
kg CO <sub>2</sub> -eq kg/FLW	3.324 ± 0.0005d	2.764 ± 0.0005d	3.513 ± 0.0005c	2.923 ± 0.0005c	4.000 ± 0.0005b	3.327 ± 0.0005b	4.296 ± 0.0005a	3.573 ± 0.0005a
<b>Lifespan</b>								
kg CO <sub>2</sub> -eq/kg LWG	6.355 ± 0.040d	5.412 ± 0.040d	6.487 ± 0.040c	5.520 ± 0.040cd	6.834 ± 0.040b	5.800 ± 0.040b	7.049 ± 0.040a	5.974 ± 0.040a
kg CO <sub>2</sub> -eq/kg FLW	5.919 ± 0.037d	5.040 ± 0.037d	6.051 ± 0.037c	5.149 ± 0.037c	6.400 ± 0.037b	5.432 ± 0.037b	6.616 ± 0.037a	5.607 ± 0.037a
kg CO <sub>2</sub> -eq/kg born	87,000 ± 1.554d	74,085 ± 1.554d	90,924 ± 1.554cd	77,374 ± 1.554cd	101,723 ± 1.554b	86,343 ± 1.554b	108,755 ± 1.554a	92,190 ± 1.554a

†Adapted from Vera et al. (2002) and Ramírez-Restrepo et al. (2020). FLW, Final LW.  
 † Based on target slaughterhouse LW SCEs of 405, 414, 438, and 453 kg from Wiedemann et al. (2015).  
 Least-squares mean values (± SEM) in the same row within the same LWG columns bearing different letters through SCEs are significantly different at P ≤ 0.05.

fattened rotationally for 24 months on *B. decumbens* and *B. humidicola* pastures. Although León-Llanos et al. (2022) and the present study used animals from experimental cow-calf systems, differences between the present calculations and León-Llanos et al. (2022) can be explained by the higher initial age (10-11 months), initial LW (246 kg), and stocked paddocks (2.8 head/ha) used by the latter authors which in turn reflected in lower DLWGs (0.442 kg). It is also important to note that León-Llanos et al. (2022) did not assess heifers and used a crop-based supplement during the dry season period.

Rincón and Villalobos (2021) raised Brahman yearlings (18 months of age - 240-280 kg) on rotationally grazed *B. decumbens* pastures or mixed with the tannin-containing legumes [Lascano et al., 1990; International Center for Tropical Agriculture (CIAT), 2016] including *Centrosema molle* (accession CIAT 15160), *C. macrocarpum* (accession CIAT 15799), and *Grona heterocarpa* subsp. *ovalifolia* (syn. *Desmodium ovalifolium* cultivar Maquenque) that yielded average daily liveweight gains (DLWGs) of 0.437, 0.687, 0.396, and 0.440 kg, respectively in Experiment 1 (22 months). A second, shorter experiment (14 months) on the same pastures, resulted in mean DLWGs of 0.545, 0.744, 0.563, and 0.573 kg, respectively. Thus, the final LWs (495-504 kg) recorded by Rincón and Villalobos (2021) fall within the present scenario (SCE) 6 and SCE 7 estimations and these values reflect the model's mean steers' target processing LW (494 kg). Similarly, the mean DLWG (0.487 kg), across heifers and steers set by the model, and the overall DLWG (0.486 kg) on *B. decumbens* after 36 months of grazing (Rincón and Villalobos, 2021) emphasize the predictive capability of the model considering the continuous growth rate from weaning to slaughter approach. However, carcass traits and CO<sub>2</sub>-eq CH<sub>4</sub> concentration in carcass yields were not estimated by Rincón and Villalobos (2021).

The methodology employed in this research provided strong evidence to support the view that LWGs, grazing management, and processing LW frameworks exert an impact on intensification in the beef farming systems (BFS) of the well-drained native savanna ecosystem (WNSE). Slaughtering cattle at a younger age will play a significant role in commodity markets for homogenous products within gender groups or in supply chains where there is much likelihood of heterogeneous quality products from adult cattle. Nevertheless, emphasis on plant characteristics that relate to nutritional and feeding values, and persistence to address increasing climate extremes, shifts, and changes from seasons to years should provide long-term benefits and future opportunities for research and development of the industry. This may require the integration of fodder resources such as trees and shrubs to supply protein, energy, and other nutrients into tropical grazing systems (Vandermeulen et al., 2018a).

Previous studies from WNSE (Ramírez-Restrepo and Vera, 2019) reported that Brahman-influenced cull cows (10-13 years) and steers (3-5 years) can achieve CCWs of 169-193 kg and 202-226 kg, respectively when grazed on *Andropogon gayanus* plus *Stylosanthes capitata* pastures after 144-201 days of fattening, while CCWs of 176-194 kg (cull cows) and 187-211 kg (steers) were observed on *B. humidicola* pastures during 146-181 days. Therefore, as the choice of cattle categories for fattening on improved pastures and/or fodder resources is an important consideration for farmers, further appropriate modeling studies are required to determine the benefits

TABLE 3 Estimated animal performance and methane (CH<sub>4</sub>) emissions of growing commercial Brahman (*Bos indicus*) stockers-yearlings<sup>‡</sup>, and young steers on *Brachiaria decumbens* pastures associated with a common daily liveweight gain (LWG) of 0.516 kg and three processing target LW scenarios (SCEs).

	Backgrounding	SCE 5 <sup>†</sup>	SCE 6 <sup>†</sup>	SCE 7 <sup>†</sup>
Number of animals	55	55	55	55
Grazing (days)	414 ± 7.99d	487 ± 7.99c	562 ± 7.99b	756 ± 7.99a
Final age (months)	21.77 ± 0.268d	24.20 ± 0.268c	26.64 ± 0.268b	32.99 ± 0.268a
LW gain (LWG, kg)	213 ± 3.73d	253 ± 3.73c	291 ± 3.73b	391 ± 3.73a
Final LW (kg)	395 ± 2.25d	435 ± 2.25c	474 ± 2.25b	574 ± 2.25a
Grazing period				
DMI (kg/day)	6.359 ± 0.056d	6.708 ± 0.056c	6.975 ± 0.056b	7.658 ± 0.056a
CH <sub>4</sub> (g/day)	112.3 ± 1.23d	119.9 ± 1.23c	126.1 ± 1.23b	142.0 ± 1.23a
CH <sub>4</sub> (g/kg DMI/day)	17.64 ± 0.040d	17.86 ± 0.040c	18.07 ± 0.040b	18.54 ± 0.040a
CH <sub>4</sub> (kg/head/phase)	46.51 ± 0.633d	58.02 ± 0.633c	70.37 ± 0.633b	106.95 ± 0.633a

<sup>‡</sup> Adapted from Vera et al. (2002) and Ramírez-Restrepo et al. (2020).

<sup>†</sup> Derived from Ramírez-Restrepo and Vera (2019), and <sup>†</sup> Wiedemann et al. (2015). DMI, Dry matter intake.

Least-squares mean (± SEM) values in the same row bearing different letters are significantly different at P ≤ 0.0001.

of complementary fattening of young and adult cattle practices to diversify farm outputs while meeting consumers' expectations and delivering increased economic returns to producers.

## Estimated production patterns, methane emissions, and carcass metrics

The model interpolation of LWs and CH<sub>4</sub> emissions between weaning, slaughter, and lifespan proportions allowed the differentiation in CF of young BFS. The analysis indicated that weaning LW to slaughter LW ratios of 0.3932, 0.3848, 0.3634, and 0.3517 ± 0.0076 were achieved in heifers' SCEs 1, 2, 3, and 4, respectively whilst ratios of 0.4194, 0.3850, and 0.3179 ± 0.0089 corresponded to steers' SCEs 5, 6, and 7, respectively. Likewise, it was shown that significant differences in the overall growth from birth to weaning between heifers (0.533 ± 0.004 kg) and steers (0.620 ± 0.007 kg), their birth LW to weaning LW ratios (0.1799 ± 0.001 vs

0.1612 ± 0.002), and their cumulative CH<sub>4</sub> emissions before fattening (7.73 ± 0.300 kg vs 9.20 ± 0.351 kg) can be linked to the differential significant magnitudes of weaning to slaughter and weaning to lifespan CH<sub>4</sub> ratios in heifers (0.1301 ± 0.001 vs 0.1443 ± 0.003) and steers (0.1137 ± 0.001 vs 0.1241 ± 0.002). In particular, the pattern of LWGs during the rearing period in a pasture-based system corresponds to the value of LW at 12 months as a proportion of 21 months of age on cumulative production (Handcock et al., 2020) while LWs and DLWGs in real-time can be predicted in *B. indicus* cattle during growing and finishing phases (Comminotte et al., 2020).

Taken together, these results indicate that the within and between individual animal variability and herd-level variation in the LW recorded database and the predicted DMI and CH<sub>4</sub> emissions were also coupled with the natural variation in measured LWs, DMIs, and CH<sub>4</sub> outputs from cattle while in accurate respiratory chambers (Ramírez-Restrepo and Vera, 2019; Zhang et al., 2021). It is important to observe that we hypothesized that suckling growth paths would affect lifetime production and the sustainable efficiency

TABLE 4 Estimated carbon dioxide equivalent (CO<sub>2</sub>-eq) methane emission impact of commercial Brahman (*Bos indicus*) steers' grazing on *Brachiaria decumbens* pastures before slaughter with three contrasting scenarios (SCEs).

	SCE 5 <sup>†</sup>	SCE 6 <sup>†</sup>	SCE 7 <sup>†</sup>
Fattening phase			
kg CO <sub>2</sub> -eq/kg LWG	7.822 ± 0.063c	8.232 ± 0.063b	9.302 ± 0.063a
kg CO <sub>2</sub> -eq/kg FLW	4.531 ± 0.039c	5.047 ± 0.039b	6.333 ± 0.039a
Lifetime metrics			
kg CO <sub>2</sub> -eq/kg LWG	5.622 ± 0.031c	6.078 ± 0.031b	7.242 ± 0.031a
kg CO <sub>2</sub> -eq/kg FLW	5.254 ± 0.031c	5.713 ± 0.031b	6.883 ± 0.031a
kg CO <sub>2</sub> -eq/kg born	81.322 ± 1.620c	96.200 ± 1.620b	140.345 ± 1.620a

Adapted from <sup>†</sup> Ramírez-Restrepo and Vera (2019) and <sup>†</sup> Wiedemann et al. (2015) considering target processing liveweight (LW) SCEs of 435 kg and 474 kg, and 574 kg, respectively.

FLW, Final LW; LWG, Liveweight gain.

Least squares mean values (± SEM) in the same row bearing different letters between SCEs are significantly different at P ≤ 0.0001.



TABLE 5 Lifespan carbon dioxide equivalent (CO<sub>2</sub>-eq) methane (CH<sub>4</sub>) efficiency indices from carcass composition<sup>†</sup> of young Brahman (*Bos indicus*) heifers and steers grazing on *Brachiaria decumbens* pastures<sup>‡</sup> with contrasting liveweight (LW) slaughter scenarios (SCEs)<sup>†</sup>.

	CH <sub>4</sub> efficiency indices		
	kg CO <sub>2</sub> -eq/kg CCW	kg CO <sub>2</sub> -eq/kg LM	kg CO <sub>2</sub> -eq/kg EP
<b>Heifers</b>			
<b>SCE 1</b>			
Low	12.404 ± 0.078d	20.412 ± 0.129d	78.510 ± 0.497d
High	10.561 ± 0.078d	17.379 ± 0.129d	66.843 ± 0.497d
<b>SCE 2</b>			
Low	12.682 ± 0.078c	20.869 ± 0.129c	80.269 ± 0.497c
High	10.790 ± 0.078c	17.756 ± 0.129c	68.295 ± 0.497c
<b>SCE 3</b>			
Low	13.411 ± 0.078b	22.070 ± 0.129b	84.884 ± 0.497b
High	11.382 ± 0.078b	18.730 ± 0.129b	72.039 ± 0.497b
<b>SCE 4</b>			
Low	13.864 ± 0.078a	22.814 ± 0.129a	87.488 ± 0.497a
High	11.750 ± 0.078a	19.336 ± 0.129a	74.372 ± 0.497a
<b>Steers</b>			
SCE 5	11.011 ± 0.070c	18.119 ± 0.116c	69.689 ± 0.446c
SCE 6	11.992 ± 0.070b	19.734 ± 0.116b	75.902 ± 0.446b
SCE 7	14.424 ± 0.070a	23.735 ± 0.116a	91.291 ± 0.446a

<sup>†</sup> Slaughter LWs of 405 (SCE 1), 414 (SCE 2), 438 (SCE 3), and 453 (SCE 4) kg in heifers (Wiedemann et al., 2015) using low (0.428 kg/day) and high (0.516 kg/day) fattening LW gains across SCEs. Steers' processing LWs of 433 kg (SCE 5) and 474 kg (SCE 6); and 574 kg (SCE 7) were derived from Ramírez-Restrepo and Vera (2019), and Wiedemann et al. (2015), respectively.

<sup>‡</sup> Adapted from Velásquez and Rios (2010) and Ramírez-Restrepo and Vera (2019); and <sup>§</sup> Vera et al. (2002) and Ramírez-Restrepo et al. (2020).

EP: Edible protein. CCW, Cold carcass weight; LM, lean meat.

Least-squares mean values (± SEM) in the same column and within the same animal category bearing different letters amongst SCEs are significantly different at P ≤ 0.05.

of carcass yields. The mathematical output supports this hypothesis, as we provided insights into the implications of measurements obtained at differential LW and age at slaughter that can be caused by the same variation from birth to weaning on the same pasture with a pivotal effect on the overall CF at the system level. Connectedly, Foote et al. (2016) indicated that in ad libitum-fed beef-finishing heifers and steers, their differential appetite, DLWGs, and feed efficiency are consistently regulated by the circadian-blood expression of levels of acyl ghrelin (gut-peptide hormone), total ghrelin (acyl and desacyl), and ghrelin ratio (acyl: total ghrelin). Hence the current model can be used as part of a whole-farm model to predict the effects of pasture intensification strategies on production dynamics and the environmental footprint of beef herds in the Llanos (Vera et al., 2023).

This study also contributes to current knowledge by documenting the range of values on lifetime CH<sub>4</sub> emissions from finished heifers (60.03 to 88.15 ± 0.470 kg) and steers (67.30 to 116.23 ± 0.593 kg) and the subsequent carcass metric implications. This is shown from the calculated CH<sub>4</sub> yield ranges of 18.1–18.4 (heifers) and 17.9–18.5 (steers) that match the values from open-circuit respiration chambers values with *B. indicus* influenced heifers (18.07) and steers (18.4–19.0) that were with fed fresh grasses as reported by Ku-Vera et al. (2018) and Meat and Livestock Australia (MLA, 2020), respectively. Although in

agreement with Skidmore et al. (2022), the present modeling effort followed a single-issue life cycle assessment approach across a wide range of slaughter regimes, the current predictive values for steers (24.2–32.9 months) are well below the estimated steers' lifetime CH<sub>4</sub> emissions of 151.23 kg (36 months) and 201.83 kg (48 months) from Brazilian pasture-based BFS. Interestingly, while using the Intergovernmental Panel on Climate Change (IPCC) Tier 2 methodology Skidmore et al. (2022) argued that it is practicable to slaughter lifetime grazing heifers with 168.12 kg of CH<sub>4</sub> emissions at 36 months of age while the present modeling showed that un-supplemented younger heifers (23.9–30.7 months) can be slaughtered at a reduced time to lower enteric CH<sub>4</sub> emissions by ~44%.

The results from this study point out that at different levels of intensification, the lifespan C footprint at the farm gate is in the range of 5.040 to 6.616 kg CO<sub>2</sub>-eq/kg FLW in heifers and 5.254 to 6.883 kg CO<sub>2</sub>-eq/kg FLW in steers. On average, these values are 43.4%, 45.4%, 51.0%, 55%, and 77% lower than the Australian methodologically-variable cradle to farm-gate life cycle assessment estimates of 10.5 CO<sub>2</sub>-eq/kg beef LW (Eady et al., 2013; 2016), 10.9 CO<sub>2</sub>-eq/kg beef LW (Ridoutt, 2021), 12.2 CO<sub>2</sub>-eq/kg beef LW (Wiedemann et al., 2016), 13.3 kg CO<sub>2</sub>-eq/kg beef LW (MLA, 2022), and 25.8 CO<sub>2</sub>-eq/kg beef LW sold (Eady et al., 2016). Furthermore, present lifetime means of 6.179 kg CO<sub>2</sub>-eq/kg LWG for heifers and 6.314 kg CO<sub>2</sub>-eq/kg LWG

TABLE 6 Estimated greenhouse gas (GHG) emissions and overall carbon balance in young Brahman (*Bos indicus*) heifers and steers grazing on *Brachiaria decumbens* pastures across weaning-fattening systems characterised by contrasting liveweight (LW) processing scenarios (SCEs).

Parameters	SCE 1		SCE 4		SCE 5	SCE 7
	Low	High	Low	High		
Grazing days	565	468	677	561	488	756
CO <sub>2</sub> -eq enteric CH <sub>4</sub> (kg/ha/year)	2,049.8	2,055.7	2,195.6	2,201.4	2,214.2	2,633.4
CO <sub>2</sub> -eq CH <sub>4</sub> from feces (kg/ha/year)	231.7	233.3	244.4	245.4	248.7	283.9
CO <sub>2</sub> -eq N <sub>2</sub> O from feces (kg/ha/year)	6.0	6.1	6.3	6.4	6.4	7.3
CO <sub>2</sub> -eq N <sub>2</sub> O from urine (kg/ha/year)	140.7	141.6	148.4	149.0	151.0	172.4
CO <sub>2</sub> -eq of mineral supplement intake (kg/ha/year)	14.88	14.88	16.14	16.18	16.29	19.93
Total animal CO <sub>2</sub> -eq GHG emissions (kg/ha/year)	2,443	2,452	2,611	2,618	2,637	3,117
<b>Estimation of overall C balance</b>						
SOC to 1 m depth, medium texture soil (Mg/ha)	130-160	130-160	130-160	130-160	130-160	130-160
Standing aboveground (shoot) DM biomass (Mg/ha)	5.1-9.1	5.1-9.1	5.1-9.1	5.1-9.1	5.1-9.1	5.1-9.1
Standing belowground (root) DM biomass (Mg/ha)	8.3-10.5	8.3-10.5	8.3-10.5	8.3-10.5	8.3-10.5	8.3-10.5
Total DM biomass (Mg/ha)	13.4-19.6	13.4-19.6	13.4-19.6	13.4-19.6	13.4-19.6	13.4-19.6
CO <sub>2</sub> -eq from soil CH <sub>4</sub> (kg/ha/year)	-6.64	-6.64	-6.64	-6.64	-6.64	-6.64
CO <sub>2</sub> -eq from soil N <sub>2</sub> O (kg/ha/year)	225	225	225	225	225	225
CO <sub>2</sub> -eq from fertilizer inputs and tillage (kg/ha/year)	51.1	51.1	51.1	51.1	51.1	51.1
CO <sub>2</sub> -eq total GHG at the system level (kg/ha/year)	2,713	2,721	2,880	2,888	2,906	3,387
CO <sub>2</sub> -eq SOC accumulation rate (Mg/ha/year)	3.66-11.0	3.66-11.0	3.66-11.0	3.66-11.0	3.66-11.0	3.66-11.0
Overall C footprint at the system level (Mg/ha/year)	-0.947 to -8.287	-0.939 to -8.276	-0.780 to -8.120	-0.772 to -8.112	-0.754 to -8.094	-0.273 to -7.613

Heifers' processing liveweights (LWs) of 405 (SCE 1) and 453 (SCE 4) kg from Wiedemann et al. (2015) were reached using a daily low (0.428 kg) and high (0.516 kg) LW gains.

Target slaughter LWs of 433 kg (SCE 5) and 574 kg (SCE 7) in steers were derived from Ramírez-Restrepo and Vera (2019), and Wiedemann et al. (2015), respectively.

CO<sub>2</sub>-eq: Carbon dioxide equivalent. CH<sub>4</sub>: Methane. Mg, Megagram; N<sub>2</sub>O, Nitrous oxide; SOC, Soil organic carbon; Negative CO<sub>2</sub>-eq values for soil C for overall C footprint imply SOC accumulation.

for steers are 42% and 80% lower than the CO<sub>2</sub>-eq/kg LWG fattening range indices of 10.9 and 30.9 suggested by the cradle to farm-gate life cycle assessment estimations for the Colombian piedmont plains using 2019 refined IPCC parameters (González-Quintero et al., 2022). Alternatively, if a CH<sub>4</sub> GWP<sub>100-28</sub> metric (Myhre et al., 2013) is introduced to compare with the assumed CH<sub>4</sub> EF of 1.5 t CO<sub>2</sub>-eq/animal equivalent (AE; 455 kg LW)/year which is used to estimate the C balance of the Queensland beef industry (QLD Government, 2019) or the 1.56 t CO<sub>2</sub>-eq/AE/year for farm C accounting (Ekonomou et al., 2020), constant heifers' LWs of 438 and 453 kg, emit 1.365 vs 1.390 t CO<sub>2</sub>-eq/year while 1.225, 1.289, and 1.451 t CO<sub>2</sub>-eq/year emissions, respectively equate to stable steers' LWs of 435, 474, and 574 kg. These disparities provide the foundation to simulate the environmental impacts of alternative finishing LWs by choosing the assessment methodology and production option that makes sense in the context of sustainable productivity at the BFS level for assisting a low-C emission future. It is also relevant to recognize that 33% and 47% of the variation in predicted CO<sub>2</sub>-eq emissions per kg LW in BFS is explained by weaning percentage and averaged DLWGs, respectively (Wiedemann et al., 2016).

On the other hand, the model predicted a range of values of 10.5-13.8, 17.3-22.8, and 66.8-87.4 kg CO<sub>2</sub>-eq/kg of CW, lean meat, and edible protein for heifers and 11.0-14.4, 18.1-23.7, and 69.9-91.2 for steers, respectively for steers. Overall, they represent 19.9% for heifers and 20.7% for steers from the total (cumulative) carcass-reference

values of CH<sub>4</sub> emission that would be expected from multiparous Brahman cull cows (8.7 years) that were continuously bred and fattened for 86 days on *B. decumbens* pasture (Ramírez-Restrepo et al., 2023). These estimated values are in contrast with Ridoutt's (2021) estimate of 25.5 kg CO<sub>2</sub>-eq/kg of edible beef. Nevertheless, such estimations underscore the value of 16.7 CO<sub>2</sub>-warming-eq (CO<sub>2</sub>-w.e.)/kg of edible beef (Ridoutt, 2021) which aligns the future warming with the permanent change in the rate of short-lived GHGE like CH<sub>4</sub> (Lynch et al., 2020). Hence, results from the model used in this study may support published values by the potential use of the new GWP\* CO<sub>2</sub>-w.e. metrics to further review the CF of the beef industry of the WNSE.

### Estimated overall C footprint at the system level and implications for sustainable regional beef farming systems

The present study estimated the enhancement of soil organic carbon (SOC) storage at different stages of the BF system. First, the long periods of grazing by heifers (677 days) and steers (756 days) strike a positive balance between on-farm productivity, CO<sub>2</sub>-eq SOC accumulation, and climate change mitigation. The notion that conservatively managed grazing of tropical BFS negatively imprints the environment is not tenable. Indeed, positive trade-offs are

involved, and farmers may need to make sensible resource management decisions regarding the appropriate allocation of pastures and animal stocks to ensure red meat target-setting and choose the relative contribution of pastoral abatement strategies.

This is consistent with the view that in the Colombian Orinoquia, increased SOC storage at deep soil layers (30–100 cm), reduced N<sub>2</sub>O emissions from beef urine deposition, and viable land-based agendas of CO<sub>2</sub> removal from the atmosphere can be achieved through the ability of biological nitrification inhibition, N uptake from the ammonium source, and the deep rooting of *B. humidicola* (Costa et al., 2022). Hyman et al. (2022) showed a large potential for SOC storage in Colombia's Eastern High Plains. They found less SOC storage than Fisher et al. (1994) and indicated that earlier high levels of SOC accumulation in well-managed pastures returned to a lower equilibrium value under inadequate management conditions. Thus, these two recent reports on SOC stocks in the Llanos not only highlight the need for improving the management of native savanna and degraded pastures across the 1 million ha study but also infer that land-use changes in the WNSE can vary widely in the balance between beef outputs and the overall CF at the farming system level (Vera-Infanzón et al., 2023).

Furthermore, results from this study suggest that early weaning-fattening systems in the tropics may also offer the opportunity for climate mitigation by transferring C credits within or outside the BFS involving land transactions and promoting C markets. Brahman-influenced cow-calf herd systems in the WNSE may be not only close to C neutral under estimated conventional and early weaning management practices (583 vs 579 kg CO<sub>2</sub>-eq/ha/year; Ramírez-Restrepo et al., 2019b) but also may act as C sinks at the system level by removing atmospheric CO<sub>2</sub> across six consecutive RCs by grazing on *B. decumbens* pastures during the cow-calf-bull breeding phase (-1,180 to -8,513 kg CO<sub>2</sub>-eq/ha/year; Ramírez-Restrepo et al., 2020). These C sinks may also contribute toward SOC storage imbalances caused by land use change, cropland use, or complementary routine animal feed supplementation locally or elsewhere. Therefore, climate stabilization may be nurtured from land use efficiency through pasture management and the adoption of a climate-neutral target strategy with improved production from the meat industry (MLA, 2021).

The current predictions from this study provide dimensional insights to reduce slaughter age while monitoring GHGE at the system level. However, this approach did not assess the effect of *B. decumbens* pastures mixed with legumes that contain secondary metabolites that may influence even more on sustainable ruminant intensification (Ramírez-Restrepo and Barry, 2005). Therefore, it is suggested that year-round productivity should not underestimate the feeding value of forage resources containing secondary compounds (Ramírez-Restrepo and Charmley, 2015; Durmic et al., 2017; Vandermeulen et al., 2018b) to further reduce the impact on the C cycle by using the present fattening framework. This argument is strengthened by the counter-balancing effect of LWs and age targets on animal GHGE vs the reduction in GHGE from shorter fattening periods, especially considering not only that CP concentration in *B. decumbens* plus legumes swards can be 33% higher than in *B. decumbens* alone pastures (Rincón and Villalobos, 2021) but also the effect of condensed tannins-containing legumes shifting N

digestion and increasing fecal N concentration (Waghorn et al., 1987), thereby mitigating CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O emission from excreta in the soil (van Cleef et al., 2022), and increasing soil N retention in grazed pastures (Slebođnik, 2020).

The present estimates also suggest that replacement heifers raised on *B. decumbens* pastures may favor lifetime breeding systems grazing higher-quality pastures or if transferred, could positively impact extensive cow-calf operations that are subject to improved decision-making (Vera-Infanzón and Ramírez-Restrepo, 2020; Vera-Infanzón and Ramírez-Restrepo, 2022). Nevertheless, defining the physiological and genomic limits on selection pressure on beef genotypes that may have a significant environmental effect remains to be an intriguing issue if grazing low CH<sub>4</sub> emitters and efficient producers are targeted. Interestingly, our understanding is limited in many basic details related to the physiological systemic effects of blood CH<sub>4</sub> concentration in Brahman cattle (Ramírez-Restrepo et al., 2016a).

Likewise, the current early breeding and backgrounding stages may offer a potential window of opportunity for the transition to other BFS practices that may reduce the GWP of the national GHG inventory. This can be achieved through the finishing of beef cattle on feedlots that are potentially driven by the feed supplementation of ecologically relevant compounds (Tedeschi et al., 2021). Nevertheless, as feed-intensive practices are inevitably linked to the provision of high-concentrated diets, plausible BFS should consider that a kg of feed-milled supplement at the farm gate may represent 0.93 kg CO<sub>2</sub>-eq under a life cycle assessment methodology (Adom et al., 2013). Relatedly, the evaluation of trade-offs, synergies, and challenges between land use, breeding goals, plant by-products, profitability, environmental stability, and consumers' recognition of WNSE-BFS in a circular planet-friendly food system should be similarly addressed (Oosting et al., 2022). Hence, as the transformation of finishing BFS on the WNSE is not well documented, future advances will depend on research focused on the integration of beef genotypes, grazing systems with an emphasis on deep-rooted pasture grass and legume species, and several fattening-supplemented practices under grazing or feed yard conditions to assist decision-making and to address environmental policy issues.

## Conclusions

The present modeling, complemented with earlier studies, provides benchmark results that were obtained under good, but not exceptional, pasture and animal management conditions against which less detailed datasets from on-farm records may be evaluated in future research. As expected, heavier slaughter LWs increased enteric CO<sub>2</sub>-eq CH<sub>4</sub> emissions, but these increases in heifers were smaller with higher LWGs during the fattening phase and under the lifetime perspective. Based on the same LWG across the steer's fattening phase, a 32% rise in the slaughter LWs led to an 84% increase in enteric emissions while lifespan emissions when expressed per kg of final LW or per kg born increased by 31% and 72.6%, respectively. Regardless of slaughter LW, larger LWGs during the fattening phase resulted in an average carcass CH<sub>4</sub> efficiency index for heifers and steers of 70.4 and 79.0 kg CO<sub>2</sub>-eq/kg edible protein, respectively. Lastly, assuming conservative and practicable

management of the *B. decumbens* grass pasture examined, all the finishing systems simulated showed potential C neutrality and net-zero C emission profiles when considering total GHGE from animals, pasture, and soil vs the estimated soil C capture over seven seasons at the system level. Thus, these beef grazing systems have the potential to accomplish substantial SOC accumulation through effective land-based removal of atmospheric CO<sub>2</sub> while ensuring sustainable nutritional security and mitigating climate change. Sustainable beef farming systems could ensure socioeconomic-climate justice in the Orinoco River Basin of Colombia.

## Data availability statement

The datasets presented in this article are not readily available because model development and generated datasets in this study are legally protected by the intellectual property rights of CR Eco-efficient Agriculture Consultancy (CREAC<sup>®</sup>) and R. R. Vera Infanzón Private Consultant Services. Requests to access the datasets should be directed to CR-R, c.ramirez@creac.com.au.

## Ethics statement

Ethical review and approval was not required for the animal study because the source of animal data is based on the preservation, reuse, and repurposing of heritage files generated ethically in the Neotropical savanna environment of Colombia.

## Author contributions

CR-R: Oversaw data collection from the animal study, Investigation, Data curation, Conceptualization, Methodology, Writing, Review and Editing. RV-I: Oversaw data collection from the animal study, Investigation, Data curation, Conceptualization, Methodology, Writing, Review and Editing. IR: Methodology, Writing, Review and Editing. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

Author CR-R is the Founder & CEO of CR Eco-efficient Agriculture Consultancy CREAC<sup>®</sup>. Author RV- is the Founder & Director of R. R. Vera Infanzón Private Consultant Services.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be constructed as a potential conflict of interest.

CREAC<sup>®</sup> and R. R. Vera Infanzón Private Consultant Services were involved in the study design, the screening, analysis, and interpretation of data, article writing, and the decision to submit it for publication.

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