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RESEARCH ARTICLE

Carbon footprint of mixed farming crop-livestock rotational-based grazing beef systems using long term experimental data

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Abstract

In the context of ever-growing demand for food and associated concerns regarding the environmental impacts of high-input agricultural systems, there is growing interest in mixed farm enterprises to deliver greater sustainability compared with mono-enterprise production systems. However, assessments of such systems are complex and require high-resolution data to determine the true value and interconnectivity across enterprises. Given the scarcity of information on mixed crop–livestock systems and the difficulties of its analysis, we perform life cycle assessment using temporally high-resolution data (2019–2022) from a long-term experiment in South America to evaluate the 'cradle-to-farmgate exit' greenhouse gas emissions intensities of four rotational crop–livestock systems. Systems evaluated were continuous cropping: 2 years of continuous cropping; short rotation: 2-year continuous cropping plus 2-year pasture; long rotation: 2-year continuous cropping followed by 4-year pasture; and forage rotation: continuous pasture. Emissions intensities for beef throughput were reported as kilograms of carbon dioxide equivalents (CO_2-eq) per kilogram of liveweight gain (LWG) using the Intergovernmental Panel for Climate Change's Sixth Assessment Report (AR6 2021) CO_2 characterisation factors. Point estimate results were found to be 11.3, 11.8, 11.8 and 16.4 kg CO_2-eq/kg/LWG for continuous cropping, short rotation, long rotation and forage rotation, respectively. Emission averages arising from crops, which were separated from animal-based emissions using economic allocation, were 1.23, 0.53 and 0.52 kg CO_2-eq/kg for soybean, wheat and oat, respectively. The inclusion of soil organic carbon stock changes had notable effects on reducing each system's emissions: by 22.4%, 19.2%, 25.3% and 42.1% under continuous cropping, short rotation, long rotation and forage rotation, respectively, when soil organic carbon was included. Given there are few life cycle assessment studies available on such mixed-enterprise 'semi-circular' systems, particularly with novel primary data, this study adds critical knowledge to agri-food-related sustainability literature by addressing environmental issues in complex production systems compared to extant and broad coverage of mono-enterprise systems.

Keywords Carbon footprint · Sustainability · Food security · Grazing

1 Introduction

Demand for agricultural produce is expected to grow between 1.1 and 1.5% per year over the next 10 years driven primarily by an ever-increasing global population (OECD/FAO 2022). Meeting this new market demand presents many broad sustainability challenges, not least optimising agricultural land use to ensure adequate and equitable nutritional provision whilst increasing crop intensity (i.e. yields) and improving herd efficiency through, for instance, higher feed conversion ratios in livestock systems (McAuliffe et al. 2017; OECD/FAO 2022). Global agricultural productivity will need to be increased by 28% over the next decade. To make matters even more complicated, to achieve the Paris

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Climate Change Agreement's reduction targets related to agriculturally sourced greenhouse gas (GHG) emissions, production increases cannot be solved globally simply by increasing quantities of material inputs (e.g. inorganic fertilisation; imported feed) as observed in 'conventional' or intensive farming practices.

The livestock sector is thought to be responsible for ~11% of anthropogenically induced GHG emissions globally (FAO 2023). Animal feed–related GHG emissions contribute considerably to both monogastric and ruminant production systems, which are predominantly associated with direct and indirect soil emissions (i.e. nitrous oxide, N_2O, and carbon dioxide, CO_2; McAuliffe et al. 2017) as well as direct and indirect land use change (e.g. deforestation and soil inversion CO_2 emissions). Depending on the level of pre- and post-farmgate manufacturing and processing, high proportions of system-scale GHGs are typically produced at the farm level as demonstrated by one of the few extant studies which explores the full supply chain of beef systems (Asem-Hiablie et al. 2019). In Uruguay, meat represented 18% of total exportations in 2023 (Uruguay XXI 2023), thus demonstrating the importance of domestic animal-based agricultural enterprises. According to the National Inventory Report (SNRCC - MA 2021), which uses Global Warming Potential over a 100-year time-horizon (GWP_{100}), emissions from enteric fermentation in livestock, predominately from ruminants, accounted for 45.7% whilst emissions of N_2O from managed soils accounted for 20.3% of the sector's total emissions. Most Uruguayan ruminant livestock production occurs on natural grasslands (NG, i.e. native pastures with low, or no, inputs and generally extensive land occupation; de Faccio Carvalho et al. 2021). However, due to the aforementioned increase in food demand globally (in addition to higher international prices of material input commodities driven by global shocks, e.g. the war in Ukraine; Rawtani et al. 2022), Uruguayan farmers are diversifying their activities. For instance, non-native pasture species are being introduced to swards to improve animal performance and soil quality (García-Préchac et al. 2004) whilst potentially reducing their GHG emissions via lower nitrogen content in excreta (Soteriades et al. 2019) and/or increased digestibility in forage (Takahashi et al. 2019). Mixed crop–livestock systems fit into a (semi-)circular economy concept by producing crop on-farm to either sell directly or feed animals, rather than purchasing it externally. Such approaches reduce feed purchase risks with respect to market volatility (Mustafa et al. 2023) and have a knock-on effect of reduced land use and resource depletion (e.g., rock phosphate) as most feed is produced using the same farm's by-products (e.g. manure and excreta producing natural soil nutrient regeneration).

Vast amounts of scientific publications address environmental impacts associated with livestock production using life cycle assessment (LCA) (de Vries and de Boer 2010; de Vries et al. 2015; Takahashi et al. 2019). However, addressing environmental impacts through LCA in crop–livestock systems is a challenge due to inherent complexities surrounding shared land producing multiple co-products exacerbated by scarce primary data availability. Furthermore, complexities surrounding soil organic carbon (SOC) sequestration and how to evaluate soil carbon dynamics in agricultural LCA is also problematic (Goglio et al. 2015). Crop–livestock systems represent 17% of the total agricultural area in Uruguay (DIEA - MGAP 2022), meaning there are substantial opportunities to simultaneously explore environmental trade-offs of rotational systems whilst adding to the knowledge base both globally (of mixed-farming systems) and nationally (of underrepresented nations with high-quality life cycle inventory analysis (LCI) data). The primary aim of this work, therefore, was to compare 'semi-circular', multi-produce cattle rearing systems widely adopted in Uruguay with a 'traditional' forage-only cattle system, whilst analysing their potential impacts related to climate change. To achieve this, we evaluated 'cradle-to-farmgate exit' GHG emission intensities of four mixed crop–livestock systems in Uruguay using GWP_{100} (IPCC 2019a, 2021) with different intensities in land use over a 3-year period (2019–2022). As the use of GWP has been questioned in terms of appropriate allocation of environmental burden in livestock systems (Manzano et al. 2023), in addition, we evaluated the methodological effect of using an alternative climate-related metric, specifically global temperature change potential over a 100-year time horizon (GTP_{100}; based on the modelled temperature impact of different gases relative to CO_2 at a specified time following an emission pulse) using IPCC's (2021) GTP characterisation factors which bestow substantially lower CO_2-eq coefficients to biogenic methane (~6 compared to GWP_{100}'s ~27).

2 Materials and methods

This study follows international protocols to calculate carbon footprints using an LCA approach as recommended by BSI PAS 2050 (2011) and ISO 14044 (ISO 2006) to compare emissions intensities of different pasture-based cattle production systems integrated with cropping systems (Segura et al. 2023). Typically, as opposed to other novel methodological applications described by McAuliffe et al. (2020), LCA comprises four steps: (1) goal and scope definition, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA) and (4) interpretation (e.g. sensitivity and uncertainty analyses). We covered the entire production cycle in the case of crops from winter 2019 to summer 2022 (Southern Hemisphere seasons). In the case of livestock production, however, the system boundary focusses on post-weaning stages of the cattle life cycle as the systems under investigation raise cattle at various growth stages (i.e. rearing and finishing). Multi-produce systems, which will be described in detail in Section 2.1, are entirely interlinked; in other words, crops receive nutrients from grazing cattle whilst the same animals receive feed from crops, thereby making each output a co-product at the system boundary scale.

2.1 Study site

The long-term pasture crop rotation experiment adopting no-tillage management was installed in 1995 at the 'Palo a Pique' experimental platform in Treinta y Tres (33°16′ S, 54°29′ W), a multifunctional farm-scale trial supported by the National Institute of Agricultural Research (INIA) in Uruguay (Fig. 1). The annual mean (±SD) accumulated rainfall in the experimental site from 1995 to 2022 was 1249 ± 72.0 mm per year. The mean, maximum and minimum air temperatures for the same period were 23 ± 0.1 °C and 11 ± 0.6 °C, respectively. The experimental design of each system is shown in Table 1 (Pereyra-Goday et al. 2022).

It should be noted that measurements and subsequent LCI development in this paper utilises data from the third phase of the Palo a Pique Long-Term Experiment ('Land Expansion and Livestock Intensification'), which started in 2019. In 2019, an experimental redesign was carried out to better-reflect local, 'on the ground' farming as described by Rovira et al. (2020). Relevant changes occurring during this transition were the relocation of the permanent pasture system, the addition of grassland as a support area (i.e. a 'safety net' of land dedicated to minimising effects of potential biotic and abiotic stresses) in each system, and the inclusion of unique livestock production strategies for each system which reflects typical farming practices in the study site's region.

The continuous cropping system (CC, 12 ha) operates under a rotation with two crops per year. Continuous cropping does not rotate with pastures, but it is complemented with an external area (6 ha) of an improved pasture comprising tall fescue (*Festuca arundinacea* L.), birdsfoot trefoil (*Lotus corniculatus* L.) and white clover (*Trifolium repens* L.) which is re-seeded every 5 years with the same species to ensure sustained establishment. The short rotation (SR, 24 ha) alternates 2 years of crop production identical to CC

Figure 1 Palo a Pique long-term experiment, Treinta y Tres, Uruguay. The picture shows several plots of crop–livestock systems. Credits: M. Oxley.

Table 1 Pasture and crop sequence for each rotation at Palo a Pique long-term experiment, Treinta y Tres, Uruguay. P: Pasture follows by the age of the pasture (1 to 2 in short rotation and 1 to 4 in long rotation). Note that primary data from years 4 to 6 has not yet been collected, but due to the rotational nature within each system on an annual basis, the full 6-year cycle can be represented from primary data collected during years 1–3.

Rotation	Purpose of crop phase	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Continuous cropping (CC)	Crop	Oat/sorghum	Black oat/soybean	Wheat/sorghum			
	Grazing	Oat/sorghum	Ryegrass/moha	Oat/sorghum			
Short rotation (SR)	Crop	Idem CC	Idem CC	Wheat + P1	P2		
	Grazing	Idem CC	Idem CC	P1	P2		
Long rotation (LR)	Crop	Idem CC and SR	Idem CC and SR	Wheat + P1	P2	P3	P4
	Grazing	Idem CC and SR	Idem CC and SR	P1	P2	P3	P4
Forage rotation (FR)	Grazing	Fescue	Fescue	Fescue	Fescue	Fescue	Fescue

followed by 2 years of grass–legume pastures utilising Yorkshire fog (*Holcus lanatus* L.) and/or Italian ryegrass (*Lolium multiflorum* L.) interspersed with red clover (*Trifolium pratense* L.) at a target coverage rate of 50%. The long rotation system (LR, 36 ha) also alternates 2 years of crops identical to CC and SR followed by 4 years of grass–legume pastures composed of tall fescue, birdsfoot trefoil and white clover. The fourth system, forage rotation system (FR, 24 ha), is seeded with tall fescue and does not rotate with arable crops just between forage (tall fescue) paddocks.

Each crop–livestock system (i.e. systems that rotate crop and pastures: CC, SR and LR) was split into two halves within paddocks (Table 1): one half for human-edible crop production (defined as 'crop area'), which was seeded with oat (*Avena byzantina* L.), black oat in CC (*Avena strigosa*) and wheat (*Triticum aestivum*) in winter, and soybean (*Glycine max*) and sorghum (*Sorghum sudanense* L.) in summer. The remaining areas were allocated to grazing cattle (defined as 'livestock area') which were seeded as follows: Italian ryegrass and oat in winter, with sorghum and moha (*Setaria italica* L.) in the following summer. Winter crops and pastures were sown between March and June and typically harvested in November. Summer crops were planted in October and November with harvesting occurring in April. Cover crops (i.e. black oat) were harvested for hay in October thus providing additional feed provision for cattle. For CC, SR and LR, animals enter their respective experimental farm platforms in April or May each year and remained for 1 year (rearing animals) or, in the case of finishing animals, until delivery of target weights for the slaughterhouse. GHG emissions were calculated for all animals using IPCC (2019a, b) equations using an individual-animal approach originally detailed in McAuliffe et al. (2018) which were included in the LCI to ensure that systems with poorer performing animal's GHGs were captured (e.g. particularly in the case of animals spending >1 year on-farm). As reported by Pereyra-Goday et al. (2022), CC system focused on rearing male calves with 32 reared in 2019, 34 in 2020 and 35 in 2021. In SR, rearing heifers were managed, with 44, 49 and 46 reared in 2019, 2020 and 2021, respectively; finishing cattle during May and September, with 15, 10 and 10 cattle finished in 2019, 2020 and 2021, respectively. In LR, the objective was rearing male calves and finishing steers over a period of 18 months with 50 male calves (~6 months old) allocated to LR in 2019, 2020 and 2021. FR was the only system that begins at the end of the spring (Nov–Dec) with yearling steers. The objective of the livestock strategy in FR was to produce a finished steer ready for slaughter in 12–15 months (47, 30, 35 and 41 steers entered the system in December 2018, December 2019, November 2020 and November 2021, respectively). The four systems maintained British beef breeds (Aberdeen Angus and Hereford–Angus cross), randomly distributed. Data pertaining to animal performance is shown in Table 2.

Importantly, the experiment lacks complete replications for the full duration of the trial; however, due to the statistical design of the four individual systems, all phases of rotations occur each year represented by paddocks of 3 ha in CC, SR and LR, thus enabling modelling of the entire rotations by proxy. In other words, the systems are assumed to be operating at steady state over 6 years based on 3 years of high-resolution primary data collection and analysis. Forage rotation's 24-ha area was divided into five paddocks of 4.8 ha each corresponding with tall fescue seeded in 2013 (9.6 ha), 2014 (9.6 ha) and 2020 (4.8 ha). Each rotation has an auxiliary 'support area' of natural grassland (NG) to ensure the animals have grazing access under conditions outside of a farmers' control (e.g. during periods with low forage availability in the systems due to (a)biotic stressors), thus ensuring the animals are maintained independently within each system (i.e. each system comprising livestock has its own dedicated area to avoid cross-system 'contamination'). The proportion of NG area (in addition to primary seeded pasture land occupation) was 33, 29, 26 and 33% of the total area for CC, SR, LR and FR, respectively. Cattle grazed annual forage crops (Italian ryegrass, oat, sorghum and moha), permanent pastures (in forage and crop areas), permanent improved pasture (in CC) and NG. Detailed information about the experimental design, management and yields can be found in Pereyra-Goday et al. (2022) and Rovira et al. (2020).

Table 2 Animal performance average (2019–2022) in pasture crop rotation at the Palo a Pique long-term experiment in Treinta y Tres, Uruguay (ADG: average daily gain; TOF: time on farm as days).

Pasture crop rotation	Entry weight (kg/animal)	Exit weight (kg/animal)	ADG (kg/animal/day)	TOF
Continuous cropping—calves	190±23.6	377±35.9	0.59±0.264	330±22
Short rotation—heifers	156±19.7	333±31.5	0.58±0.197	316±8
Short rotation—cows	473±51.8	529±51.2	0.59±0.308	102±21
Long rotation—calves	185±26.6	361 ±36.8	0.58±0.153	337±39
Long rotation—steers	369±34.1	511±37.2	0.65±0.179	224±25
Forage rotation—steers	313±65.5	497±45.1	0.65±0.316	279±6

2.2 System boundaries and functional unit

A schematic of system components and boundaries is provided in Fig. 2. As mentioned above, the two subsystems (livestock and crop) are interconnected through livestock grazing on permanent pastures whilst simultaneously receiving and providing nutrients to the crop area. This is accomplished via the circularisation of nutrients from urine and dung, and the production of sorghum and hay in crop areas to feed animals in the livestock area.

The boundary adopted was 'cradle to farmgate exit' as described by McAuliffe et al. (2018) which focused on finishing beef systems. The logic behind this is that the suckler herd is not part of Palo a Pique long-term experiment, and therefore there is little-to-no data available and furthermore, the objective of this study was to quantify environmental impacts of the mixed crop–livestock trial's systems and their potential differences in terms of GHG emissions, which would have been diluted if the suckler herd was included using secondary data (e.g. commercial LCA databases), thereby obscuring differences between common farming practices in the study site's region.

Regarding crop production, the entire cycle from seed production to harvest was considered, as well as all upstream emissions associated with material inputs such as fertiliser, in line with the crop–livestock systems (CC, SR, and LR; Fig. 2). Each crop cycle (summer and winter, respectively) takes about 6 months under regional, seasonal climatic conditions. All inputs (e.g. fertilisers, pesticides, etc.) and outputs (i.e. GHG losses to air and co-products) related to each production process were quantified, whereas farm buildings and infrastructure processes were excluded as they are considered negligible (McAuliffe et al. 2018) in certain agricultural systems, particularly at the study site where animals remain outdoors all year with the exception of calving, which is outside the current system boundary.

Given that the assessed systems have different outputs (four crops, including grass, and beef liveweight gain (LWG)), the functional unit considered was (1) 1 kg of product obtained, with results presented as kilograms of carbon dioxide equivalent (CO_2-eq) per (a) kilogram of LWG, (b) kilograms of soybean, (c) kilograms of oat and (d) kilograms of wheat; and (2) 1 ha. Given complexities surrounding disaggregating GHG emissions between animals and plants (i.e. they both 'share' the same land and both produce multiple co-products beyond the farmgate; Guinée et al. 2004), livestock production was separated from crop production using farm records of sales (i.e. the primary source of income for each of the systems) and subsequently economic allocation (see Section 2.4 for further information).

2.3 Inventory analysis and impact assessment

The majority of model parameters utilised in this study were collected as primary trial-based data. All animals were weighed every 30 days and individual performance was calculated as daily LWG assuming linear growth between weighing events. Three grazing exclusion cages (0.4 × 1.0 m) were used per grazing paddock (3–5 ha) to estimate daily pasture growth as kilograms of dry matter (DM) per hectare per day every 30 days according to the methodology proposed by Lynch (1947). Crude protein (CP, %), metabolisable energy (ME, MJ/kg DM) and neutral detergent fibre (NDF, %) were analysed monthly and analysis was conducted using standard methods (AOAC 1990) in the Animal Nutrition Laboratory of INIA La Estanzuela (Colonia, Uruguay). Annual SOC stock rate changes were estimated using best available measured data between 2015 and 2021

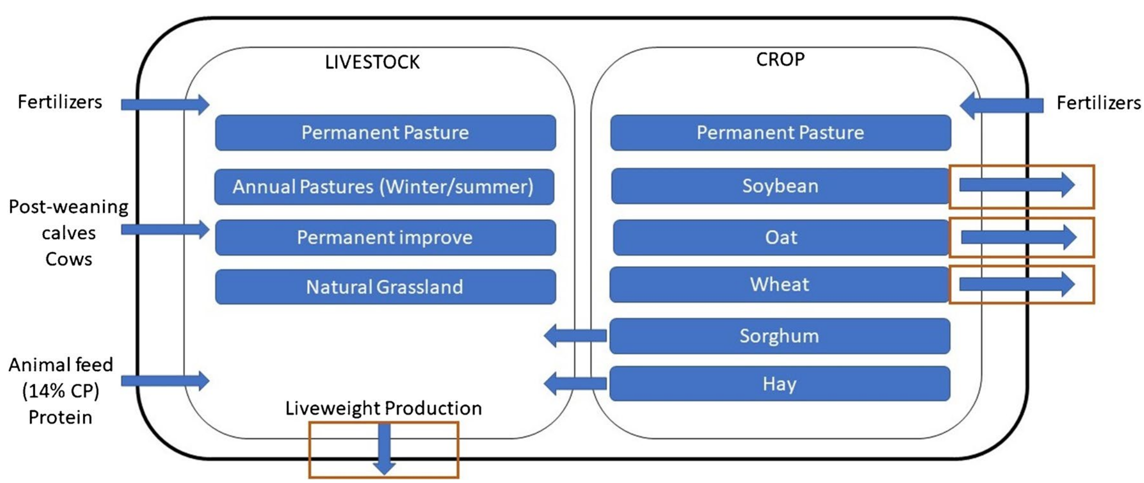

Figure 2 Pasture crop rotation components and boundaries at Palo a Pique. The external black line represents system boundary of the study. Red rectangles and arrows show outputs from the long-term experiment in Treinta y Tres, Uruguay (i.e. produce sold to downstream stakeholders).

(30 cm depth), as described by Pravia et al. (2019), and then multiplied by the number of experimental years (i.e. three) for each paddock. Soil samples were analysed according to Wright and Bailey (2001) in the Plant, Soil and Water Laboratory in INIA La Estanzuela (Colonia, Uruguay).

Information of all inputs in each system (2019–2020, 2020–2021 and 2021–2022) are reported in Table 3. The LCI was calculated from data reported by Pereyra-Goday et al. (2022) and from the experiment's management records. Background processes such as transport-based emissions were sourced from the *ecoinvent* database (Wernet et al. 2016). Embedded emissions associated with the production of fertilisers, pesticides, seed production and minor quantities of supplemental feed were sourced from geographically representative data provided by INIA (2022). Emissions from livestock, pastures and crops were estimated using IPCC's (2019b) Tier 2 approach. GHG emissions arising directly and indirectly from animals were calculated for each period between two weighing intervals (30 days between each weighing event) using data from individual animals within the LCI. Pasture quality was also measured during each interval to align CP (%) and digestible energy (DE, %) with temporal growth rates (Supplementary Material 1). Once the LCI was conducted capturing temporal variability, all GHGs were summed to obtain a value of total emissions per system to provide clear interpretation. Emissions from pastures and crops were additionally calculated separately and summed to obtain the total of each system. Specific equations and constants used are detailed in Supplementary Material 2.

Lastly, GHG emissions were estimated according to IPCC (2019a, b) refinements using the global warming potential over a 100-year time horizon (GWP_{100}) characterisation factors detailed in the Sixth Assessment Report (AR6; IPCC 2021). All systems were modelled in SimaPro V9.3.0.3 (PRé Consultants 2022), and LCIAs were subsequently interpreted using the same software (details regarding interpretation provided in Section 2.4). Within SimaPro's latest IPCC GWP_{100} impact assessment (excluding carbon feedback), biogenic CH_4 and N_2O are respectively assumed to have 27.2 and 273 times greater climatic impacts than CO_2 (IPCC 2021; PRé Sustainability).

2.4 Interpretation

For sensitivity analyses, given the unique mixed-farm 'semi-circular' systems, we presented results primarily on an output basis disaggregated by each commodity's total revenue across the 3 years of primary data collection. Based on best practice and evidence that allocation can have a profound

Table 3 Inventory of all major material inputs and outputs for each pasture crop rotation (3 years of data, 2019–2022) at the Palo a Pique long-term experiment, Treinta y Tres, Uruguay (CP: crude protein).

Parameter	Unit	Continuous cropping	Short rotation	Long rotation	Forage rotation
Total area (include natural grassland area)	ha	24	34	56	36
Pasture crop rotation area	ha	12	24	36	24
Permanent improved area	ha	6	0	0	0
Natural grassland area	ha	6	10	20	12
Yield					
Soybean	kg	21,276	22,335	24,840	–
Wheat	kg	13,272	16,125	15,531	–
Sorghum	kg	29,772	33,903	31,758	–
Oat	kg	–	10,896	13,074	–
Liveweight production	kg	19,659	27,610	48,796	29,792
Fertiliser					
N	kg	3547	5337	5474	11,615
P (P_2O_5)	kg	2759	3623	3897	2045
K (K_2O)	kg	1572	1981	1916	432
S	kg	191	227	335	0
Pesticides (herbicides and insecticides)	L	533	634	625	113
Seeds	kg	4018	5235	6229	393
Diesel for machinery	L	1145	1727	1724	654
Feed for animals					
Protein (48% CP)	kg	385	846	4293	–
Supplement (14% CP)	kg	–	–	8327	16,280

effect on interpretation (Rice et al. 2017), we also report decomposed emissions between co-products using mass allocation to separate multifunctional-system outputs (i.e. the total yield of each product leaving the farmgate).

In addition to testing allocation assumptions, recent work has demonstrated the effect of functional unit choices on agri-food LCA results (e.g. McAuliffe et al. 2023a, b; Manzano et al. 2023) in the context of nutritional value (e.g. protein), and Zira et al. (2021) who explored differences between mass/volume and area-based functional units. As each system has a different land occupation and various combinations of co-products (or indeed a single commodity in the case of FR), we also calculated LCIA on an area basis (1 ha) and reported the results to add novel evidence to earlier work carried out on agricultural functional units, particularly given the low representation of mixed crop–livestock systems in the sustainability literature combined with the interconnectivity between each (co)product as discussed at the beginning of this section.

Given ongoing debates concerning LCA subjectivity and the effect of impact assessment method choices (e.g. Lynch 2019), following the procedure proposed by McAuliffe et al. (2023b) we also calculated global temperature change potential over a 100-year time horizon (GTP_{100}; based on the modelled temperature impact of different gases relative to CO_2 at a specified time following an emission pulse) using IPCC's (2021) GTP characterisation factors which bestow substantially lower CO_2-eq coefficients for biogenic methane (~6 compared to GWP_{100}'s ~27). Carbon dynamics were tested for sensitivity by analysing each system with and without SOC uptake included.

Finally, a Monte Carlo analysis was carried out to assess uncertainties both within (i.e. 95% confidence intervals) and across systems using pairwise iterations in the latter case. Monte Carlo simulations were conducted within SimaPro V9.3.0.3 (Pré Consultants 2022), and each assessment was run under 1000 permutations. Distributions of individual GHGs were calculated manually using IPCC (2019a, b) emission factor ranges (see McAuliffe et al. 2018's supplementary material for individual gas's distribution shapes), whilst *ecoinvent's* Pedigree Matrix was used to determine uncertainties associated with background (i.e. embedded) emissions.

3 Results and discussion

3.1 Intersystem comparison

Productivity and subsequent yields were found to be different among systems (Pereyra-Goday et al. 2022). From May 2019 to April 2022, systems that included high proportions of rearing animals (CC and SR) produced higher levels of LWG per hectare than finishing animals due to the typical growth curve of beef cattle (CSIRO 2007). LWG was 13% lower in LR (369 kg/ha/year) and 26% lower in FR (310 kg/ha/year) relative to CC and SR (426 and 418 kg/ha/year, respectively). Crop production per hectare was influenced by the presence of the pasture phase in the rotation and was consequently higher in LR and SR than CC. Climatic conditions (drought and water excess) during the experimental period explain resultant high variability in wheat and oat yields. Crop yield (t/ha/year) for soybean was 2.36 ± 0.136, 2.48 ± 0.348 and 2.76 ± 0.227 in CC, SR and LR, respectively, whereas crop yield for wheat was 2.21 ± 2.051, 2.68 ± 2.015 and 2.59 ± 2.022 in CC, SR and LR, respectively. Oat yield was 1.82 ± 0.871 and 2.18 ± 0.028 to SR and LR.

Although area (i.e. land use/occupation) is not necessarily relevant in agri-food LCAs (e.g. comparing housed monogastric livestock systems with similar feed rations), in the current case (i.e. mixed crop–livestock systems), total emissions intensity reported as kilograms of CO_2-eq per hectare allows the expression of impacts from the viewpoint of local producers (Picasso et al. 2014). Values reported as emissions per hectare were 2795, 2734, 2727 and 2607 kg CO_2-eq/ha/year for CC, SR, LR and FR, respectively. These values included emissions arising from both crop and livestock areas of each farming system.

The minor differences observed among systems could be explained by the fact that the crop livestock systems, when they are analysed, present trade-offs to reduce negative impacts of crop or livestock agriculture; namely, the most efficient livestock strategy (CC) in terms of low GHG emissions per kilogram of LWG is associated with a rotation with more intensive utilisation of synthetic inputs and the highest intensity of land use without pastures in rotation (reflected by the lowest carbon restoration prediction as will be discussed in Section 3.3). Conversely, the least efficient livestock strategy (finishing cattle in LR and FR) is associated with a rotation with fewer inputs and the inclusion of pastures in rotation, as described by Rovira et al. (2020). The values obtained in the current study are similar to others reported by Picasso et al. (2014), where values of emissions intensity per area were within the range of 2000 to 2500 kg CO_2-eq/ha, exclusively for livestock systems. The authors also identified a trend of decreasing emissions per hectare when productivity per hectare increased, a trend supported by Styles et al. (2018) in the context of dairy intensification, albeit with caveats such as displaced production which may reduce local emissions whilst increasing net emissions as the trading nation may be less environmentally efficient than domestic production.

Total emissions intensity per kilogram of product under economic allocation is provided in Table 4. In general, LWG leaving the farmgate provided 85–94% of the total revenue in systems which rotated with crops, whereas it was 100% in

Table 4 Emissions (kg CO_2-eq/kg of liveweight gain, soybean, oat and wheat), using economic allocation for each pasture crop rotation at the Palo a Pique long-term experiment, Treinta y Tres, Uruguay.

Product	Continuous cropping	Short rotation	Long rotation	Forage rotation
Liveweight	11.3	11.8	11.8	16.4
Soybean	1.36	1.24	1.01	–
Wheat	0.61	0.54	0.43	–
Oat	–	0.57	0.47	–

FR. Total revenue from crops (soybean, oat and wheat) was 15% in CC, 11.7% in SR and 6% in LR (see Supplementary Material 3). Economic prices of crops were equal among systems, as harvested crops were sold to the same industry, and the values changed only across years. However, livestock prices were different according to date of sale, animal category and final liveweight. For perspective, kilograms of CO_2-eq per US$ was 2.4, 1.8, 1.7 and 1.5 under CC, SR, LR and FR, respectively.

According to Pelletier et al. (2015), economic allocation is an effective way to reflect the hierarchy in systems where there are multiple co-products by appropriately assigning responsibility for the associated environmental burdens to the primary economic outputs, which largely aligns with the function of agricultural systems. In other words, economic allocation is generally the preferred approach for biological systems such as primary food production (and beyond, pending the system boundary). Recently, Kyttä et al. (2022) described economic allocation as an accurate method, particularly when utilised in livestock systems, as it reflects the reality that drives the production system as described above and discussed in more detail by Ardente and Cellura (2012). In the current study, LWG is the main product under the hierarchical logic proposed by Pelletier et al. (2015), and it was therefore targeted as the main product for deep interpretation.

Emissions intensity was reported as kilograms of CO_2-eq per kilogram of LWG; apart from FR, impacts were similar among systems, regardless of livestock strategy. Results are consistent with the aforementioned trade-offs between livestock strategies and crop rotation interactions. Results reported in terms of CO_2-eq per kilogram of LWG were similar to others reported by Picasso et al. (2014) who investigated backgrounding and finishing systems in a review of different production systems in Uruguay with different feed rations (6.9–16.7 kg CO_2-eq/kg LWG); Dick et al. (2015) compared extensive versus intensive systems in Southern Brazil (9.2–22.5 CO_2-eq/kg LWG) and Ruviaro et al. (2015) for systems including cow-calf operation (18.3–42.6 CO_2-eq/kg LWG). Most comparable cases considered grazing animals with the inclusion of legumes, fertilisation and grazing management. On the other hand, results obtained by McAuliffe et al. (2018) showed values of 16–20 kg CO_2-eq/kg LWG in grazing systems in Southwest England for finishing cattle (steers and heifers equally split within three herds) with a housing period during winter under humid temperate conditions.

Crop production results obtained should be interpreted cautiously due to oat and wheat being highly affected by climatic conditions during the trial, as reported by Pereyra-Goday et al. (2022). Shrestha et al. (2020) conducted an LCA of wheat rotations and evaluated different scenarios of allocation for wheat production. Their study showed similar values to our findings: 0.79 kg CO_2-eq/kg of wheat under economic allocation and 0.62 kg CO_2-eq/kg of wheat under mass allocation. The same authors conclude that rotations and diversification in crop production systems, combined with the necessity to understand synergies and trade-offs when evaluating environmental impacts of crops, require deeper exploration in the context of global GHG reduction ambitions (e.g. the Paris Climate Change Agreement). Bearing this in mind, our results could be considered as a novel evidence base for values of kilograms of CO_2-eq per kilogram of wheat, soybean and oat, as management in the four trials reported herein is similar to management carried out on commercial farms in the study region (Rovira et al. 2020).

3.2 Intra-system emissions

The process contribution per kilogram of LWG is presented in Table 5. The largest share of emissions per kilogram of LWG was derived from enteric fermentation, which presents 52–72% of total livestock GHG emissions. Similar values were reported by several authors, referring to grazing ruminants with direct deposition of manure in the field (de Figueiredo et al. 2017; Dick et al. 2015; Picasso et al. 2014). Conversely, the proportion of enteric fermentation's emissions were lower on a mass-based functional unit in systems that included manure management (Ogino et al. 2007; Weiss and Leip 2012).

The second largest source of emissions was direct N_2O from soils followed by fertiliser production, contributing between 8.4–14.2% and 8.4–16.1%, respectively. These results could be explained by the dependence of fertilisers in all crops. Naturally, Uruguayan soils are deficient in phosphorus (P) and nitrogen (N) (Madeira 2019), which drive the use of fertilisers in crops every year. For instance, FR showed higher N_2O emissions compared to the other systems, due to the use of 184 kg N/ha/year, as detailed in Table 3.

3.3 Soil organic carbon inclusion

Given climate-focused actions to reduce emissions in line with achieving net-zero carbon economies (CIEL 2020),

Table 5 Processes contribution (kg CO_2-eq/kg of liveweight gain) for each pasture crop rotation at the Palo a Pique long-term experiment, Treinta y Tres, Uruguay.

Process	Continuous cropping	Short rotation	Long rotation	Forage rotation
Enteric fermentation (CH_4)	7.49	8.62	7.30	8.53
Direct emissions (N_2O)	1.06	1.00	1.42	2.63
Indirect emissions (N_2O)	0.32	0.24	0.33	1.37
Fertiliser use	1.34	0.99	1.59	2.32
Inputs (seeds, fuel, feed, pesticides)	0.40	0.25	0.39	0.17
Urea emissions	0.12	0.08	0.12	0.63
Manure management (CH_4)	0.01	0.01	0.01	0.01
Manure management (N_2O)	0.56	0.65	0.59	0.72
Total	11.3	11.8	11.8	16.4

Table 6 Emissions (kg CO_2-eq/kg of liveweight gain, soybean, oat and wheat), using economic allocation and soil organic carbon mitigation for each pasture crop rotation at the Palo a Pique long-term experiment, Treinta y Tres, Uruguay.

Product	Continuous cropping	Short rotation	Long rotation	Forage rotation
Liveweight	8.77	9.44	8.81	9.45
Soybean	1.06	1.00	0.76	–
Wheat	0.47	0.44	0.32	–
Oat	–	0.46	0.35	–

in order to consider the potential of mitigation through SOC sequestration, we included SOC stock change rates per year. Significant changes were obtained when SOC sequestration was included (Goglio et al. 2015). The mitigation potential through SOC sequestration during May 2019–April 2022 was 22.4, 19.2 and 25.3% for CC, SR and LR, respectively. FR had the highest value of carbon uptake, perhaps unsurprisingly given the additional carbon inputs from faeces and DM production, thus potentially off-setting emissions up to 42.1%. That being said, potential GHG off-setting as a percentage showed similar values among CC, SR and LR; as a result, it is important to consider the total emissions (i.e. farm-scale rather than per unit of produce) when considering local mitigation measures and/or technologies. This value was substantially lower in CC (201,214 kg CO_2-eq) compared with SR (229,622 kg CO_2-eq), LR (458,186 kg CO_2-eq) and FR (281,509 kg CO_2-eq). In terms of kilograms of CO_2-eq mitigated through SOC sequestration, the best performance was obtained in FR and LR, which supports results presented by Teague et al. (2016).

Emissions intensity (kg CO_2-eq/kg product) considering economic allocation and SOC mitigation is presented in Table 6. Although extant literature recommends 10 years between two soil samples to estimate SOC variation (Goglio et al. 2015), in our study we used 6 years. This is arguably a limitation of our study; however, we assessed our assumption based on best practice by reporting emissions with (baseline results) and without SOC stock changes per year.

SOC sequestration in LCA is difficult to quantify accurately as historical land use is often unknown and carbon-stock changes are frequently excluded from system boundaries (Goglio et al. 2015). Results obtained can be different depending on scale (i.e. farm, plot, life cycle), with a greater geographical scope generally associated with greater heterogeneity in soil properties and thus the soil's potential as a carbon sink (Soussana et al. 2010). In this regard, results could show a wide variability according to soil quality and structure, farm type, climate (and microclimates) as well as farm management, as explained by Lal (2004). Results presented here show the potential mitigation of GHG at the farm level but cannot be extrapolated to broader geographic regions. Picasso et al. (2014) estimated mitigation in GHG emissions through SOC sequestration of 17% in livestock systems in Uruguay, whereas Dollé et al. (2011) reported mitigation of emissions in livestock systems in France of 24 and 53% including SOC sequestration. It should be noted, however, that SOC stock changes across studies are typically incomparable due to different methodological options for the calculation of soil carbon uptake as demonstrated by Mogensen et al. (2014).

3.4 Methodological comparisons

Figure 3 demonstrates estimations of uncertainty through Monte Carlo simulations, considering SOC mitigation, with a confidence interval of 95%. Differences detected across systems were not significant when calculated under pairwise permutations. Interestingly, and supportive of the earlier discussion of SOC stock change uncertainty, pairwise calculations to test the inclusion versus the exclusion of SOC were significant in all comparisons ($p < 0.05$). However, readers should be aware that the uncertainty results are dependent on numerous factors as outlined above which are difficult to capture using Monte Carlo analysis, and therefore we are

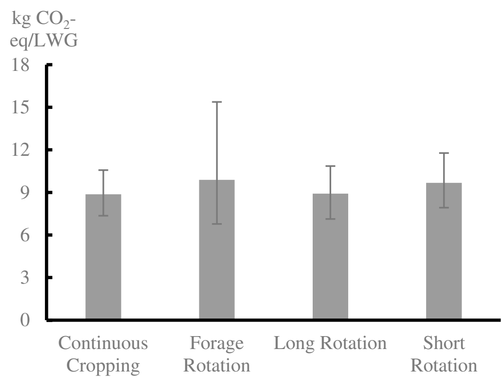

Figure 3 Results of Monte Carlo simulations for each pasture crop rotation at Palo a Pique long-term experiment, Treinta y Tres, Uruguay. Error bars represent 95% confidence intervals. LWG: liveweight gain; CO_2-eq: CO_2 equivalent.

simply reporting our findings rather than claiming SOC can truly reduce emissions by nearly half in all systems.

3.5 Sensitivity analysis

3.5.1 Mass allocation

Results for our sensitivity analysis to allocation methods showed differences in allocation of emissions to each product in each system. In crop production, variations in emissions' distributions were detected. For the three systems on average, net emissions increased by 87–95%, 71–79% and 82–88% for wheat, soybean and oats, respectively, when they were analysed considering mass allocation compared to economic allocation. Emissions for liveweight decreased considerably when mass allocation was tested, being 59, 57 and 14% lower for CC, SR and LR, respectively. Conversely to economic allocation which is predicated on the value of a given product either at a point in time or as a rolling average, mass allocation does not consider value which could arguably reflect the quality of throughput (Kyttä et al. 2022). Within our study, this is a central aspect as mixed pasture–crop rotations evaluated herein produced different crops (soybean, wheat and oat) and LWG (meat), which have different nutrient profiles, e.g. protein content, structure (e.g. limiting amino acids and anti-nutritional factors such as phytates in crops) and, ultimately, digestibility (McAuliffe et al. 2023a, b). The diverging results of the different allocation procedures underline the importance of avoiding arbitrary choices and selecting an appropriate method that fits the objectives of the analysis (Michiels et al. 2021). An alternative approach could consider nutrient density content of outputs in each system to evaluate environmental impacts from a nutritional standpoint as performed by Lee et al. (2021) for suckler beef. However, this would require substantial nutritional analysis of all outputs of the system, which was not possible in the current study based on primary data.

3.5.2 Global temperature change potential

As discussed in Section 2, a sensitivity analysis was carried out to test differences between GTP_{100} and GWP_{100}, or the climate change impact as quantified by the predicted change in radiative forcing and relative temperature, respectively, over a 100-year period, considering the significant emissions of biogenic methane originating from enteric fermentation in ruminants, and the ongoing debate regarding GWP_{100} due to its potential tendency to overestimate methane's impacts (McAuliffe et al. 2023b). Values to convert CH_4 to CO_2-eq were 5.38 and 27.9, whereas values to convert N_2O were 233 and 273 under GTP_{100} and GWP_{100} for both gases, respectively. As explained by Reisinger and Ledgard (2013), alternative impact assessments such as GTP_{100} significantly change the balance between CH_4 and N_2O and could change the overall cost and associated profitability for farmers if a price was applied to agricultural emissions (e.g. carbon credits). Understandably given the drastically different CH_4 characterisation factors, enteric CH_4 is the most affected GHG under contrasting metrics. As a result, the relative proportion of CH_4 emissions in the overall emissions intensity was reduced by 27.6, 34.6, 24.2 and 17.5% in CC, LR, SR and FR, respectively. The relative contribution of N_2O to the overall emissions intensity increased on average by 11% under GTP_{100} compared to GWP_{100}. Total emissions intensities per kilogram of LWG were reduced by 4.7, 4.3, 5.2 and 8.5 kg CO_2-eq/kg LWG in CC, LR, SR and FR, respectively (i.e. emissions intensities as kg CO_2-eq/kg LWG using GTP were 58.4, 63.5, 55.9 and 48.2% lower than emissions using GWP_{100} applied to CC, SR, LR and FR). For a country like Uruguay, where the agricultural sector represents the most important source of GHG emissions, the use of alternative metrics could elucidate novel GHG emission mitigation and/or off-setting strategies by demonstrating that gaseous emissions other than CH_4 also require urgent abatement attention (N_2O in the case of agriculture; Takahashi et al. 2019). For example, agriculture's contribution to national emissions reduced from 73% of total GHGs under GWP_{100} to 55% under GTP_{100} (SNRCC - MA 2021).

However, it is important to note that there is no 'right' metric: an impact assessment should be chosen to answer a specific research question (e.g. if individual gaseous temporal changes are a study's focus, then GWP* may be the most appropriate metric; Cain et al. 2019). Although climate change impact assessments are gaining more attention (Allen et al. 2022), this is not a new issue for carbon footprints and other sustainability assessments focusing on GHG emissions. As discussed by Reisinger and Ledgard (2013), the quantification of emissions is important, but moreover, the authors conclude that different impact assessments answer different questions. Finally on the topic of LCIA, it is important to acknowledge that IPCC (2021) recommend testing GHG emissions calculations and associated impact assessments through sensitivity analyses (either cross-time horizons or cross-impact assessments, pending the research question and system context). This invariably makes interpretation and communication more challenging, but it is a critical exercise to demonstrate to stakeholders, policymakers and consumers that there are considerable complexities involved in assessing a product or service's contribution to climate change.

3.6 Implications for mixed pasture crop rotation

Herein, we address the GHG emissions intensities associated with mixed pasture crop rotation, underpinned by temporally high-resolution agronomical data. Although the systems evaluated have different livestock production strategies, we can draw useful conclusions in terms of general responses to various management practices.

First, we note the importance of including pastures in rotational farming and the potential of pastoral swards to reduce input use (e.g. synthetic inorganic N fertilisers) through an increase in biological N fixation (Carswell et al. 2022; McAuliffe et al. 2018), potentially improved SOC sequestration in certain production systems (Pravia et al. 2019) and greater productivity through the use of high-quality, managed pastures (Szymczak et al. 2023). Although this is a geographically restricted study (i.e. conclusions cannot be made from a global perspective), such management practices appear to achieve high average daily growth and improved biomass productivity in temperate climates, thereby reducing emissions per kilogram produced which has been demonstrated previously (Carvalho et al. 2018; de Souza Filho et al. 2019). Enhancing productivity has the potential to yield improvements in the economic strength of crop–livestock rotational systems (Leahy et al. 2020). Secondly, the exclusive utilisation of food produced within the system for animal feed facilitates emission reductions (e.g. from transportation) and enhances the utilisation of crop residues, concurrently integrating nutrients into the soil through the deposition of manure and urine. Nevertheless, achieving an optimal balance between crops and livestock within these systems poses several challenges associated with land utilisation and nutrient use efficiency (Xu et al. 2023).

On the other hand, data sourced from long-term, large-scale trials enables us to explore potential risks and benefits of agricultural systems currently underrepresented in extant LCA literature. This is particularly helpful to the LCA evidence base as our work predominantly adopts temporally high-resolution primary data, thereby better informing those who consume, and indeed produce, the four included (co) products. Finally, pasture crop rotations have the potential to produce ecosystem services (e.g. reduce erosion, pollination and biological control of pests) and reduce environmental impacts without compromising economic sustainability. This presents an opportunity for future research to explore broader sustainability trade-offs including different impact categories such as eutrophication, water scarcity and fossil fuel depletion, as well as a more holistic viewpoint considering biodiversity, economic (e.g. projected changes in supply and demand for Uruguay's primary agricultural exports) and social (e.g. human and animal welfare) ramifications of different multifunctional systems. Considering the importance of meat towards the nation's total income, it is of critical importance to explore the 'steps to sustainable livestock' (Eisler et al. 2014; Rivero et al. 2021) from as many lenses as possible to ensure land use is optimised and consumers are provided with transparent and unbiased information which acknowledges weaknesses in modelling exercises via uncertainty analyses and testing the sensitivity of subjective decision making, e.g. allocation and impact assessment characterisation factors, and the role of livestock in a circular bio-economy (utilising 'waste' streams and land not suited to or in combination with crops).

4 Conclusions

Our findings present a novel evidence base simultaneously tackling environmental modelling issues in mixed crop–livestock systems, whilst providing insights into locally representative and understudied farming practices in South America to produce food and feed. These practices allow to reduce environmental degradation, creating semi-circular multifunctional farming systems which feed both human and animals simultaneously. The underlying data also explores a variety of material inputs and outputs, as well as flows to and from nature, differing across land management trials, thus further elucidating optimal local practices which may realise sustainable solutions. Given there are few life cycle assessment studies available on such mixed-enterprise 'semi-circular' systems, particularly with novel primary data, this study adds critical knowledge to agri-food-related sustainability literature by addressing environmental issues in complex production systems compared to extant and broad coverage of mono-enterprise systems.

We emphasise the significance of our findings in light of the widespread use of these production systems in South America and the lack of information regarding their environmental impacts. Furthermore, methodological approaches to assess said impacts of such complex, multi-produce farming systems are scant in extant literature, and as such, we propose a robust framework to inform relevant stakeholders about uncertainties, some of which are substantial, when conducting carbon footprints. Whilst a broader assessment of impact categories (e.g. eutrophication, acidification, fossil depletion, water scarcity, etc.) is required to fully reveal the benefits and risks associated with mixed crop and livestock systems, our study contributes to improving geographical coverage of LCA data in the context of a growing demand for information concerning production systems including mixed crop–livestock enterprises.

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Authors' contributions Conceptualisation: FPG, GAM, AJ, PR, WA, MJR. Methodology: FPG, GAM, AJ, TT. Data analysis: FPG, GAM, AJ. Writing—original draft: FPG, GAM, AJ. Writing—review and editing: FP-G, GAM, AJ, TT, PR, WA, MRFL, MJR.

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Data availability The integrity of the data used in this study is included in it and in the Supplementary Material.

Declarations

Ethics approval This study is exempt from ethics approval since livestock were submitted to common farming practices and no regulated procedure was carried out.

Consent to participate All the research participants gave their informed consent to participate in this study.

Consent for publication The authors confirm that all the participants gave their informed consent to participate in the study.

Conflict of interest The authors declare no competing interests.

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