PLOS CLIMATE

REVIEW

The sustainable transformation of the Colombian cattle sector: Assessing its circularity

Alejandro Parodi[1]*, Sara Valencia-Salazar[2,3], Ana María Loboguerrero[4], Deissy Martínez-Barón[5], Enrique Murgueitio[6], Ian Vázquez-Rowe[7]

1 Animal Production Systems Group, Wageningen University & Research, Wageningen, the Netherlands, **2** The College of the Southern Border (ECOSUR), Livestock and Environment, San Cristobal de las Casas, Mexico, **3** International Center for Tropical Agriculture (CIAT), Palmira, Colombia, **4** Bioversity International, Rome, Italy, **5** Alliance of Bioversity International and CIAT, Palmira, Colombia, **6** Centro Para la Investigación en Sistemas Sostenibles de Producción Agropecuaria (CIPAV), Barrio El Cedro, Cali, Colombia, **7** Department of Engineering, Peruvian LCA & Industrial Ecology Network (PELCAN), Pontificia Universidad Católica del Perú, San Miguel, Lima, Peru

* alejandro.parodiparodi@wur.nl

Citation: Parodi A, Valencia-Salazar S, Loboguerrero AM, Martínez-Barón D, Murgueitio E, Vázquez-Rowe I (2022) The sustainable transformation of the Colombian cattle sector: Assessing its circularity. PLOS Clim 1(10): e0000074. https://doi.org/10.1371/journal.pclm.0000074

Editor: Ferdous Ahmed, IUBAT: International University of Business Agriculture and Technology, MALAYSIA

Published: October 12, 2022

Funding: This study was funded by the Network on Circular Food Systems within the Global Research Alliance (AP and IVR), the Dirección General de Investigación at PUCP with the project FAI-0001-2021 (IVR) and the CGIAR Trust Fund (AML and DMB).The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: I have read the journal's policy and the authors of this manuscript have the following competing interests: AML is a member of the PLOS Climate editorial board

Abstract

Circular food systems are increasingly acknowledged for their potential to contribute to the transition towards sustainable futures. In a circular food system, the use of finite and limited resources is minimized, and nutrients in residual streams and inedible biomass for humans are reused as inputs in the bioeconomy. Livestock has become relevant in this narrative for upcycling nutrients contained in food by-products and grass resources into nutritious food for humans without using human-edible resources. Evaluating on-going national sustainability initiatives in the livestock sector is key to determine if circularity elements are already represented and to identify new opportunities and pathways for the future. In this paper we synthetize the environmental actions promoted by different initiatives driving the sustainable transformation of Colombian cattle production systems and assess the inclusion of circularity elements in these actions. The proposed environmental actions were concentrated in the conservation of remaining natural ecosystems, zero-deforestation and the sustainable intensification of cattle production through silvopastoral and paddock rotational systems. Circularity was addressed by some initiatives via the use organic fertilizers and the use of manure as fertilizers or feedstock for bioenergy generation. However, given that cattle farming is often practiced in low-input systems where the collection of by-products for reutilization (e.g., manure) is not always feasible, these actions are expected to have limited impact in the sector. Silvopastoral systems can positively promote circularity by creating the conditions for internal nutrient recycling via litterfall, biological nitrogen fixation, phosphorus solubilization, and presence of beneficial insects. However, to avoid food-feed competition and to remain circular, these should only be installed in agricultural areas unsuitable for crop production. In areas where crops can grow, other production systems that prioritize the production of plant biomass for human consumption (i.e., agrosilvopastoral systems, mixed crop-livestock systems or forms of crop intercropping) should be considered.

1. Introduction

Circularity is a model of production and consumption with potential to contribute to the actions needed to restore food systems towards more sustainable futures. A circular food system seeks to minimize the use of finite and limited resources such as arable lands or phosphorus, reduce nutrient losses along the food chain (i.e., production, processing, distribution, consumption and waste disposal), and increase nutrient recovery to reuse it as food, feed, fertilizer or biomaterials [1, 2]. By replacing greenhouse gas (GHG)-intensive raw inputs such as mineral fertilizers and feeds with soil amendments and feeds originated from recovered materials, a circular food system can contribute to climate-resilient and low-emission practices [3, 4]. As the concept of circularity is rooted on the principle of preventing nutrient losses and upcycling nutrients from residual streams, circularity can reduce food loss and waste and their associated environmental impacts along food supply chains. In addition, given the recent dramatic increase in fertilizer and fuels prices caused by major supply chain disruptions (e.g., COVID-19, the war in Ukraine), adopting circular interventions that target the recovery and valorization of residual organic streams could reduce the reliance on external inputs (e.g., fertilizers, feeds) and increase countries' self-sufficiency.

Livestock has become relevant in the narrative of circular food systems for its role in upcycling the nutrients contained in residual streams and grassland biomass from non-arable lands, into nutritious human edible foods and manure [5]. By doing so, livestock becomes a source of food without competing with humans for food and land. To date, different modelling studies have acknowledged the potential contribution of circular food systems to foster food security and to lower livestock environmental footprints on human diets at regional (i.e., European Union) and global levels [6–8]. Policy instruments to guide the transition towards a circular food system are being created in Europe, and initiatives are being launched to increase the development and implementation of circularity in other regions of the world [9, 10].

Despite the gaining momentum of circular food systems in parts of the global north and the ongoing efforts to promote it worldwide, there is a need to determine how circularity is envisioned and represented in the global south. This is relevant for designing and implementing circular interventions in line with local contexts and to harmonize the new efforts with the existing initiatives that aim to make local food systems more sustainable. In this review we focus on the Colombian cattle sector, a main contributor to GHG emissions, but also a key sector on which Colombia substantially relies to meet its mitigation targets. Our review is structured as follows. First, we describe how cattle farming is structured in Colombia. Second, we list and synthetize the main public and private initiatives setting the standards and directions for the sustainable transformation of Colombian cattle systems. Third, based on the actions promoted by the initiatives, we assess which circularity elements are present and discuss the challenges and opportunities for a circular livestock sector in Colombia.

2. Cattle production systems in Colombia

Colombia is the fourth country with the largest livestock herd in the Americas (i.e., more than 28 million cattle heads), and the 14th worldwide [11, 12]. The Colombian livestock sector is dominated by farms with less than 50 animals, representing more than 80% of the national cattle herd [11]. However, land concentration is extreme, with 1% of landholders possessing 81% of the agricultural productive land in 2014 [13]. In fact, many of the grazing lands and a substantial part of the cattle herd are the result of decades of land-grabbing via cattle ranching and forced migration of smallholders [14–16].

Cattle is reared throughout the country, but the Andean, Caribbean and Orinoquia regions hold more than 85% of the national herd and lands used for cattle ranching (see Fig 1A–1C).

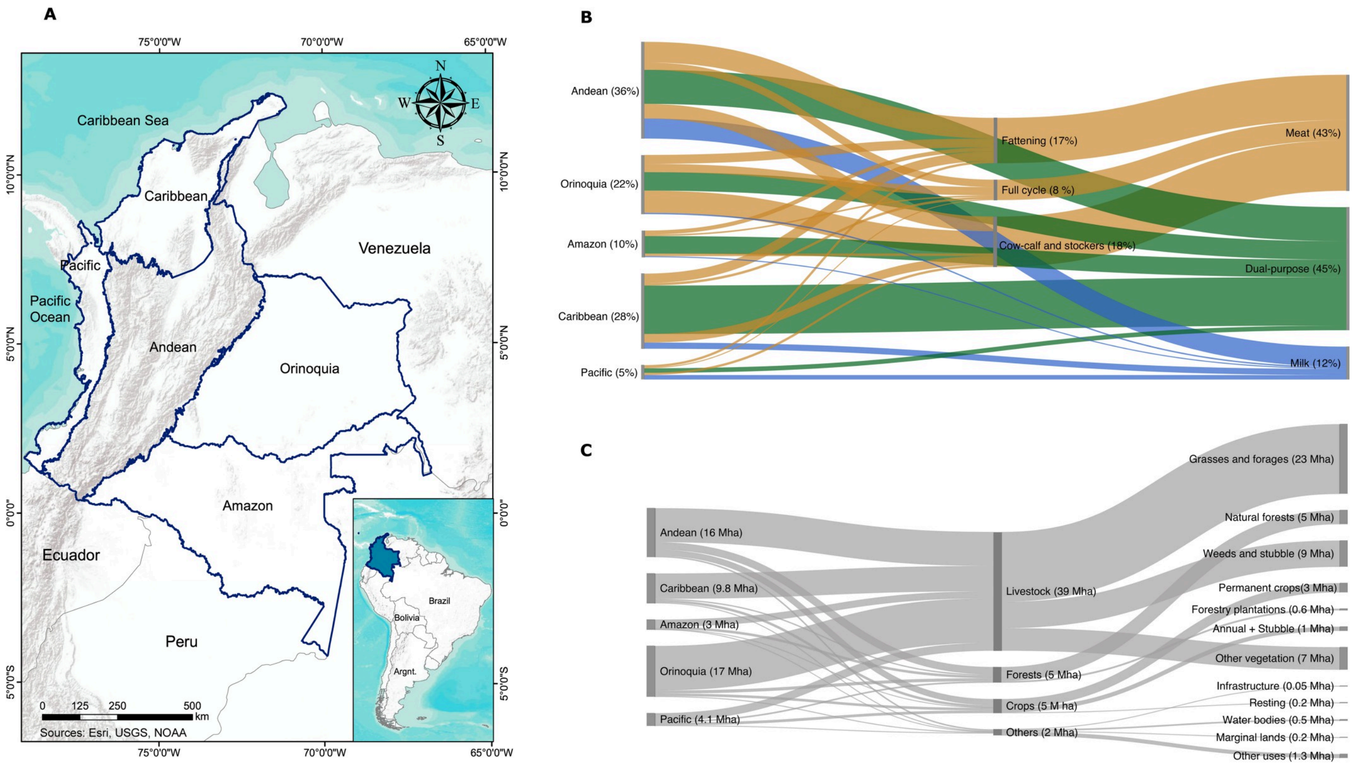

Fig 1. A. Map of Colombia and its regions. The map base layer was produced by Esri, USGS and NOAA and was obtained from https://server.arcgisonline.com/ArcGIS/rest/services/World_Terrain_Base/MapServer. The terms of use for the map base layer in academic publications can be found at https://doc.arcgis.com/en/arcgis-online/reference/static-maps.htm. B. Composition of cattle herd in Colombia per region and orientation type (i.e., meat in orange, dual-purpose in green and milk in blue). Percentages indicate the contribution of each region and orientation type relative to the national herd. C. Agricultural land use in millions of hectares in Colombia for 2019. Data obtained from [17].

https://doi.org/10.1371/journal.pclm.0000074.g001

The sector is mainly oriented to beef production (43%), whereas milk only represents 12% of the national herd. The remaining 45% is linked to dual-purpose activities, i.e., beef and milk (45%) (Fig 1B). Most of the beef commercialized in Colombia comes from fattening farms, representing 39% of the beef national herd [17]. Fattening farms depend mostly on cow-calf farms for weaning calves, and at a lower extent on dual-purpose farms [18]. The different growth stages along the cattle's life cycle are usually carried out in different farms. This leads to cattle being transported throughout the country, making it difficult to know where the animals are coming from. In 2016, the Agricultural and Livestock Colombian institute (ICA for its acronym in Spanish), was only able to trace 10% of the national cattle herd [19].

Most beef cow-calf and fattening farms are managed under low-input extensive grazing systems. Cattle mainly graze on natural pastures, receive limited supplementation of forages and concentrates, and have low productivity [18]. Mineral supplementation (e.g., calcium, phosphorus, magnesium) is one of the few inputs commonly used throughout farms [20, 21]. In Colombia, nearly 60% of the current grazing lands have low stocking densities, below 0.5 animal units (AU) ha^{-1}, and only 13% more than 1 AU ha^{-1} (1 AU = 454 kg) [22]. Grasslands are usually overgrazed [23], which not only leads to the degradation of soil and water resources [24, 25] and low cattle productivities per unit of land, but may also contribute indirectly to further deforestation [16].

Colombia has been researching and debating land-sharing and land-sparing approaches for decades, to intensify current systems and conserve the remaining natural ecosystems [26, 27].

Even though Colombia hosts vast dry and humid natural savannahs where livestock farming originated, most cattle farming takes place in pastures cultivated in biodiversity-rich areas such as dry forest, lowland tropical forests, Andean *páramos* (i.e., montane grasslands and shrublands) and cloud forests [28, 29]. Intensification is usually proposed to reduce the environmental impact per unit of product, under the logic that a higher productivity would reduce the individual product footprint. Examples of intensification recommendations for the local Colombian context include the adoption of improved pastures with higher fertilization rates than current ones [18], rotational grazing schemes [30], use of tropical forages with secondary metabolites with potential to reduce methane emissions [31] and the adoption of silvopastoral systems [32, 33]. Although it has been acknowledged that all these practices can have potential to reduce the environmental footprint of the Colombian livestock sector [26, 34–36], several barriers limiting their adoption exist, including high costs and risks, and limited access to financial capital, technical assistance and information.

3. Initiatives and environmental interventions driving the sustainable transformation of the Colombian cattle sector

3.1. Initiatives

Based on decades of experimental and applied research in the domain of sustainable cattle systems in the different Colombian agroecological zones, production systems and regions, multiple initiatives have flourished and are being implemented to transform the Colombian livestock sector (Table 1). These initiatives have been divided into two groups: voluntary sustainability standards (VSS) and public policy instruments.

The VSS are rules related to a wide range of sustainability metrics that producers, traders, manufacturers, retailers or service providers may be asked to follow in order to avoid harming people and the environment during the processes they perform [37]. We identified five active VSS schemes in Colombia, which included three product labels (i.e., GANSO, Angus Azul and the Livestock Environmental Label), a public-private agreement (i.e., zero-deforestation agreement) and a multi-stakeholder platform (i.e., Colombian Roundtable for Sustainable Cattle Production (MGS-Col, for its acronym in Spanish)). Details on each VSS are presented in the S1 Text. Although other large projects and initiatives have been implemented, we decided to

Table 1. Initiatives driving the sustainable transformation of the Colombian livestock sector.

Type	Name	Set by	Monitored by	Target product	Impact
Voluntary Sustainability Standards (VSS)	GANSO	NGO	Third party (private audit)	Meat	At least 15,000 ha (so far)
	Angus Azul	Company	First party	Meat	At least 23,500 ha (so far)
	Livestock Environmental Label	Government	Third party (Incontec)	Meat and milk	Recently launched, no tangible impacts.
	Zero deforestation agreement	Government, companies, NGO	Second or third party	Meat and milk	33 active members
	Colombian Roundtable for Sustainable Cattle Production	NGO, companies, producers	No monitoring	Meat and milk	62 active members (43 from the private sector)
Public policy	Nationally Appropriate Mitigation Action for Sustainable Bovine production (NAMA-bovine)	Government	Government	Meat and milk	Recently launched. Expects to cover 1.6–3.6 M ha and 11500–25300 farms.
	National Policy for Sustainable Bovine Production (GBS 2021–2050)	Government	Government	Meat and milk	Recently launched. Expects to transform the whole national cattle sector by 2050.

https://doi.org/10.1371/journal.pclm.0000074.t001 focus on these due to their implementation and readiness on a commercial scale or for having direct influence on the entire sector.

In the policy arena, as of 2022, there are two main policy instruments that specifically focus on the sustainable transformation of the Colombian cattle sector. One is the recently launched Nationally Appropriate Mitigation Action for sustainable bovine production (NAMA-bovine) [38]. It sets the actions needed to reduce GHG emissions and increase carbon storage in cattle production systems to meet Colombia's international commitment to reduce cattle-related GHG emissions 15% to 33% by 2050 (i.e., equivalent to 5–11 Mt CO_2eq $year^{-1}$). Land-based mitigation measures account for 70% of Colombia's updated Nationally Determined Contribution (NDC) target and the NAMA-bovine plays a key role to achieve it [39].

The other policy is the National Policy for Sustainable Bovine Production (PNGBS, for its acronym in Spanish) 2021/2050 [40]. This policy is the result of a participatory process led by the MGS-Col, that seeks to define the roadmap for 2021–2050 to modernize and reconvert Colombian livestock systems towards low emission and climate-resilient systems [19].

3.2. Environmental actions proposed by the initiatives

The actions proposed to improve the sustainability of the Colombian cattle sector were classified into four groups: conservation and restoration of natural ecosystems and resources, land use and feeds, soil health and fertilization and waste management (see Table 2 and S1 Table). It is important to consider that not all actions have to be complied simultaneously. Some voluntarily sustainability standards (VSS) have minimum criteria to be certified, followed by a continuous monitoring for the implementation of more environmental actions.

Table 2. List of environmental actions proposed by the different initiatives.

	Voluntary Sustainability Standards				Public policies	
Actions	**GANSO**	**Angus Azul**	**Livestock Environmental Label**	**Zero-deforestation agreement**	**PNGBS**	**NAMA—Bovine**
Conservation and restoration of existing natural ecosystems and resources						
Destine a portion of the farm area for conservation	x	x	x			x
Restore areas currently used by livestock either via natural regeneration, agroforestry systems or reforestation	x	x	x	x		x
Halt deforestation	x	x		x		
Implement water use plans that optimize water use and reduce losses	x	x	x			
Protect natural water bodies from direct use by livestock		x	x			x
Land use and feeds						
Implement silvopastoril systems	x	x	x	x	x	x
Implement paddock rotation systems for forage production	x		x		x	x
Reduce methane enteric fermentation via livestock diets (feed additives, improved digestibility)	x				x	
Produce all feed within the farm		x				
Soil health and fertilization						
Implement soil conservation practices (e.g., keep vegetation cover, use green manures).	x	x	x			
Use of organic fertilizers	x					x
Organic waste management						
Recover nutrients from organic waste (including manure) via composting or anaerobic digestion	x		x			x
Implement a waste management plan for the collection, storage and disposal of hazardous waste	x		x			

https://doi.org/10.1371/journal.pclm.0000074.t002

3.2.1. Conservation and restoration of natural ecosystems and resources. One of the outcomes of the land sharing and sparing debate has been to reduce the grazing areas devoted to extensive cattle ranching with the aim to increase conservation areas [26]. In fact, most of the initiatives consider the conservation of remaining natural ecosystem patches or their restoration; however, they differ in what portion of the farm should be protected. For instance, GANSO requires that at least 5% of the farm's area should be conserved. In contrast, the Livestock Environmental Label establishes that the conservation area should represent a minimum of 11% of the total area and, if the farm does not meet the minimum area, it must comply with a transition agreement to reach the 11% thresholds in a three-year period.

Angus Azul mentions that in areas where the natural ecosystem has a canopy coverage of less than 20%, the farm must have areas designated for the conservation or recovery of natural ecosystems, equivalent to at least 20% of the livestock production area. NAMA-bovine promotes the freeing of areas where cattle productivities are low for their ecological restoration. In those cases in which the conservation is unfeasible due to insufficient area for natural ecosystems, restoration of degraded lands is the preferred action. Restoration of lands for conservation can be performed via natural regrowth of vegetation and through the establishment of silvopastoral systems or forest plantations. The use of silvopastoral systems as a restoration strategy corresponds to the myriad environmental benefits they provide without decoupling their production advantages [41].

It must be noted that all three schemes (i.e., GANSO, Angus Azul and the Livestock Environmental Label) require that the farms that adhere must consider actions to protect water resources from damage, pollution and losses. This is expected to be performed via the installation of channeling systems to drinkers, rainwater collection systems, and the installation of physical barriers to prevent direct contact between livestock and natural water sources.

3.2.2. Land use and feeds. All initiatives analyzed promote the implementation of silvopastoral systems (e.g., live fences, scattered trees, fodder hedges, semi-intensive and intensive silvopastoral systems) and the application of rotational grazing systems as sustainable intensification strategies. Both interventions are proposed to increase plant biomass per unit of area with less external inputs. Silvopastoral systems, in particular, can lead to multiple environmental benefits for climate change mitigation and biodiversity, mainly via higher rates of carbon sequestration in above- and below-ground biomass, temperature cooling, reduced methane emissions from enteric fermentation (i.e., by provisioning forages that contain secondary metabolites that modify ruminal fermentation) and improved landscape connectivity. For instance, the soil carbon accumulation in silvopastoral systems established in the Colombian Caribbean ranged from 60.6 to 65.1 t ha^{-1} $year^{1}$, while in a traditional pasture system without trees in the same area, the soil carbon accumulation was 38.3 t ha^{-1} $year^{-1}$ [42].

In other Colombian region increases in total carbon stocks (i.e., sum of soil and biomass) of 0.57, 6.24 and 2.06 Mg C ha^{-1} yr^{-1} have been found for pasture, forage banks and silvopastoral systems, respectively [43]. Silvopastoral systems, independently of their spatial extent, can offer cooling benefits ranging from -0.32˚C to -2.4˚C per 10 metric tons of woody carbon per hectare [44]. Secondary metabolites ingested by livestock via specific plant species can reduce methane emissions by 20%-30%, although results can be very variable depending on the characteristics of the metabolite [45, 46]. In addition, the NAMA-bovine scheme argues that silvopastoral systems allow higher stocking rates; therefore, they can indirectly liberate grazing lands for conservation purposes. In silvopastoral systems, depending on the intensification level, stocking rates can range between 4 heads/ha^{-1} and 4.6 heads/ha^{-1}, which is much higher than the average 0.6 animal heads/ha that characterizes current extensive systems [41]. Although it is not a common practice, some initiatives allow the import of feeds and promote forage conservation practices to reduce grazing pressure. Only Angus Azul mentions that forages should be produced within each farm.

3.2.3. Soil health and fertilization. GANSO, Angus Azul and the Livestock Environmental Label specifically propose adopting soil conservation practices. These include mulching, using green manure and other organic fertilizers, practice conservation tillage and reducing livestock transit in slopes, among others. Although not specifically mentioned, most of these practices favor the proliferation of soil macrofauna such as dung beetles which play a key role in nutrient management of pasture systems [47]. Only GANSO and the Livestock Environmental Label recommend setting fertilization plans in amounts that are safe for the environment; however, no specific limits are set.

3.2.4. Waste management. The treatment of organic waste is only present in three of the six initiatives and with limited scope. GANSO and the Livestock Environmental Label encourage the use of biological processes such as composting, vermicomposting, to be used as a soil amendment or for energy production (i.e., biogas). They also encourage the adequate collection, storage and disposal of hazardous waste (i.e., veterinary medicines, agrochemicals, etc.). They do not specify, however, which type of residues should be targeted and how these should be collected. In contrast, NAMA-bovine is more specific on this, targeting the utilization of manure collected in milking rooms as an organic fertilizer, and the collection of manure from slaughterhouses, livestock exhibition and trading fairs to produce biogas and fertilizers (i.e., as digestate).

4. Assessing circularity in sustainable interventions

Evaluating whether circularity is embedded in sustainable interventions currently promoted by the different initiatives depends on what is considered to be circular. Here, we evaluate circularity from a nutrient and food-feed competition perspective based on the frameworks developed by Harder et al. (2021) [2] and De Boer and Van Ittersum (2018) [1], respectively. These frameworks were selected for approaching circularity with a food systems approach.

4.1. Nutrient-circularity in Colombian cattle systems

From a nutrient perspective, food systems' circularity interventions seek to reduce nutrient losses from residual streams by recovering those nutrients and reusing them in agricultural production [2]. Nutrient circularity can have two interpretations depending on whether the focus is on the inputs or the outputs. Input circularity relates to the share of nutrient needs that are supplied with recirculated nutrients. Output circularity relates to the share of nutrients in residual streams which are recirculated within or outside the system [2]. Applied to cattle production systems, input nutrient circularity is mainly linked to the types of fertilizers and animal feeds, whereas output circularity is linked to the use of manure and livestock carcass.

4.1.1. Input circularity–fertilizers. Fertilization in the Colombian cattle context is mainly linked to the fertilization of pastures, as more than 95% of cattle farms are grass-based [17]. Most Colombian cattle systems are managed under extensive conditions and are characterized by a low use of fertilizers [18, 48]. However, it is known that fertilization of pastures, combined with other management measurements such as rotational grazing result in improved systems that can intensify productivity per unit of land and, hence, break the extensive model that predominates currently [48].

Although the initiatives do not directly propose fertilization regimes, the use of circular fertilizers is somehow covered under the term *organic fertilizers*, which are traditionally obtained from recycled sources. GANSO refers to the use of chemical fertilizers and fertilization plans if these are safe for the environment and suggests considering the use of organic fertilizers. The

NAMA-bovine refers to the use of bedding material, composted manure and digestates obtained from slaughterhouses, livestock fairs and exhibition events to fertilize pastures. In the PNGBS, the current use and promotion of mineral fertilizers instead of organic fertilizers is criticized; however, there are no clear actions proposed to promote organic fertilizers in cattle production systems.

Silvopastoral systems, proposed by all initiatives, intrinsically contribute to circularity, as the whole system is based on taking advantage of the internal nutrient recycling processes occurring between trees, shrubs, pastures, and animals to minimize the use of external inputs [41, 49]. For instance, in silvopastoral systems, nitrogen-fixing shrubs such as *Leucaena leucocephala* can fix atmospheric nitrogen at rates ranging from 77 kg ha^{-1} to 250 kg ha^{-1} [50, 51]. Phosphorus, a limiting mineral in most acidic tropical soils due to Al and Fe immobilization can be solubilized and made available for plant uptake when the mycorrhiza and microbiota related to specific trees and shrubs are planted in high densities [52]. In addition, as silvopastoral systems support mixed dung beetle assemblages and other macrofauna, the relocation of cow manure (i.e., transport of manure above or below ground) and the incorporation of organic matter to the soil is favored [53, 54].

4.1.2. Input-circularity feeds. Input-circularity associated with cattle feed is linked to the use of agricultural streams such as crop residues and food processing by-products as part of cattle diet rations. In Colombia most cattle production systems consume pastures and forages in the 23.5 million ha of area currently utilized for cattle ranching [17]. Hence, the use of feeds such as crop by-products, grains, legumes and tubers are not common. In certain specialized dairy systems some by-products such as wheat bran, soybean husk, palm cake, dairy whey are re-used as feed [55], whereas bone and blood meals are commonly reused as sources of calcium and phosphorus for mineral supplementation to livestock. In this context, it is not surprising that the use of circular external feeds is mainly absent and even discouraged by some initiatives. For instance, Angus Azul, by demanding that all feeds be produced within the farm, excludes the use of by-products produced in other lands (e.g., palm cake).

The use of circular feeds could have major relevance for the future sustainability of the Colombian specialized dairy sector. Worldwide, highly productive specialized dairy systems depend on high nutrient quality ingredients (i.e., concentrates based on cereals, grains, and legumes) to sustain the high milk yields. LCA studies usually conclude that intensive systems are the ones producing milk with the lowest footprint [48, 56, 57], as usually the GHG emissions per unit of product are lower compared to other less intensified systems. Under this production-oriented way of expressing the sustainability of food products (i.e., expressing impacts per kg of product), high-yielding systems will be favored [58]. However, considering that high-quality ingredients or the arable lands to produce them are not infinite, and that many of these ingredients are human-edible, their use as animal feed contributes to food-feed competition, an issue that environmental footprint metrics struggle to grasp in its full complexity [59]. Avoiding food-feed competition via the utilization of circular feeds is consequently key for the transition towards future sustainable and food-secure food systems [60–62], and should be incorporated in the sustainability agenda for Colombian dairy and monogastric livestock systems.

4.1.3. Output-circularity manure. In most Colombian cattle systems, cattle urinate and deposit excreta directly in extensive areas where they forage and rest. Although this guarantees nutrient cycling, it is known that the presence of manure dungs can lead to the formation of rejected patches, which limits grass intake as cattle refuse to graze in these areas [63]. This is unlikely to be a limitation in most Colombian cattle systems due to low stocking densities, but may need to be accounted for in intensive grazing systems to correctly estimate fresh grass allowance [64]. Given that the collection of manure in grazing systems is unfeasible, the key to improving the recycling of manure nutrients in pastures relies on the proliferation of entomofauna. Insects such as tunnelling dung beetles are vital for nutrient recycling and plant health in pasture systems [47], and can also contribute to improve cattle health [65].

Some of the initiatives include circular practices for manure management while cattle are not grazing. The NAMA-bovine accounts for the collection of manure in milking rooms, slaughterhouses, livestock fairs and exhibition events. While the amount of manure excreted per animal in these places is infimal compared to what is excreted in pasture lands, estimates show that manure emissions reach nearly 4000 t CO_2eq/year in the 233 slaughterhouses that operate throughout the country, and 5000 t CO_2eq/year in the 54 livestock fairs that take place every year. NAMA-bovine suggests implementing circular practices such as composting and anaerobic digestion to produce biogas and digestate, although it points out that the high nitrous oxide emissions assumed for manure composting could lead to higher GHG emissions than the reference scenario. *"However, NAMA-bovine does not account for avoided emissions and carbon sinks associated to compost use, which influences the net carbon balance of composted animal manures substantially"*.[3]. GANSO and the Livestock Environmental Label recommend managing the organic residues via circular practices such as composting, vermicomposting and anaerobic digestion. However, in neither case it is specified if manure is included, and if so, how it would be collected.

4.1.4. Output-circularity livestock carcass. Most cattle carcass and offal obtained in slaughterhouses are utilized, independently of the degree of automation of the slaughter plant. The skin, horns, hooves, bones, blood, the tassel of the tail, among others, are examples of leftovers that are inputs for other industries as ingredients for animal feed (except for ruminants to avoid the transmission bovine spongiform encephalopathy), leather, and human food (e.g., blood). Although the reuse of animal leftovers is a common practice, none of the initiatives, except NAMA-bovine, which suggests producing bioenergy via anaerobic digestion, has a dedicated part to describe and suggest practices for the reuse of these animal parts.

4.2. Food-feed competition in Colombian cattle systems

In a circular food system food-feed competition (i.e., the use of human edible food as livestock feed) is avoided by primarily using arable lands for the production of plant biomass for direct human consumption. In such a system, livestock is solely fed on residual streams from food production and grassland biomass from non-arable lands [1]. In that way, the production of human edible food is maximized, and livestock plays a key role for the supply of macro and micronutrients key for human nutrition without using additional arable land [5].

In Colombia, all the sustainable interventions promote the implementation of silvopastoral systems in pasture lands currently used for cattle farming (Table 2). Only the Livestock Environmental label, stated that silvopastoral systems should also include the production of human-edible foods. The switch in land use from grasslands to silvopastoral systems is expected to result in a series of positive environmental outcomes for climate change mitigation, nutrient cycling and biodiversity (see section 3.2.2). The land-use circularity framework by De Boer and Van Ittersum (2018) does not refer specifically to silvopastoral systems as circular; however, if implemented in non-arable lands, these systems would be, in principle, circular and preferable than just having livestock grazing on pastures. The reason for this is that silvopastoral systems, if adequately managed, can produce more plant biomass than pastures, increase the amount of meat, milk and manure per unit of area as compared to pasture-based systems, promote internal nutrient recycling and simultaneously supply wood, fruits and diverse ecosystem services [32, 66].

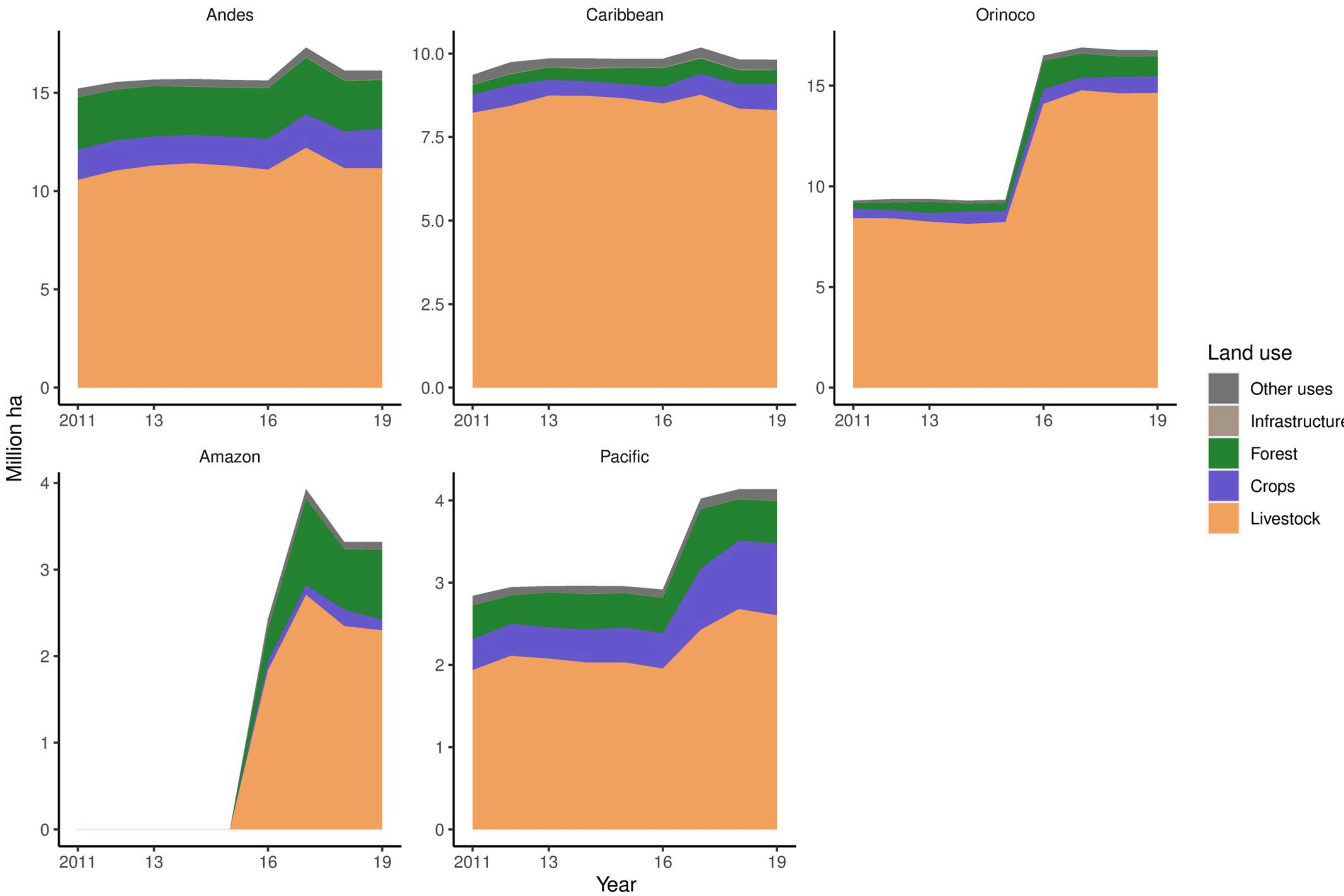

Fig 2. National and regional land use within agricultural units from 2011 to 2019. Note the different units in the Y axis. Data were obtained from the 2019 agricultural national survey [68].

https://doi.org/10.1371/journal.pclm.0000074.g002

In Colombia, land devoted to livestock has increased in the last decade in most regions, while the land destined to crops has remained relatively constant, except in the Pacific region (Fig 2). The grazing lands devoted to livestock are not only linked to areas where crops cannot grow, but are also the result of decades of land-grabbing via cattle ranching, forced migration of smallholders and deforestation [14]. By 2010, 39% of the grazing area in Colombia was covered with introduced grasses, 19% was present in pasture-crop-natural area mosaics, 7.5% was covered with shrublands, and 34% corresponded to natural grasslands [22]. While most of the attention has focused on identifying grazing areas where livestock should be excluded due to low productivities, high environmental impacts and illegal use of lands [22, 67], there has been less interest in quantifying which areas with current livestock use could incorporate crops. From a food-feed competition circularity point of view, this is a relevant knowledge gap that needs to be fulfilled. Such an output would allow comparing the consequences in terms of food security, GHG emissions and the environment of implementing other land uses that prioritize food production for direct human consumption instead of pastures and cattle.

Previous Latin American experiences have shown that the establishment of cropping systems in grazing lands can lead to negative outcomes for food security and the environment with the adoption of large-scale monocultures for bioenegy and feed purposes [69–71]. To avoid such negative outcomes, it is important to implement circular food systems produced under agroecological practices [72]. Agrosilvopastoral systems (i.e., land use that combines crops, trees, shrubs, pastures and animals) can be promising alternative, as these can offer all the environmental and productive benefits of silvopastoral systems and provide food for direct human consumption keeping the synergies intrinsic to mixed crop-livestock systems. Other options such as mixed crop-livestock systems and intercropping systems managed under agro-ecological practices could also be considered [73, 74].

5. Conclusions

After decades of research and pilot projects, different initiatives that promote the sustainable transformation of cattle systems have taken hold in Colombia. These include voluntary standard schemes that certify cattle products that meet minimum environmental criteria, and national policies that aim to make the sector more sustainable. Among the environmental actions proposed, those that stand out are the zero-deforestation agreement, the conservation of remaining natural ecosystems and resources or their restauration, and the sustainable intensification of cattle production systems via the implementation of silvopastoral systems and paddock rotational systems.

While assessing the inclusion of nutrient circularity in the initiatives, we found that some of them included circularity elements such as the use of organic fertilizers, and the collection and use of manure. However, in the short-term these actions are expected to have limited impact as the intensification of cattle farming is expected to occur mainly in low-input systems and in a context where the collection of by-products for utilization (e.g., manure) is not always feasible. In such low-input systems, improved nutrient management and circularity will depend on natural nitrogen fixation and phosphorus solubilization via shrubs and trees, and the presence of beneficial insects such as dung beetles. Silvopastoral systems, the preferred sustainable intensification action promoted by all initiatives, may contribute to climate change mitigation and nutrient circularity via internal nutrient recycling. However, in some areas these systems might not be circular from a food-feed competition perspective if they are installed in lands suitable for crop production. The evaluation of areas with potential to be used for crop cultivation in current grazing areas has remained unattended in the sustainable land intensification debate for Colombia. We propose that in these areas, pasture lands should be replaced with agrosilvopastoral systems that integrate crops, trees, pastures and livestock. Quantifying the extent of these areas is the first step and, thereafter, existing circular frameworks and models could be useful to measure the impact of adopting circular land uses for food security, resilience, livelihoods, and environmental sustainability.

Supporting information

S1 Text. Explanation of the voluntary sustainability standards (VSS).
(DOCX)

S1 Table. Detailed environmental actions proposed by the different initiatives per theme and sub-theme.
(DOCX)

References

1. De Boer IJ., Van Ittersum MK. Circularity in agricultural production. Wageningen; 2018. Available: http://library.wur.nl/WebQuery/wurpubs/fulltext/470625
2. Harder R, Giampietro M, Smukler S. Towards a circular nutrient economy. A novel way to analyze the circularity of nutrient flows in food systems. Resour Conserv Recycl. 2021; 172: 105693. https://doi.org/10.1016/J.RESCONREC.2021.105693

3. Vergara SE, Silver WL. Greenhouse gas emissions from windrow composting of organic wastes: Patterns and emissions factors. Environ Res Lett. 2019; 14: 124027. https://doi.org/10.1088/1748-9326/AB5262
4. Boldrin A, Andersen JK, Møller J, Christensen TH, Favoino E. Composting and compost utilization: Accounting of greenhouse gases and global warming contributions. Waste Manag Res. 2009; 27: 800–812. https://doi.org/10.1177/0734242X09345275 PMID: 19748950
5. Van Zanten HHE, Van Ittersum MK, De Boer IJM. The role of farm animals in a circular food system. Glob Food Sec. 2019; 21: 18–22. https://doi.org/10.1016/j.gfs.2019.06.003
6. van Hal O, de Boer IJM, Muller A, de Vries S, Erb K-H, Schader C, et al. Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. J Clean Prod. 2019; 219: 485–496. https://doi.org/10.1016/j.jclepro.2019.01.329
7. Schader C, Muller A, Scialabba NE-H, Hecht J, Isensee A, Erb K-H, et al. Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. J R Soc Interface. 2015; 12: 1–13. https://doi.org/10.1098/rsif.2015.0891 PMID: 26674194
8. Van Selm B, Frehner A, De Boer IJM, Van Hal O, Hijbeek R, Van Ittersum MK, et al. Circularity in animal production requires a change in the EAT-Lancet diet in Europe. Nat FOOd |. 2022;3. https://doi.org/10.1038/s43016-021-00425-3
9. Van Berkum S, Dengerink J. Transition to sustainable food systems: the Dutch circular approach providing solutions to global challenges. Wageningen; 2019. Available: www.wur.eu/economic-research
10. Circular Food Systems Network | Global Research Alliance. [cited 12 Apr 2022]. Available: https://globalresearchalliance.org/research/integrative/networks/circular-food-systems-network/
11. ICA-FEDEGAN. Censo Pecuario Nacional—2019. Censo bovino en Colombia. 2020.
12. FAOSTAT. Crops and livestock products. 2021 [cited 17 Dec 2021]. Available: https://www.fao.org/faostat/en/#data/QCL
13. Armenteras D, Negret P, Melgarejo LF, Lakes TM, Londoño MC, García J, et al. Curb land grabbing to save the Amazon. Nat Ecol Evol 2019 311. 2019; 3: 1497–1497. https://doi.org/10.1038/s41559-019-1020-1 PMID: 31666736
14. Urrego-Mesa A, Infante-Amate J, Tello E. Pastures and Cash Crops: Biomass Flows in the Socio-Metabolic Transition of Twentieth-Century Colombian Agriculture. Sustain 2019, Vol 11, Page 117. 2018; 11: 117. https://doi.org/10.3390/SU11010117
15. Garcia Corrales LM, Avila Rangel H, Gutierrez Llantoy R. Land-use and socioeconomic changes related to armed conflicts: A Colombian regional case study. Environ Sci Policy. 2019; 97: 116–124. https://doi.org/10.1016/J.ENVSCI.2019.04.012
16. Dávalos LM, Holmes JS, Rodríguez N, Armenteras D. Demand for beef is unrelated to pasture expansion in northwestern Amazonia. Biol Conserv. 2014; 170: 64–73. https://doi.org/10.1016/J.BIOCON.2013.12.018
17. DANE. Encuesta nacional agropecuaria (ENA). 2019 [cited 17 Dec 2021]. Available: https://www.dane.gov.co/index.php/estadisticas-por-tema/agropecuario/encuesta-nacional-agropecuaria-ena
18. González-Quintero R, Bolívar-Vergara DM, Chirinda N, Arango J, Pantevez H, Barahona-Rosales R, et al. Environmental impact of primary beef production chain in Colombia: Carbon footprint, non-renewable energy and land use using Life Cycle Assessment. Sci Total Environ. 2021; 773: 145573. https://doi.org/10.1016/j.scitotenv.2021.145573 PMID: 33940733
19. MGS. Bases Técnicas para la Formulación de la Política Nacional de Ganadería Bovina Sostenible. Bogotá; 2019. Available: https://cgspace.cgiar.org/bitstream/handle/10568/103242/PGBS_Bases_Tecnicas_PNGBS_30.08.2019.12_AGOSTO.pdf?sequence=1&isAllowed=y
20. McDowell LR. Mineral deficiencies and toxicities and their effect on beef production in developing countries. In Symposium: Beef cattle production in developing countries. Edinburgh: University of Edinburgh; 1976. pp. 216–241.
21. Laredo MA, Gómez J. Fluctuaciones minerales en pastos tropicales. I. Braquiaria en los Llanos Orientales. Rev ICA. 1980; 15: 71–8.
22. Zuluaga A, Etter A, Nepstad D, Chará J, Stickler C, Warren M. Colombia's pathway to a more sustainable cattle sector: A spatial multi-criteria analysis. Land use policy. 2021; 109: 105596. https://doi.org/10.1016/J.LANDUSEPOL.2021.105596
23. González-Quintero R, Sánchez-Pinzón MS, Bolívar-Vergara DM, Chirinda N, Arango J, Pantévez HA, et al. Technical and environmental characterization of Colombian beef cattle-fattening farms, with a focus on farm size and ways of improving production: https://doi-org.ezproxy.library.wur.nl/101177/0030727019884336. 2019; 49: 153–162. https://doi.org/10.1177/0030727019884336

24. Navarrete D, Sitch S, Aragão LEOC, Pedroni L. Conversion from forests to pastures in the Colombian Amazon leads to contrasting soil carbon dynamics depending on land management practices. Glob Chang Biol. 2016; 22: 3503–3517. https://doi.org/10.1111/gcb.13266 PMID: 26929394

25. Podwojewski P, Poulenard J, Zambrana T, Hofstede R. Overgrazing effects on vegetation cover and properties of volcanic ash soil in the páramo of Llangahua and La Esperanza (Tungurahua, Ecuador). Soil Use Manag. 2002; 18: 45–55. https://doi.org/10.1111/J.1475-2743.2002.TB00049.X

26. Lerner AM, Zuluaga AF, Chará J, Etter A, Searchinger T. Sustainable Cattle Ranching in Practice: Moving from Theory to Planning in Colombia's Livestock Sector. Environ Manage. 2017; 60: 176–184. https://doi.org/10.1007/s00267-017-0902-8 PMID: 28624912

27. Tapasco J, LeCoq JF, Ruden A, Rivas JS, Ortiz J. The Livestock Sector in Colombia: Toward a Program to Facilitate Large-Scale Adoption of Mitigation and Adaptation Practices. Front Sustain Food Syst. 2019; 0: 61. https://doi.org/10.3389/FSUFS.2019.00061

28. Van Ausdal S. Pasture, profit, and power: An environmental history of cattle ranching in Colombia, 1850–1950. Geoforum. 2009; 40: 707–719. https://doi.org/10.1016/J.GEOFORUM.2008.09.012

29. Etter A, Van Wyngaarden W. Patterns of Landscape Transformation in Colombia, with Emphasis in the Andean Region. https://doi-org.ezproxy.library.wur.nl/101579/0044-7447-297432. 2000; 29: 432–439. https://doi.org/10.1579/0044-7447-29.7.432

30. Teutscherová N, Vázquez E, Sotelo M, Villegas D, Velásquez N, Baquero D, et al. Intensive short-duration rotational grazing is associated with improved soil quality within one year after establishment in Colombia. Appl Soil Ecol. 2021; 159: 103835. https://doi.org/10.1016/J.APSOIL.2020.103835

31. Valencia Salazar SS, Piñeiro Vázquez AT, Molina Botero IC, Lazos Balbuena FJ, Uuh Narváez JJ, Segura Campos MR, et al. Potential of Samanea saman pod meal for enteric methane mitigation in crossbred heifers fed low-quality tropical grass. Agric For Meteorol. 2018;258. https://doi.org/10.1016/j.agrformet.2017.12.262

32. Murgueitio ER, Chará JO, Barahona RR, Cuartas CC, Naranjo JR. Los Sistemas Silvopastoriles Intensivos (SSPI), herramienta de mitigación y adaptación al cambio climátic. Tropical and Subtropical Agroecosystems. Universidad Autónoma de Yucatán; 2014. pp. 501–507.

33. Chará J, Rivera J, Barahona R, Murgueitio R. E, Deblitz C, Reyes E, et al. Intensive Silvopastoral Systems: Economics and Contribution to Climate Change Mitigation and Public Policies. Adv Agrofor. 2017; 12: 395–416. https://doi.org/10.1007/978-3-319-69371-2_16

34. Arango J, Ruden A, Martinez-Baron D, Loboguerrero AM, Berndt A, Chacón M, et al. Ambition Meets Reality: Achieving GHG Emission Reduction Targets in the Livestock Sector of Latin America. Front Sustain Food Syst. 2020; 4: 65. https://doi.org/10.3389/FSUFS.2020.00065/BIBTEX

35. FEDEGAN SENA. Modelo de gestión y transferencia de conocimiento en ganadería bovina colombiana. Bogotá; 2013.

36. Rivera JE, Chará J. CH4 and N2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems. Front Sustain Food Syst. 2021; 5: 370. https://doi.org/10.3389/FSUFS.2021.657936/BIBTEX

37. UNFSS. Voluntary sustainability standards. today's landscape of issues & initiatives to achieve public policy objectives. Geneva; 2012. Available: https://unfss.org/wp-content/uploads/2012/05/unfss-report-issues-1_draft_lores.pdf

38. NAMA-Bovina. Acción de mitigación nacionalmente apropiada de la ganadería bovina sostenible en Colombia. Bogotá; 2021. Available: https://cgspace.cgiar.org/bitstream/handle/10568/114670/ReporteNAMA08_10_2021final.pdf?sequence=1

39. CAT. Colombia | Climate Action Tracker. 2020 [cited 28 Feb 2022]. Available: https://climateactiontracker.org/climate-target-update-tracker/colombia/

40. MADR, MADS. Lineamientos de política para la ganadería bovina sostenible—GBS 2021–2050. Bogotá; 2021.

41. Murgueitio E, Calle Z, Uribe F, Calle A, Solorio B. Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. For Ecol Manage. 2011; 261: 1654–1663. https://doi.org/10.1016/J.FORECO.2010.09.027

42. Contreras-Santos JL, Martínez Atencia J, Cadena Torres J, Fallas Guzmán CK. Evaluación del carbono acumulado en suelo en sistemas silvopastoriles del Caribe Colombiano. Agron Costarric. 2020 [cited 14 Apr 2022]. https://doi.org/10.15517/RAC.V44I1.39999

43. Landholm DM, Pradhan P, Wegmann P, Sánchez MAR, Salazar JCS, Kropp JP. Reducing deforestation and improving livestock productivity: greenhouse gas mitigation potential of silvopastoral systems in Caquetá. Environ Res Lett. 2019; 14: 114007. https://doi.org/10.1088/1748-9326/AB3DB6

44. Zeppetello LRV, Cook-Patton SC, Parsons LA, Wolff NH, Kroeger T, Battisti DS, et al. Consistent cooling benefits of silvopasture in the tropics. Nat Commun 2022 131. 2022; 13: 1–9. https://doi.org/10.1038/s41467-022-28388-4 PMID: 35121752

45. Rivera J, Molina I, Chará J, Murgueitio E, Barahona R. Intensive silvopastoral systems with Leucaena leucocephala (Lam.) de Wit: productive alternative in the tropic in view of the climate change. Pastos y Forrajes. 2017; 40: 171–183. Available: http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S0864-03942017000300001

46. Ku-Vera JC, Jiménez-Ocampo R, Valencia-Salazar SS, Montoya-Flores MD, Molina-Botero IC, Arango J, et al. Role of Secondary Plant Metabolites on Enteric Methane Mitigation in Ruminants. Front Vet Sci. 2020; 7: 584. https://doi.org/10.3389/fvets.2020.00584 PMID: 33195495

47. Bertone MA, Green JT, Washburn SP, Poore MH, Watson DW. The Contribution of Tunneling Dung Beetles to Pasture Soil Nutrition. Forage & Grazinglands. 2006; 4: 1–12. https://doi.org/10.1094/FG-2006-0711-02-RS

48. González-Quintero R, Kristensen T, Sánchez-Pinzón MS, Bolívar-Vergara DM, Chirinda N, Arango J, et al. Carbon footprint, non-renewable energy and land use of dual-purpose cattle systems in Colombia using a life cycle assessment approach. Livest Sci. 2021; 244: 104330. https://doi.org/10.1016/J.LIVSCI.2020.104330

49. Calle Z, Murgueitio E, Chará J, Molina CH, Zuluaga AF, Calle A. A Strategy for Scaling-Up Intensive Silvopastoral Systems in Colombia. https://doi-org.ezproxy.library.wur.nl/101080/105498112013817338. 2013; 32: 677–693. https://doi.org/10.1080/10549811.2013.817338

50. Bueno-López L, Camargo-García JC. Nitrógeno edáfico y nodulación de Leucaena leucocephala (Lam.) de Wit en sistemas silvopastoriles. Acta Agron. 2015; 64: 349–354. Available: https://revistas.unal.edu.co/index.php/acta_agronomica/article/view/45362/53193

51. Sarabia-Salgado L, Solorio-Sánchez F, Ramírez-Avilés L, Alves BJR, Ku-Vera J, Aguilar-Pérez C, et al. Increase in Milk Yield from Cows through Improvement of Forage Production Using the N2-Fixing Legume Leucaena leucocephala in a Silvopastoral System. Anim 2020, Vol 10, Page 734. 2020; 10: 734. https://doi.org/10.3390/ANI10040734 PMID: 32340205

52. Phan TC, Merckx R. Improving phosphorus availability in two upland soils of Vietnam using Tithonia diversifolia H. Plant Soil 2005 2691. 2005; 269: 11–23. https://doi.org/10.1007/S11104-004-1791-1

53. Montoya-Molina S, Giraldo-Echeverri C, Montoya-Lerma J, Chará J, Escobar F, Calle Z. Land sharing vs. land sparing in the dry Caribbean lowlands: A dung beetles' perspective. Appl Soil Ecol. 2016; 98: 204–212. https://doi.org/10.1016/J.APSOIL.2015.10.017

54. Vazquez E, Teutscherova N, Lojka B, Arango J, Pulleman M. Pasture diversification affects soil macrofauna and soil biophysical properties in tropical (silvo)pastoral systems. Agric Ecosyst Environ. 2020; 302: 107083. https://doi.org/10.1016/J.AGEE.2020.107083

55. Alimentro. Alimentos del trópico para alimentación animal—AlimenTro | Datos Abiertos Colombia. 2021 [cited 12 Jan 2022]. Available: https://www.datos.gov.co/Agricultura-y-Desarrollo-Rural/Alimentos-del-tr-pico-para-alimentaci-n-animal-Ali/6arb-d547/data

56. Bell MJ, Wall E, Russell G, Simm G, Stott AW. The effect of improving cow productivity, fertility, and longevity on the global warming potential of dairy systems. J Dairy Sci. 2011; 94: 3662–3678. https://doi.org/10.3168/jds.2010-4023 PMID: 21700056

57. Hagemann M, Hemme T, Ndambi A, Alqaisi O, Sultana MN. Benchmarking of greenhouse gas emissions of bovine milk production systems for 38 countries. Anim Feed Sci Technol. 2011;166–167: 46–58. https://doi.org/10.1016/J.ANIFEEDSCI.2011.04.002

58. Salou T, Le Mouël C, van der Werf HMG. Environmental impacts of dairy system intensification: the functional unit matters! J Clean Prod. 2017; 140: 445–454. https://doi.org/10.1016/J.JCLEPRO.2016.05.019

59. Van Zanten HHE, Herrero M, Van Hal O, Röös E, Muller A, Garnett T, et al. Defining a land boundary for sustainable livestock consumption. Glob Chang Biol. 2018; 24: 4185–4194. https://doi.org/10.1111/gcb.14321 PMID: 29788551

60. Van Zanten HHE, Mollenhorst H, Bikker P, Herrero M, De Boer IJM. The role of livestock in a sustainable diet: a land-use perspective. Animal. 2016; 10: 547–549. https://doi.org/10.1017/S1751731115002694 PMID: 26689533

61. Oosting S, van der Lee J, Verdegem M, de Vries M, Vernooij A, Bonilla-Cedrez C, et al. Farmed animal production in tropical circular food systems. Food Secur. 2021; 1–20. https://doi.org/10.1007/S12571-021-01205-4/FIGURES/3

62. Mottet A, de Haan C, Falcucci A, Tempio G, Opio C, Gerber P. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Glob Food Sec. 2017; 9: 1–8. https://doi.org/10.1016/j.gfs.2017.01.001

63. Verwer C, Schooten VH, Houwelingen VK, Philipsen AP, Eekeren VN, Lenssinck F. Rejection of grass around dung pats; influence of smell, taste or both? Grassl Sci Eur. 2016; 21: 430–432.

64. Klootwijk CW, Holshof G, de Boer IJM, Van den Pol-Van Dasselaar A, Engel B, Van Middelaar CE. Correcting fresh grass allowance for rejected patches due to excreta in intensive grazing systems for dairy cows. J Dairy Sci. 2019; 102: 10451–10459. https://doi.org/10.3168/jds.2018-16120 PMID: 31495629

65. Nichols E, Spector S, Louzada J, Larsen T, Amezquita S, Favila ME. Ecological functions and ecosystem services provided by Scarabaeinae dung beetles. Biol Conserv. 2008; 141: 1461–1474. https://doi.org/10.1016/J.BIOCON.2008.04.011

66. Broom DM. Land and Water Usage in Beef Production Systems. Anim 2019, Vol 9, Page 286. 2019; 9: 286. https://doi.org/10.3390/ani9060286 PMID: 31142031

67. MADR-UPRA. Identificación general de la frontera agrícola en Colombia. Escala 1:100.00. Bogotá; 2018. Available: https://www.minagricultura.gov.co/Normatividad/Projects_Documents/IDENTIFICACION GENERAL DE LA FRONTERA.pdf

68. DANE. Encuesta Nacional Agropecuaria—Serie histórica por departamento usos del suelo (2012 –II semestre 2019). 2019.

69. Graesser J, Aide TM, Grau HR, Ramankutty N. Cropland/pastureland dynamics and the slowdown of deforestation in Latin America. Environ Res Lett. 2015; 10: 034017. https://doi.org/10.1088/1748-9326/10/3/034017

70. Müller R, Müller D, Schierhorn F, Gerold G, Pacheco P. Proximate causes of deforestation in the Bolivian lowlands: An analysis of spatial dynamics. Reg Environ Chang. 2012; 12: 445–459. https://doi.org/10.1007/S10113-011-0259-0/FIGURES/6

71. Fehlenberg V, Baumann M, Gasparri NI, Piquer-Rodriguez M, Gavier-Pizarro G, Kuemmerle T. The role of soybean production as an underlying driver of deforestation in the South American Chaco. Glob Environ Chang. 2017; 45: 24–34. https://doi.org/10.1016/J.GLOENVCHA.2017.05.001

72. Nicholls CI, Altieri MA. Nuevos caminos para reforzar la resiliencia agroecológica al cambio climático. Berkeley: SOCLA books; 2017. Available: https://foodfirst.org/wp-content/uploads/2017/10/Libro-REDAGRES-Caminos-a-la-resiliencia.pdf

73. Carvalho PC de F, Peterson CA, Nunes PA de A, Martins AP, Filho W de S, Bertolazi VT, et al. Animal production and soil characteristics from integrated crop-livestock systems: toward sustainable intensification. J Anim Sci. 2018; 96: 3513–3525. https://doi.org/10.1093/jas/sky085 PMID: 29917103

74. Chai Q, Nemecek T, Liang C, Zhao C, Yu A, Coulter JA, et al. Integrated farming with intercropping increases food production while reducing environmental footprint. Proc Natl Acad Sci U S A. 2021;118. https://doi.org/10.1073/pnas.2106382118 PMID: 34518225