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

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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 synthesize 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).
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>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Set by</th>
<th>Monitored by</th>
<th>Target product</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voluntary Sustainability Standards (VSS)</td>
<td>GANSO</td>
<td>NGO</td>
<td>Third party (private audit)</td>
<td>Meat</td>
<td>At least 15,000 ha (so far)</td>
</tr>
<tr>
<td></td>
<td>Angus Azul</td>
<td>Company</td>
<td>First party</td>
<td>Meat</td>
<td>At least 23,500 ha (so far)</td>
</tr>
<tr>
<td></td>
<td>Livestock Environmental Label</td>
<td>Government</td>
<td>Third party (Incontec)</td>
<td>Meat and milk</td>
<td>Recently launched, no tangible impacts.</td>
</tr>
<tr>
<td></td>
<td>Zero deforestation agreement</td>
<td>Government, companies, NGO</td>
<td>Second or third party</td>
<td>Meat and milk</td>
<td>33 active members</td>
</tr>
<tr>
<td></td>
<td>Colombian Roundtable for Sustainable Cattle Production</td>
<td>NGO, companies, producers</td>
<td>No monitoring</td>
<td>Meat and milk</td>
<td>62 active members (43 from the private sector)</td>
</tr>
</tbody>
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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$_2$eq 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. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| **Actions**                     | **Voluntary Sustainability Standards** | **Public policies** |
|                                 | **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 | x |          |          |
| Implement water use plans that optimize water use and reduce losses | x | x | x | x |          |          |
| Protect natural water bodies from direct use by livestock | x | x | x | x |          |          |
| Land use and feeds |                      |                |                      |                  |          |                |
| Implement silvopastoral systems | x | x | x | x | x | x |
| Implement paddock rotation systems for forage production | x | x | x | x | x | x |
| Reduce methane enteric fermentation via livestock diets (feed additives, improved digestibility) | x | x | x | x |          |          |
| Produce all feed within the farm | x | x | x | x |          |          |
| Soil health and fertilization |                      |                |                      |                  |          |                |
| Implement soil conservation practices (e.g., keep vegetation cover, use green manures). | x | x | x | x |          |          |
| Use of organic fertilizers | x | x | x | x |          |          |
| Organic waste management |                      |                |                      |                  |          |                |
| Recover nutrients from organic waste (including manure) via composting or anaerobic digestion | x | x | x | x |          |          |
| Implement a waste management plan for the collection, storage and disposal of hazardous waste | x | x | x | x |          |          |

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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 silvo-pastoral 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 entomo-fauna. 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$_2$eq/year in the 233 slaughterhouses that operate throughout the country, and 5000 t CO$_2$eq/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].
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 bioenergy 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

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].

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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


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