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Proceeding Paper

Comparing the Sustainability and Circularity of Two Livestock Production Systems in the Sierra Norte of Puebla, Mexico [†]

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Abstract: In this study, integrated crop–livestock production systems (ISG) were compared against intensive (RF) and semi-intensive feedlot systems (FS). A sustainability evaluation incorporating multidimensional indicators and a circularity assessment using biomass, energy, and nutrient indicators were performed. Complete integration of the crop and livestock components greatly increased the productivity of the ISG system, reducing the environmental impact and guaranteeing an adequate level of self-reliance; thus, sustainability was greatly improved when compared to RF. Circularity indicators of ISG and FS mostly showed no differences, but there was a general trend of ISG to improve energy, nutrient cycling, and vegetable biomass production.

Keywords: integrated systems; grazing; sustainability; circular economy

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1. Introduction

Throughout history, societies have been compelled to produce a greater quantity of food within the smallest possible area in order to meet the needs of a continuously growing population [1]. Livestock production faces an additional challenge: reducing environmental impact [2,3].

The integration of agricultural and livestock systems is a way to achieve more sustainable systems. They provide benefits such as the use of crop residues and cover crops for animal feed during dry seasons and the utilization of manure and green fertilizers to increase crop yields [4]. This approach also impacts circularity. The management of ruminant animal species, as part of an integrated system, allows for better utilization of the system's nutrients, maintaining soil fertility by reintegrating part of the consumed nitrogen and other minerals through their excreta [4–8].

Both sustainability and circularity are nested in food production systems, and their evaluation is an important tool for decision making and the adoption of better management practices. This study aimed to evaluate crop–livestock production schemes within a farm to assess the impact of different degrees of integration on the sustainability and circularity performance of the production unit.

2. Materials and Methods

2.1. Description of the Farm Production Systems

The research was carried out in the municipality of Ahuazotepec, located in the Sierra Norte of the state of Puebla, Mexico. It is a high-altitude (2268 masl) valley with a temperate climate, abundant summer rain, and dry, cold winters. In this municipality, "Rancho Laguna Seca" (RLS), a cooperating sheep and cattle family farm, was characterized and monitored for two years (2021 and 2022). RLS is a mostly integrated farm that combines crop and livestock production in different modes: crop–livestock integration through grazing and hay cutting (ISG), as well as semi-intensive feedlot production (FS). The main products obtained are milk, meat, wool, skins, and live market animals.

The farm has a total production area of 9.85 ha with dedicated plots for direct grazing and hay production (legume–gram mixed prairies), gardening, landrace maize cultivation (feed/food grain and forage/silage) + rye winter crop, as well as a 1000 m^2 barn for housing, which is where the feedlot pen is located. Fertilization of the agricultural fields is carried out by grazing animal deposition (ISG) and by spreading barn-collected manure (FS). Prairies are managed using a rotational plan based on the Voisin Rational Grazing (VRG) method, where the optimum resting point is determined by the farmer after weekly inspections. Direct grazing is performed all year long with mobile electrical fencing, while hay production is performed by cutting and sun-drying the forage when the weather allows it. Both dairy cows and ewes graze following the VRG plan with one drinking area per paddock. While the mothers graze, calves (>1 week old) and lambs (>2 weeks old) stay in pens, where calves are bottle-fed, with access to creep feed and water. Cows are milked once or twice per day and fed concentrate, and they stay in the paddock during the warm months and in the barn in the rainy season. After grazing, ewes are moved to the barn, reunited with their young, provided with water, and fed supplements depending on their productive stage. Weaned calves are intended for market/replacement animals, and most lambs are placed in independent grazing paddocks where they do not receive additional feeds (ISG). Other young heifers and steers, and rarely lambs, intended for meat production are first backgrounded in the grazing paddocks and then placed in the feedlot for fattening and finishing (FS). Culled dams and sires are also placed in the feedlot for finishing. Feedlot animals are provided with water *ad libitum*, as well as farm-produced hay/silage and a mix containing 160 g_{CP} ${kg_{DM}}^{-1}$, which includes different feeds, which vary depending on the farm's own production and the local availability of protein-rich seeds and by-products. A single fattening–finishing period in the feedlot pen consists of 90 days.

2.2. Sustainability Evaluation

The MESMIS framework was used to assess the sustainability of the whole farm integrated system (FS+ISG). Twelve indicators were selected, representing six attributes and the three sustainability dimensions (Table 1). Indicators for the ISG were derived from farm records and quantified as described in Table 1, while the reference values were estimated or defined after consulting the relevant literature and statistical databases such as the National Agricultural Survey and Economic Censuses carried out by the National Institute for Statistics, Geography and Information (INEGI for its Spanish acronym).

Table 1. Economic, environmental, and social sustainability indicators used for the evaluation of the livestock systems (2021–2022 cycle).

Dimension	Attribute	Indicator	Quantification	Reference System Value [1]	RLS Integrated System Value
Economic	Productivity	Grain Yield (GY)	Direct measurement of maize grain produced per unit of area (t ha^{-1}) [9]	3.5 (white)	4.87 (pigmented)
		Net Income (NI)	NI = Total production value − Total production costs (MXN) [10]	7930 MXN	26,220 MXN
		Benefit-to-cost ratio (BCR)	BCR = Net economic returns of the products (MXN)/production costs (inputs and labor; MXN) [9]	2.12	2.45

Table 1. *Cont.*

Dimension	Attribute	Indicator	Quantification	Reference System Value [1]	RLS Integrated System Value
Environmental	Stability, resilience, and reliability	Water use efficiency (WUE)	WUE = Yield/water used (kg m^{-3}) [9]	0.37 kg m^{-3}	2.21
		Fertilizer use efficiency (FE)	FE = Crop yield (kg ha^{-1})/fertilizer used (kg ha^{-1}) [10]	0.018	0.18
		Feed use efficiency (FUE)	FUE = Weight gain (kg)/Feed and forage consumed (kg)	0.103	0.137
Social	Adaptability	Non-paid family labor and producer involvement (UFL)	UFL = [Daily family labor (h)/Total daily labor required (h)] × 100 [9]	96.4%	57%
		Paid labor (PL)	PL = [Daily employee labor (h)/Total daily labor required (h)] × 100 [9]	3.6%	43%
	Self-reliance	Literacy	Percentage of the system actors (family, producer, employees) with a high-school education [11]	86%	100%
		External feed dependency	EFD = [External feed cost (MXN)/Total input cost (MXN)] × 100 [9]	64.9%	N.A. [2]
		Self-financing level (SF)	SF = [Government subsidization input cost (MXN)/Total production costs (MXN)] × 100 [9]	40%	17%
		Self-sufficiency	Amount of family food needs that are covered by the system production (milk, meat, grain; %)	68.4% [1]	70%

[1] Direct consultation with local producers or derived from relevant statistical or literature sources. [2] N.A.—not applicable since no feeds are purchased outside the farm.

After quantifying each indicator, the value was weighed against the reference value, thus assigning a score between 0 (worst) and 100 (best). Reference values were considered as the intermediate sustainability score of the indicator and were based on an intensive feedlot and maize cropping system typical for the region, without grazing and where no integration occurs (i.e., manure is not used to fertilize fields; maize forage/stover is not used to feed the animals).

2.3. Circularity Evaluation of the Farm Subsystems

The Nested Circularity Assessment Framework presented by Koppelmäki et al. [12] was used as the basis for this evaluation. Circularity was evaluated longitudinally for the production subsystems within the farm (FS and ISG) but only for bovine production. This is because only 15% of lambs undergo fattening and finishing stages in the feedlot. Appropriate indicators were selected for the characteristic elements of circular food systems (biomass for food and feed, energy production and consumption, and nutrient cycling):

- Biomass for food: protein produced (grains, meat, milk; kg cycle^{-1});
- Biomass for animal feed: protein produced for feed (forage; kg cycle^{-1});
- Biomass for energy: energy produced (MJ ha^{-1});
- Nutrient cycling: agricultural field nitrogen balances (N kg ha^{-1}).

FS and ISG subsystems were monitored, and farmers' records were used to obtain production data: input inventories, production of milk, meat, grain, and maize stover, as well as live weight gain. ISG manure and prairie forage production were estimated from random field sampling on grazing days. Crude protein and nitrogen in feed and food were obtained using the Kjeldahl method on (cereal, milk, meat, and forage) samples taken during the cycle. Available soil and manure nitrogen (ammonia and nitric nitrogen) were measured colorimetrically using the phenol disulfonic acid method and the Nessler reagent on appropriate extracts. Energy consumption and production were quantified by inventorying the amount of each input consumed (fertilizer, fuel, herbicide, labor, animal power, etc.) and the products obtained during the production cycle [13]. Then, these amounts were converted to their energy equivalents using values from references [14–20].

3. Results and Discussion

3.1. Sustainability of an Integrated Farm

The results obtained from the characterization of an integrated grazing livestock production system can be seen in Table 1, while indicator-weighed scores were plotted on a radial chart for comparison (Figure 1). The majority of indicators on the RLS had values that, at the very least, were equal to those of conventional feedlot systems (Table 1).

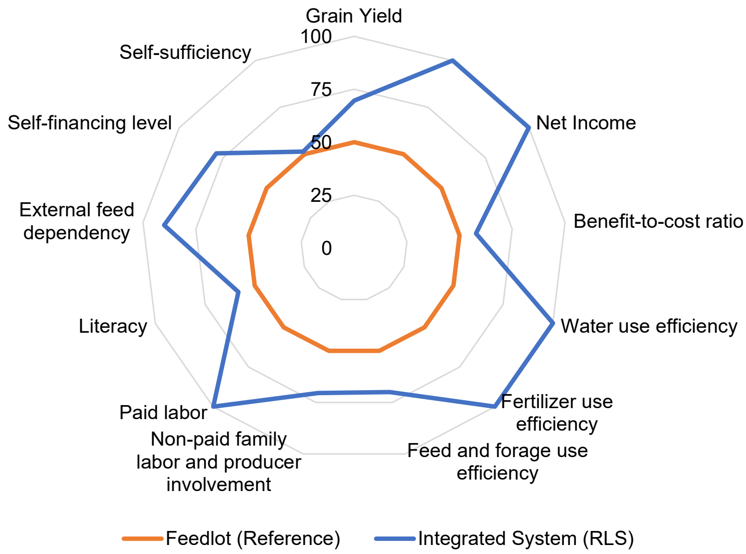

Figure 1. Radial chart for the measured sustainability indicators. The variables were standardized on a scale from 0 (worst score) to 100 (best score).

Sustainability scores revealed that the economic dimension showed the greatest improvement. NI score doubled, while GY increased by 39.2%, and the BCR increased by 15.5% in the RLS when compared to intensive cropping systems that are not integrated. The increase in productivity was due to the added value of forage production from the prairies and maize stover, as well as the production from winter cover crops (rye, vetch). RLS also had the advantage of growing pigmented landrace maize, which commands a higher market value than white varieties (10,000 MXN vs. 5000 MXN per ton). Studies have shown that diversification of activities in farms via the integration of livestock, grazing, and silvopastoral schemes can help production units become more economically profitable and resilient [21,22]. BCR score improvement was not as high as that of NI. Integration of grazing reduced feeding costs but increased the use of machinery, labor, and irrigation (water pump) for hay production and the cultivation of forage winter crops and re-sowing of clover and annual ryegrass for the prairies.

The environmental dimension also showed overall better sustainability scores in the RLS than in the reference system. The application of animal manure not only affected the costs but also improved the FE by reducing the need for chemical fertilizer in the cropping fields. Additionally, the increase in yield from the diversified production could have improved water use. In the long term, it would be expected that these results are maintained because of organic fertilization, which is known to improve soil organic matter, water retention capacity, and fertility [23,24].

Locally, young animals are thought to perform better under confinement and fed a grain-heavy diet, while grazing is perceived as a poor man's feeding strategy. Consequently, the land is intensively cropped with maize for food and feed, while high-quality forages and other feeds are imported, and maize stover (considered low-quality feed) is left on the fields or sold to smaller farms. Similar to previous studies, the high feed efficiency of

RLS highlights how an adequately planned grazing and forage-heavy diet can compare favorably to gains in intensive feedlots [25]. The implementation of such a system, however, requires the rethinking of land and resource allocation and, as mentioned above, additional efforts to ensure the quantity and quality of feed.

The attributes of the social dimension refer to the farm's ability to evolve and adapt, as well as how quickly the system actors can manage and respond to new challenges. The RLS farm has better infrastructure and a lower dependence on family labor. These conditions improved the scores for adaptability indicators, given that there are sufficient hours available to pursue improved agricultural practices [9]. A higher level of literacy and lower dependence on subsidization in RLS may have helped successfully adopt a rotational grazing system using mobile fencing in the early 1970s, very close to the publication of Voisin's foundational works. Although both the intensive and the RLS systems provide similar amounts of food for the family, ISG did so with a 79% reduction in the dependence on external feeds, indicating that integration reduces the number of inputs in the production unit, as proposed by [26].

3.2. Circularity of ISG and FS

Results for the circularity indicators can be seen in Table 2. There were no significant differences between the FS and the ISG ($p > 0.05$), except for energy efficiency, which was significantly higher in ISG. Higher energy efficiency could be expected since ISG's need for external inputs is reduced as lower amounts of imported feed, chemical fertilizer, hay cutting, and manure spreading are needed, which reduces the fuel, machinery, and transport requirements [22,27]. In that regard, other studies have found that even a short feedlot stage can greatly increase the environmental impact of cattle production in terms of fossil fuels [27]. Additionally, complete integration and rotational grazing have also been found to provide ecosystem services (carbon sequestration, biodiversity conservation, etc.) and potentially reduce emissions of livestock [28,29].

Table 2. Circularity indicators for two livestock production subsystems that are present in one family farm (2021–2022 and 2022–2023 cycles).

Circularity Element	Indicator	Item	Semi-Intensive Feedlot (FS)	Integrated Grazing System (ISG)
Biomass for food and feed	Protein produced for food (kg cycle^{-1}) and feed (kg ha^{-1})	Milk	681.93 a	673.07 a
		Meat	241.45 a	231.37 a
		Cereal (maize)	414.62 a	465.04 a
		Maize stover/silage	317.97 a	348.42 a
		Prairies	2688.33 a	2732.16 a
Biomass for energy	Energy efficiency (MJ/MJ)	Energy produced/energy consumed	4.55 a	15.90 b
Nutrient cycling	Agricultural field nitrogen balances (N kg ha^{-1})	Available N at the beginning of the cycle	87.86 a	87.86 a
		Available N at the end of the cycle	94.93 a	101.85 a

Letters indicate differences between systems ($p < 0.05$); those that do not share a letter are significantly different (Tukey method, $\alpha = 0.05$).

Numerically, a trend for improvement was also present in other indicators, showing how fully integrated subsystems can enhance circularity elements at a farm scale in terms of energy, nutrient cycling, and vegetable biomass production. Both FS and ISG were able to maintain nitrogen levels in the soil after production ended (Table 2), but it was observed that silage production required 22% less nitrogen in the ISG. These benefits could be ascribed to the better fertilization management obtained with direct manure depositions in the fields during animal grazing. Additionally, an increase in vegetable protein biomass for ISG could be due to the presence of micronutrients in manure that enhance nitrogen utilization in plants like maize [23,30]. The marginally lower animal protein production (−4% milk and −1% meat) in ISG could be due to water management since the animals only had one fixed drinking point that could not be accessed easily as the mobile fence was moved.

Although no subsystem showed complete superiority, a fully integrated crop–livestock production scheme seemed to perform as well as a more intensive one to obtain animal-derived protein. The reduced negative effects and a trend for improved circularity should encourage the farmer to fully embrace the ISG subsystem as the main production mode on the farm.

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