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Costs, Benefits and Challenges of Sustainable Livestock Intensification in a Major Deforestation Frontier in the Brazilian Amazon

Edenise Garcia [1,*], Fábio Sampaio Vianna Ramos Filho [2], Giovanni Matheus Mallmann [1] and Francisco Fonseca [1]

1 The Nature Conservancy, Belém 66035-115, Brazil; gmallmann@tnc.org (G.M.M.); ffonseca@tnc.org (F.F.)
2 Agrosuisse, Rio de Janeiro 22270-010, Brazil; framos@agrosuisse.com.br
* Correspondence: egarcia@tnc.org; Tel.: +55-91-4008-6200

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Abstract: Extensive livestock production is a major deforestation driver in the Brazilian Amazon. This study presents an assessment of the economic and environmental feasibility of sustainable livestock intensification in São Félix do Xingu municipality, a deforestation frontier with an area of more than 8.5 million hectares, and home to the largest cattle herd in Brazil. Proposed intensification was limited to approximately three animal units per hectare to avoid negative environmental impacts. Transition costs to sustainable cattle intensification were estimated for thirteen pilot farms taking into account adoption of good agriculture practices, pasture maintenance/restoration, and restoration of environmental liabilities. To move to sustainable intensification practices, a mean total annual investment of US$1335/ha ± US$619/ha would be necessary, varying from US$750 to US$2595/ha. Internal rate of return and net present value estimates indicated that the sustainable livestock intensification approach proposed was profitable in farms with more than 400 hectares of pastureland, but not in those where the pasture areas were smaller than 150 hectares. Livestock sustainable intensification also had the potential to promote social and environmental benefits, including a 54% increase in the number of contract workers, improvement of landowners' managerial skills, and workers' training, in addition to avoiding emission of 1.9 Mt CO_2eq and sequestration of 0.36 Mt CO_2eq. We conclude that the sustainable intensification of pasture areas has the potential to prevent further deforestation in the Amazon while generating social and other environmental benefits.

Keywords: livestock; sustainable intensification; Amazon; deforestation

1. Introduction

Since the early 1970s, livestock production has been one of the main economic drivers to the occupation of the Amazon. Characterized by low or zero investment in soil management practices, nutrient supply or technology, livestock became a cheap way to fill and ensure possession of large tracts of land, generally occupied by less than one head of cattle per hectare [1]. Cattle ranching also became widespread in small-sized properties, which followed the practices used in larger farms, based on successive processes of slash-and-burn of primary and secondary forest for the establishment of pastures [2]. The small herd found in smaller properties is often used for the production of dairy products, and for breeding and fattening of calves for larger farms, but overall productivity tends to be low due to both limited technical and financial capacity. Even so, small farmers perceive their herd as savings, as instruments of liquidity, and hedge against inflation [3].

Without proper pasture, animal and overall farm management practices, traditional extensive livestock systems frequently experience a sharp decline in pasture productivity after 5–15 years of grazing, leading to the abandonment of large areas [4]. Consequently, overall livestock productivity (about 80 kg of beef per hectare per year) is well below its potential of 300 kg per hectare per year [5], and forest clearance is still used as a mechanism to compensate for the low performance. Despite a significant decrease in the rate of deforestation in the Amazon of about 80% in 2015 as compared to peak rates in 2004, forest conversion still persists, and cattle ranching accounts for part of this resilient deforestation [6].

The risk of illegal deforestation and land competition due mainly to soy agricultural expansion [7] means beef production in the Amazon region needs to be more efficient. Intensification has been put forward as a main alternative to keeping livestock production profitable and environmentally sustainable at scale since it increases productivity while avoiding forest loss [8]. Cattle intensification also has the potential to make pastureland available to non-livestock-based agricultural commodities [9]. This is strategic in terms of food security considering that by 2050 worldwide demand for agricultural products is expected to increase by more than 50% [10], and that Brazil makes major contributions to the global demand for food [11].

Nevertheless, there are relevant challenges to shifting from extensive practices to intensive and sustainable livestock production in the Amazon region. The need for high investments and low access to credit, combined with a lack of technical assistance and skilled labor, an inefficient infrastructure logistics, and even cultural resistance to the adoption of new managerial practices and technologies make the task challenging. Moreover, adoption of intensification practices entails high upfront costs to farmers and low returns during the period of transition, requiring a behavior change that can only be achieved if producers are convinced of the economic viability of intensification. Considering this and taking the environmental and socioeconomic importance of beef production in the Amazon into account, the objective of this study is to provide an empirical basis for assessing the feasibility of implementing sustainable livestock intensification in consolidated areas of the Amazon region. The "sustainability" of intensification in this study hinges upon mixed perspectives: (i) land sparing effect of intensification/decreased demand for land relative to a business as usual (BAU) scenario; (ii) a "moderate" intensification approach (on average three, but no more than four animal units per hectare (AU/ha; 1 AU is equivalent to 450 kg of animal live weight); (iii) the adoption of a good agriculture practices (GAP); and (iv) the restoration of environmental liabilities. Transition costs and financial indicators were estimated taking into account the adoption of good agricultural and management practices, pasture improvement, and restoration of environmental liabilities. To this aim, the article builds deeply on results in pilot beef farms located in São Félix do Xingu (SFX), an 8.4 million-hectare municipality in the Eastern Amazon region that has experienced widespread conversion of forest to pastureland, and is currently home to the largest cattle herd in Brazil. The study starts with a description of 13 pilot properties and the approach used to estimate sustainable intensification transition costs, followed by a discussion of technical and financial results of the project implementation. The study also identifies and discusses as well risks and opportunities for the intensification of livestock in SFX, including credit needs, jobs generation, and impacts in CO_2 emissions or sequestration.

2. Materials and Methods

2.1. Study Area

Located in Southeastern Pará, São Félix do Xingu (SFX) occupies an area of 8.4 million hectares (Figure 1). More than half of the municipality is legally protected: 4.5 million hectares of indigenous lands and 1.6 million hectares of protected areas. These expanses play an important role in preventing the advance of deforestation, except for the Environmental Protection Area *Triunfo do Xingu*, less strict in its use, where pastures occupy approximately 16% (180,000 ha) of its total area. Pastureland also occupies 42% of the remaining non-protected area [12]. Although SFX has been a major deforestation frontier for the last ten years, annual forest conversion has sharply decreased during the period: the area deforested in 2015 represents 25% of that cleared in 2006 [13]. São Félix do Xingu's 2.2 million animals, most of which are beef cattle, represent 1% of the total Brazilian cattle herd population [14]. Approximately 50% of the herd in the region is intended for the full production cycle (breeding, raising and fattening), 12 percent for raising and 20 percent for fattening; the remaining is used for dairy production [15].

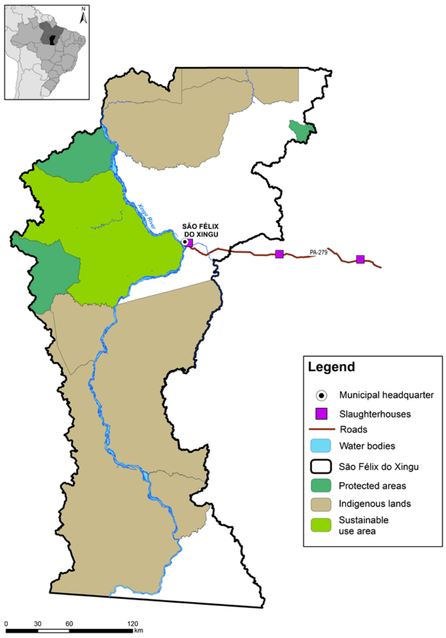


Figure 1. Map of São Félix do Xingu municipality, in Pará state, Brazilian Amazon.

2.2. Pilot Properties

Demonstration units for the development of a sustainable model of livestock intensification were set up in 13 properties with extensive livestock activities in São Félix do Xingu in 2013. The pilot properties represented a range of pasture size and degradation level in order to provide reference values for transition costs from a business as usual extensive model of livestock production to a sustainable, intensive grass-based model. Registration in the Rural Environmental Registry (known by its Portuguese acronym CAR) was an essential condition for participation in the project. The CAR is a mandatory tool for environmental compliance of all rural properties across Brazil and includes geo-referenced information about properties' boundaries, as well as the limits of their permanent preservation areas (PPA) and legal reserves, areas within private properties that need to be preserved according to the Brazilian Forest Code [16]. Permanent preservation areas encompass riparian zones, and hilltops and steep slopes that need to be restored if degraded or deforested. The legal reserve is the minimum portion of each property that must be maintained as native vegetation, and may include permanent preservation areas. In the Amazon region, this corresponds to 80% of the property area; but, in areas with approved Ecological and Economic Zoning or in properties smaller than 300 hectares, this percentage is reduced to 50% in farms where deforestation occurred prior to 2008. Areas of legal reserve deforested in excess after 26 July 2008 need to be restored in situ, whereas areas deforested before that date may be restored or offset. Shapefiles of properties were retrieved from the Pará State Rural Environmental Registry database (SIMLAM) [17] on September 2015. Overlapping areas among properties, frequently observed in the SIMLAM database, was assessed with ArcGIS 10.2 for Desktop (ESRI: Redlands, CA, USA, 2013), and whenever necessary boundaries were manually adjusted based on field survey data and digital land cover, hydrology and road maps at a 1:25,000 scale, elaborated from Spot 5 2.5-meter and RapidEye 5-meter resolution satellite images from 2012. Properties' permanent preservation areas and legal reserve assets or liabilities, including areas that needed to be restored in situ, were then identified.

A comprehensive analysis was completed for each pilot property based on field surveys, soil and remote sensing analyses, landowners' information on costs of livestock production and secondary data, in addition to cattle information (number of animals, category, age, weight, etc.). An intensification plan was defined for each property based on the analysis that aimed at reaching an average carrying capacity of 3.0 AU/ha (animal units per hectare; 1 AU is equivalent to 450 kg of animal live weight). The plans had three main components: adoption of good agricultural practices (GAP), maintenance and/or improvement of pastureland, and restoration of PPA. Farmers participated in technical and management trainings, as well as direct field technical assistance to ensure the consistent implementation of all three components. Field data from the demonstration units were extrapolated to the whole property pasture area, and projected for Years 6 and 12 of the project. According to the established intensification plan, approximately 20% of the total pasture area would be managed each year regardless of their degree of degradation so that in five years all areas would have improved. Environmental restoration and pasture intervention activities would begin in the first year; in the second, the productivity would start to increase, and by Year 6 restoration of degraded areas would be concluded and carrying capacity would be at the expected level. Sustainable intensification transition costs were estimated separately for each component, but were then added up to generate the total transition cost of each property.

The EMBRAPA [18] good agricultural practices program was adopted as a reference for sustainable livestock practices and farm management. Among a multiplicity of GAP approaches on a number of fronts [19], the EMBRAPA program was chosen because it fitted the needs of pilot farms the best, with particular focus on the following topics: whole property and human resources management, including salaries and other employees-related expenses; animal well-being (cattle health, reproductive improvement and nutrition, vaccines, sanitary control and medications, and technical and veterinary assistance); animal traceability, and soil/pasture management, including rotational grazing and no-till farming. Consequently, the adoption of good practices required several changes and adjustments to the production system in different sectors of the farm, achieved through trainings and monthly visits by rural technicians to provide technical support and monitor pastureland and herd. In addition to the topics mentioned above, the cost of GAP implementation took into account infrastructure maintenance and investment costs (housing, buildings, operational costs, machinery and equipment), and administrative costs.

Costs of pasture intervention were based on the level of degradation and the method adopted for pasture improvement, and included the price of fertilizers, lime, fodder seed, and costs for the implementation of a rotational system. Although pasture degradation is a widespread problem, there is no consensus about its definition [1]. In this study, weed infestation and bare soil were adopted as proxies of pasture degradation because they could be easily detected visually. The level and extent of degradation in the pilot properties were estimated through field analysis and mapped using GIS tools. Pastureland was classified into the following categories: null, low, medium or high degradation, defined respectively in this study as areas with weed infestation and/or bare soil cover of: 0%, >0% up to 10%, >10% up to 20%, and >20%. Differences in degradation level influenced the choice of the pasture intervention method. Basically, three alternatives were considered, individually or in conjunction: maintenance, restoration and renewal [1,20]. Pasture maintenance included mowing, weeding, fertilization, liming, and rotational grazing, and was applied to low and medium-low degraded areas. Restoration, a more intensive intervention than pasture maintenance, but with no alteration in soil structure, was used in pasture with medium degradation levels. Pasture renewal, consisting of a complete destruction and subsequent reestablishment of the pastureland, was performed in highly degraded areas.

Costs of environmental restoration were estimated only as a function of the extent of degraded permanent preservation areas. Because there was no post-2008, in situ restoration of legal reserve was not required. Fencing was needed to isolate the areas to be restored from animals. Initially, costs of a combination of fencing and sowing, and of fencing and planting seedlings were estimated for the pilot properties. However, the analysis of areas with degraded permanent preservation areas, including distance to forest fragments, indicated a good potential for regeneration of native vegetation as long as they were isolated, precluding the adoption of more expensive interventions, such as sowing or planting seedlings. Therefore, costs of environmental restoration were based on the length of fences needed to isolate the degraded areas. Fence values were obtained locally, and fence characteristics such as spacing, posts, and number of wires varied according to property characteristics. An average fence value per hectare was calculated.

Technical and economic indicators were calculated for each property for the first two years of sustainable livestock intensification and projected costs for Years 6 and 12 taking into consideration zootechnical indices, price of purchase and sale of animals, spreadsheet results (cash flow), and system efficiency indicators. The technical indicators included pastures' annual carrying capacity (AU/ha) and offtake rate. The former was estimated as the average stocking rate along the year in non-degraded pasture, and the latter corresponded to the ratio between the number of slaughtered cattle and the size of the herd over a one-year period. Economic indicators of productivity were estimated in terms of *arroba* (@—unit of weight corresponding to ~15 kg) per hectare per year (@/ha/year) and US$/ha/year. The total transition cost (US$/ha) was converted to a productivity indicator, @/ha, and this value was compared with the projected herd evolution for each property (@/ha-projected) in Years 6 and 12 of the project.

Financial indicators were used to evaluate if the proposed intensification system was viable, according to the implemented technological level. Net present value (NPV), internal rate of return (IRR), and payback (the period of time required for recouping a capital investment) were estimated for investing on pasture improvements over a 12-year period. The NPV is the difference between the sum of the present value of the benefits and the sum of the present value of the costs. The IRR is the discount rate that will make the NPV equal to zero. If the NPV is positive or the IRR exceeds a minimum acceptable rate of return (MARR), the project is worthy. The NPV method calculates additional wealth, and is considered to be more robust than the IRR method, which does not assess the financial impact, and cannot be used to evaluate projects with changing cash flows. While the NPV is calculated in terms of currency, the IRR provides the results in percentages, allowing in turn for a direct comparison with alternative investments. It is also easily understood by decision-makers who may not have a financial background [21,22]. The MARR used in this study was 6%, the same as the Brazilian savings account interest rate in the year the project started. Savings account return was used as a reference because this is a popular investment strategy among traditionally risk-averse ranchers.

Carbon footprint of sustainable livestock intensification strategies in pilot farms was compared to a business as usual (BAU) scenario. Emissions were estimated using data from Brazilian Ministry of Science and Technology [23,24] for enteric fermentation, manure, fertilization and N_2O soil emissions. CO_2 emissions from deforestation related to pasture expansion under a BAU scenario were estimated using calculated deforestation rate for non-pilot livestock farms in the SFX region from 2009–2012 projected to a 12-year period; a biomass of 100 tonnes of C per hectare was used in these estimations [25]. Carbon sequestration associated to the restoration of permanent preservation areas under sustainable intensification were estimated using an average increase in biomass of 10 tonnes of C per year [26].

2.3. Data Analyses

All data were tested for normality and homoscedasticity. For normally distributed data, results are expressed as mean ± standard deviation. Between-group differences in the mean and median were determined with the use of *t*-tests and Mann–Whitney *U* test, respectively. Pearson's correlation coefficient was used to investigate the relationship between pasture size and zootechnical and economic indicators. Sensitivity analyses were performed to determine the impact of variations of ±5% and ±10% in beef sales price, cost of pastureland intervention, and feed costs on the predicted IRR for the farms where this rate could be technically estimated under the intensification scenario. All costs considered in estimates for the pilot properties were the ones prevailing in the SFX region in 2014, and were converted from Brazilian real to US$ using the official exchange rate of 31 December 2014. For the purpose of comparisons, this date was also used to update monetary values from references published before 2014. All GIS analyses were performed using ESRI ArcGIS 10.1 software, and statistical analyses were performed using JMP 11.0.0 (SAS Institute Inc., Cary, NC, USA, 2013).

3. Results

The main characteristics of the 13 pilot properties are shown in Table 1. Total area of the farms was 40,000 ha, half of which was occupied by pastureland. Most farms were larger than 1000 ha, with pasture area ranging from 865 ha to 3320 ha. Three farms were smaller than 500 ha, and their pasture covered 44 ha, 126 ha and 426 ha. On average, 59% of the pasture area in pilot farms showed low-level degradation or were not degraded, 23% presented medium-level and 18% high-level degradation. In five properties, however, 50% of the pasture area had medium to high-level of degradation.

Table 1. Characteristics of 13 pilot properties and their pasture area, located in São Félix do Xingu region, Pará state, Brazilian Amazon.

				Pasture Condition (in Percentage of Total Pasture Area)			
Farm	**Total Area (ha)**	**Pasture Area (ha)**	**PPA [1] to be Restored (ha)**	**No Degradation**	**Low Degradation**	**Medium Degradation**	**High Degradation**
1	183	126	4.9	30	20	30	20
2	5439	2973	90.2	80	10	10	0
3	6900	1400	94	40	20	20	20
4	2934	2115	68	30	30	20	20
5	642	426	13.2	20	20	40	20
6	2558	1197	113	20	20	30	30
7	5543	865	53.7	20	20	30	30
8	1118	911	16.9	60	20	10	10
9	1820	1600	200	40	20	20	20
10	4383	2471	199	60	10	20	10
11	3171	2760	55.5	50	20	20	10
12	100	44	4.5	30	20	30	20
13	5213	3320	76.9	40	20	20	20
Total	40,003	20,208	990				

[1] Permanent preservation areas.

Figure 2 presents Partial and total transition costs per farm. A seven-fold variation in GAP-implementation costs was observed in pilot properties, with the lowest value being US$91/ha and the highest US$659/ha. On average, these costs were 2.3 times higher in the three properties with the smallest pasture area as compared to the other farms.

Annual costs of pasture intervention through restoration or renewal in pilot properties ranged from US$261/ha to US$697/ha, and maintenance costs were estimated at US$253/ha. Regrouping properties with similar level of degradation enabled differentiating them as: properties showing a clear predominance (50% or 60%) of pastureland with medium to high-level degradation ($n = 5$), farms where these levels of degradation were observed in 30% or less of the pasture area ($n = 4$), and farms in a position between these two groups ($n = 4$). A significant difference in pasture intervention costs was observed ($p < 0.01$) between the groups with the highest and lowest extent of degraded areas. Mean pasture intervention cost in the former (US$459/ha $\pm$ US$139/ha) was 57% higher than in the latter (US$292/ha $\pm$ US$28/ha). The two pilot properties with the smallest pasture areas (44 and 126 ha) were ranked first and third in terms of highest pasture improvement costs. In both cases, 50% of the pastureland had medium or high-level degradation.

Costs of environmental restoration were based on the extent of degradation in permanent preservation areas, which varied from 5 to 200 ha (Table 1). Each hectare required between 0.10 and 0.53 km of fencing, and the cost of environmental restoration ranged from US$267 to US$1867 per hectare of restored area. On average, cost of fencing alone was 12% lower than a combination of fencing and sowing, and represented only 33% of the cost of a combination of fencing and planting seedlings.

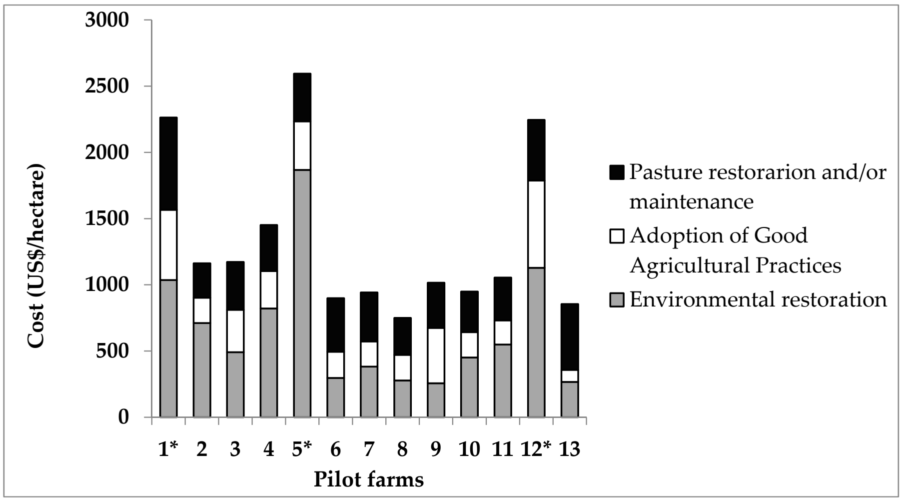


Figure 2. Transition costs in 13 pilot farms located in São Félix do Xingu region, Pará state, Brazilian Amazon. * Indicates properties with pasture area smaller than 500 ha.

To move to sustainable intensification practices, a mean total annual investment of US$1335/ha ± US$619/ha would be necessary, varying from US$750 to US$2595/ha. On average, about half of the upfront investments was associated with environmental restoration, 32% with pasture intervention and 22% with adoption of GAP. There was a significant negative correlation between pasture size and total transition cost ($r = -0.62$, $p < 0.05$). In fact, the three farms with pasture areas smaller than 500 ha made up a very distinct group, showing mean total transition cost of US$2368/ha, 131% higher than the average transition cost of all other pilot farms (US$1025/ha). In two of these properties—the ones with 44 ha and 126 ha of pasture—transition costs of all three components tended to be higher than those of larger farms, whereas in the farm with 426 ha of pasture, higher total transition cost was driven primarily by environmental restoration. On the other side of the spectrum, costs associated with the adoption of GAP were relatively low in farms with the largest pasture areas, lowering the cost of total investment needed.

The conversion of transition costs to @/ha/year indicated that an annual productivity between 3.7 and 12.7 @/ha (average 6.5 ± 3.0 @/ha) would be necessary to match the transition expenses (Figure 3). In four pilot properties, productivity in Year 1 was enough to cover transition costs, but in all other farms productivity would need to increase by 6%–100% over time to match transition costs. By Year 12, projected productivity would be enough to cover transition costs in all, but one property, creating a positive balance of up to 22 @/ha/ year, which suggests that the proposed model is technically and economically feasible especially in pasture areas larger than 400 ha. In farms presenting pasture areas smaller than 150 ha, projected yield in Year 12 was either marginally profitable (0.8 @/ha/year) or showed a deficit in relation to transition costs.

Carrying capacity in Year 1 varied from 1.0 to 1.5 AU/ha, except in one farm where it was higher than 2 AU/ha. In six out the 13 pilot farms, stocking rates in Year 1 were above pastures' carrying capacity. The projected carrying capacity (3 AU/ha) was expected to be reached at year Year 6 of the project (and it would stabilize thereafter), when restoration of degraded pastures and APPs would be completed. For three farms where greater investment in pasture fertilization, food supplementation and herd genetic selection were advanced, the scenario was revised to between 3.5 and 4 AU/ha by Year 12 of the project.

An increasing trend in offtake rate was projected for Years 6 and 12 relatively to the baseline in most pilot farms (Figure 4). In Year 1, offtake rate varied from 3.4% to 33.8%, whereas in Year 12 it would range from 20.5% to 47%, with increases reaching from 32% to almost 450%. In three farms with an offtake rate twice the average rate at the beginning of the project, a decrease between 17% and 26% would be observed in Year 12. Despite the decrease, their offtake rate was comparable to the ones projected for the other pilot farms in Year 12.

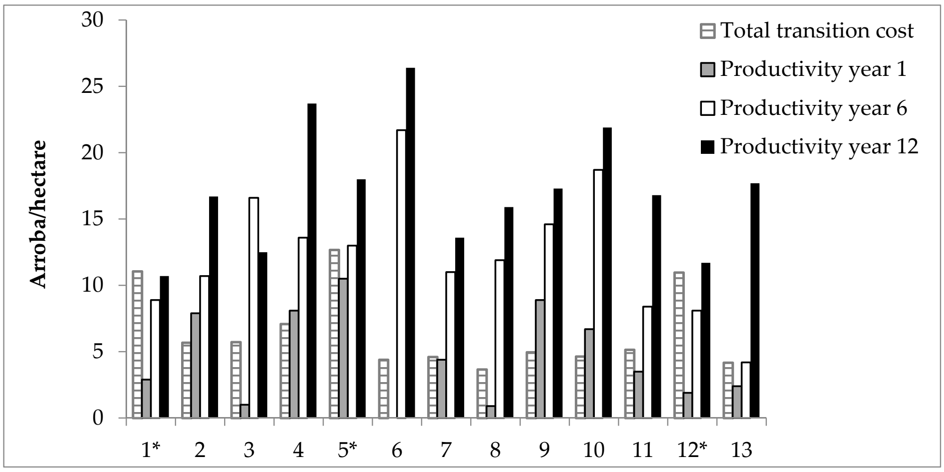


Figure 3. Total transition costs converted to a productivity indicator; observed productivity in Year 1; and projected productivity in Years 6 and 12 of the project in 13 pilot farms located in São Félix do Xingu, Pará state, Brazilian Amazon. All values are in arroba (@)/hectare (1 @ corresponds to approximately 15 kg). * Indicates properties with pasture areas smaller than 500 ha.

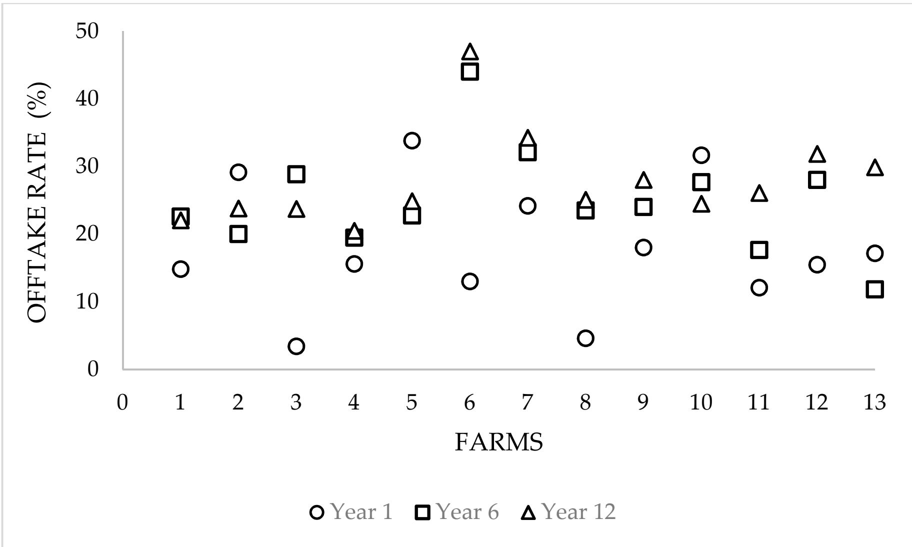


Figure 4. Offtake rate in 13 pilot farms located in São Félix do Xingu, Pará state, Brazilian Amazon calculated for Year 1 and projected for Years 6 and 12 of the project.

Financial results expressed as payback, net present value and internal rate of return, estimated for Year 12 of the project at a MARR of 6% showed that in the 10 pilot properties with a pasture area larger than 500 ha, NPV was positive and the IRR was higher than 6%. Mean NPV for these 10 properties was US$377/ha $\pm$ US$220/ha, ranging from US$128/ha to US$832/ha (Figure 5a). The NPV represented the addition to farms' wealth, or the capital gained comparatively to the investment in an alternative that earned at a nominal rate of 6% a year. In these 10 pilot farms, IRR varied from 4.5% to 22.4% (Figure 5b), and payback ranged from 7 to 11 years (Figure 5c). In the three properties with pasture area bellow 500 ha, NPV was negative as follow: −US$3490.60, −US$1780.20 and −US$162.81, in properties with pasture area of 44 ha, 126 ha and 426 ha, respectively. In the two properties with the smallest pasture area (properties number 1 and 12 in Figure 5b), the IRR could not be technically estimated, given negative cash flows, and in the third one (property number 5) it was only 3%. Payback in these three farms was 11 or 12 years.

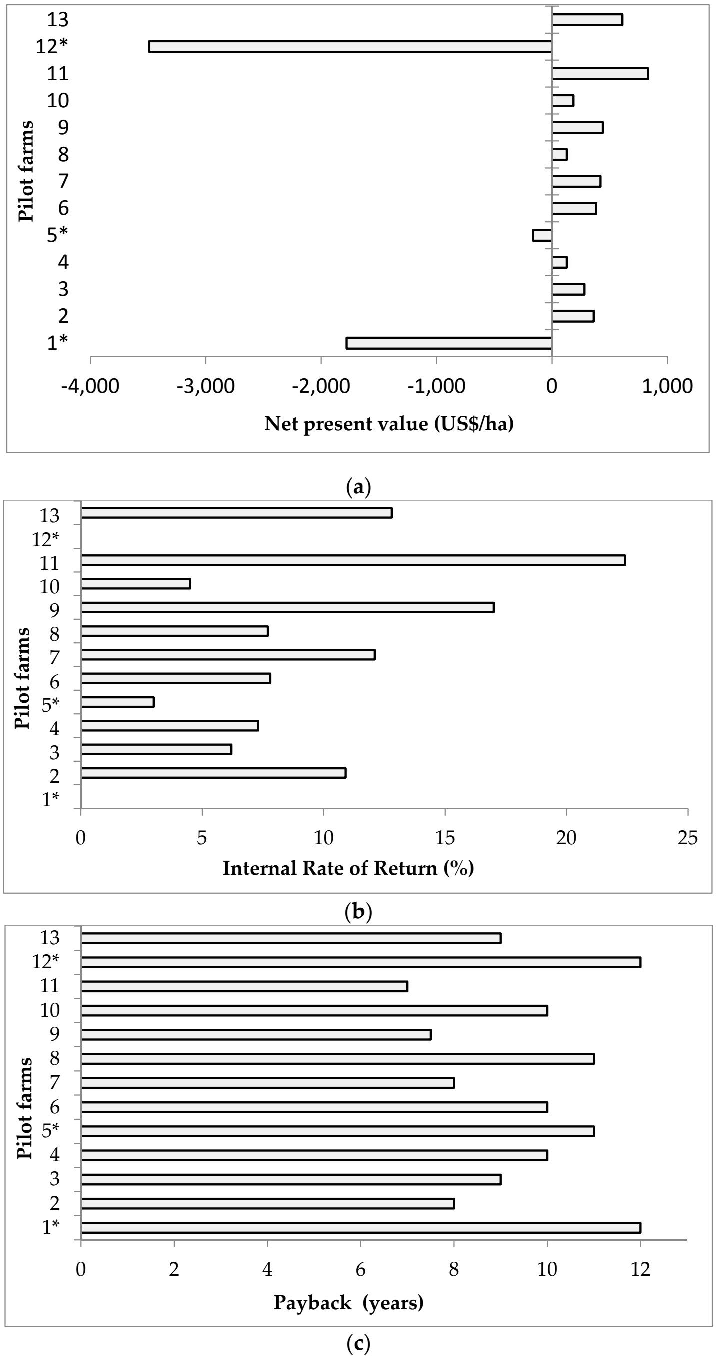
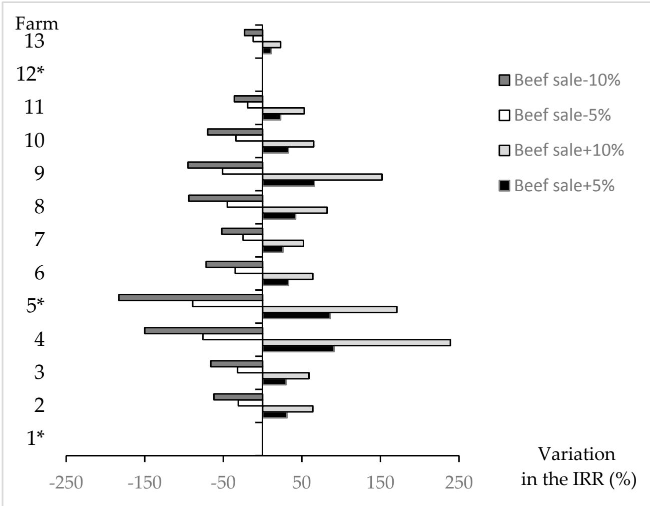


Figure 5. Financial results projected for 13 pilot farms located in São Félix do Xingu, Pará State, Brazilian Amazon: (**a**) net present value; (**b**) internal rate of return; and (**c**) payback. * Indicates properties with pasture area smaller than 500 ha.

Sensitivity analyses undertaken in farms for which IRR could be estimated showed that this indicator was particularly susceptible to variations in beef sale price (Figure 6a), increasing by up to 91% and 239% under scenarios of 5% and 10% rise in beef sale price, respectively. In the small property with estimated IRR lower than MARR, this situation would be reversed following an increase in beef sale price. Reductions in beef sale price of 5% and 10% would yield an IRR lower than MARR in four and eight properties, respectively. Variations in total feeding cost and cost of pasture intervention, either positive or negative, had a smaller impact on the IRR, which varied at most by 24% (Figure 6b,c).



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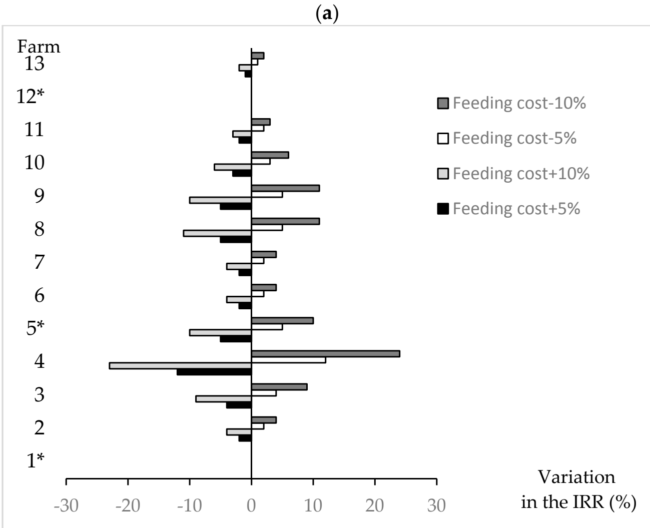

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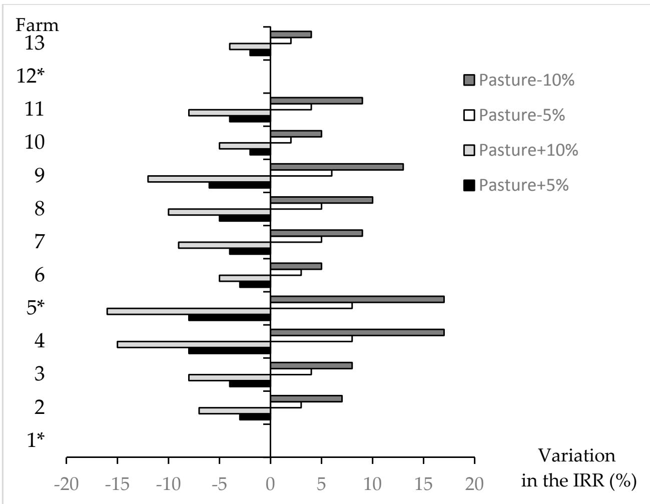

(**c**)

Figure 6. Sensitivity of internal rate of return (IRR) to ±5% and ±10% variations in prices of: (**a**) beef sale; (**b**) livestock feeding; and (**c**) pasture intervention, in 13 pilot farms located in São Félix do Xingu, Pará state, Brazilian Amazon. * Indicates properties with pasture area smaller than 500 ha. Note that for properties 1 and 12 IRR could not be estimated.

Under the sustainable livestock intensification scenario, in Year 12 of the project it is expected an increase of 54% in the number of contract workers in the pilot farms, from 143 to 220, mainly cowboys and employees in general service, such as machine helper or operator, general service assistant, driver, among others, all needed to deal with increased herd. Whereas in large farms the number of employees would increase up to three fold, in the three small farms it would be kept constant.

Estimates for the pilot farms indicated that, in Year 12 of the project, emissions generated by enteric fermentation and use of manure and fertilizers under the sustainable intensification scenario (1.69 Mt CO_2eq) would be twice those yielded under non-intensification scenarios (0.81 Mt CO_2eq). However, these emissions would be counterbalanced by the avoided deforestation of 5148 hectares, which in a BAU scenario could generate the emission of 1.9 Mt CO_2eq. Furthermore, restoration of permanent preservation areas would lead to the sequestration of almost 0.36 Mt CO_2eq.

4. Discussion

Our results indicate that the sustainable livestock intensification approach proposed is economically viable in medium to large farms located in a major deforestation frontier in the Amazon region, and can yield environmental and social benefits. When compared to the incurred transition costs, technical and financial results showed that the investment in sustainable intensification, with the adoption of GAPs, pasture intervention, and environmental restoration, was more economically rewarding than extensive livestock and conventional financial market rates. This positive outcome was observed even if the intensification model adopted was based on a conservative carrying capacity of 3 AU/ha to avoid negative environmental impacts associated with overgrazing, manure and use of fertilizers, and CO_2 and methane emissions. Our results also provide insights into the pasture size threshold under which the adoption of livestock intensification is advantageous. In farms with pastureland smaller than 500 ha, and particularly smaller than 150 ha, transition cost of all three components tended to be higher than those of medium and large farms, whereas financial results highlighted the differences between small and medium or large farms.

Mean total annual investment in intensification in the pilot properties (US\$1335/ha $\pm$ US\$619/ha) was higher than reported in other livestock intensification initiatives in the Amazon (US\$680, [27]; US\$633, [28]; US\$893—including animal acquisition, [29]) in which environmental liabilities were not considered. Indeed, about half of the upfront investments in pilot farms was associated with environmental restoration, and this component was considered in the transition costs to ensure compliance with the Brazilian Forest Code. This approach is strategic given the fear that intensification makes cattle production more profitable therefore enabling livestock expansion, which leads to more forest being converted to pasture on a medium term [4,30]. However, such expansion would require more capital, labor, infrastructure and managerial skills [4,31] and would not be cost-effective, particularly in areas with poor soils and limited access to markets. Additionally, an increase in supply can depress beef price, discouraging pasture expansion. Additionally, with the adoption of sustainable practices and restoration or compensation of environmental liabilities, it is very implausible that farmers would retrogress. This is even more unlikely considering legal risks they would incur under the prevailing governance and monitoring scenario in place, which, although not fully enforced, has brought some sense of accountability [7].

The adoption of GAP was essential to ensuring the socioeconomic and environmental sustainability of the proposed livestock intensification strategies in a region with a history of having an inefficient cattle production system. Additionally, the adoption of GAP and improvement of animal welfare can increase carcass quality. Costs of implementing GAP varied greatly among the pilot farms, being inversely proportional to pasture area. The reason is that part of the incurred costs was fixed and, therefore tended to be higher in small-sized farms on a per hectare basis.

Costs of pasture intervention per year in pilot properties were similar to the ones observed in other regions of Pará state [32,33] and the Amazon [34,35]. A three-fold variation in costs observed among pilot properties stemmed from differences in the level and extent of pasture degradation, which leads to decreased productivity of fodder plants, jeopardizing the sustainability of cattle production [36]. The level of pasture degradation is a main determinant in the choice of pasture intervention—maintenance, restoration or renewal. In more degraded areas, restoration or renewal is needed, requiring mechanized practices, in addition to soil correction and fertilizers. Furthermore, the area cannot be used for grazing during the period needed to consolidate the new pasture, estimated to be from six to twelve months. In the two pilot properties with the smallest pasture area (44 and 126 ha), 50% of the pastureland showed medium or high-level degradation, which is typical of smallholdings in the Amazon where livestock production tends to replicate the extensive model traditionally used in large farms [37]. With no access to technical assistance or financial resources, smallholders often witness a decrease in productivity in most of their land and herd, compromising the environmental, economic and social sustainability of the activity [38].

Overall, annual transition costs to sustainable intensification were much higher than annual costs of traditional extensive livestock production, estimated from US$223 to US$483/ha for small and large properties in the Amazon region [28,39]. The difference in costs often becomes a barrier to investment by most producers when considered alone, even though generally producers do not know how much they are actually profiting or losing, or what the necessary adjustments to reduce expenses or increase the productivity in their farms are. That is why it is essential that costs be analyzed taking into account the entire production system and the returns from intensification.

The productivity projected for the pilot farms in general yielded returns that exceeded investments in intensification, ensuring the viability of the transition to a sustainable intensification approach, except in the two farms with less than 150 ha of pasture. Livestock intensification would improve pasture condition resulting in more efficient conversion of feed into animal products, triggering a reduction in the age at which animals are slaughtered and increasing the number of animals ready for slaughter. The increase in the offtake rate was one of the most important production improvement indicators in pilot farms. The rate is the end result of several processes involving production cycle, including use of natural resources (soil, water, and climate) for the production of forage, herd genetics, health and reproductive efficiency, and growth rate determining the age at slaughter [40]. The efficiency of these processes determine the number of animals available for sale, and the higher the offtake rate, the higher the internal production of the herd.

Initial carrying capacity in pilot farms was generally comparable to estimates for the Amazon region of approximately 1 AU/ha [39,41,42]. In six out the 13 pilot farms, stocking rates in Year 1 were above pastures' carrying capacity, a sign that on a BAU scenario cattle ranching in these properties would become unfeasible or that land clearing would continue to compensate for a low carrying capacity. Indeed, inappropriate management practices, particularly overgrazing for long and continuous periods without adequate replacement of soil nutrients or recovery from trampling, are major causes of pasture degradation and decline in carrying capacity [20]. Under lower grazing pressure, leaf area index and root system of fodder plants can be restored, allowing greater ground cover and competitiveness with weeds [43].

The projected performance of technical indicators of productivity had a direct impact on the financial indicators, both positive and negative, according to the pasture area. IRR and NPV indicated that sustainable livestock intensification was worthwhile in medium and large farms, and risky in small pasture areas, delivering a negative return over the project time once the cost of capital was considered. However, whereas the two smallest farms failed to return a positive net cash flow within the projected 12-year period, in the property with the 426 ha-pasture, adoption of sustainable intensification could become viable in the long run, considering a positive net cash flow projected from Year 6 on. In short, financial indicators suggested a tipping point in the profitability of the proposed sustainable livestock intensification in farms that have between 126 and 425 ha of pasture. This result is in agreement with a previous study in another area of the Brazilian Amazon that found that the NPV breakeven point for livestock intensification was reached at 385 ha of pasture area [29]. This size limitation is of particular importance because a study performed during the selection of pilot farms showed that approximately

80% of the properties in the SFX municipality registered in the Rural Environmental Registry system are smaller than 300 ha, and most of them have pasture areas with less than 150 ha. Additionally, nearly one third of the deforestation that took place in SFX in 2015 happened in farms smaller than 300 ha, most of which was associated with pasture expansion. Therefore, given high implementation and environmental costs, and losses or marginal gains arising from low productivity and technical conditions, the study indicates that the adoption of a sustainable livestock intensification approach directed to smallholders in SFX region as proposed here is not viable. Other approaches should be considered, including improved breeding and genetic stock, better technical assistance and market access, and establishment of cooperatives and other associations with enhanced collective negotiating power. These approaches are also relevant for dairy production, widespread among smallholders and suffering from the same underperformance problems as the beef productive chain due to low quality of the forage, and little dairy aptitude of the herd [3,4]. Undoubtedly, public policies should prioritize lasting supporting programs to boost sustainable alternative activities tailored to small producers in the region, taking into account market demands, access limitations, lack of technical assistance, farms size, and capital constraints. Indeed, some practices are already being encouraged in the SFX region, such as the replacement of degraded pasture by cocoa-based agroforestry systems [44], generating important socioeconomic and environmental benefits, while strengthening food-security among small landholders.

In addition to resulting in increased productivity and financial gains for farms where it is viable, sustainable intensification of livestock would also promote social and environmental benefits, such as job creation and improvement of workers' skills; reduction in deforestation and in emissions of greenhouse gases (GHGs); restoration of permanent preservation areas, and of legal reserves when pertinent, leading to carbon sequestration and potentially increasing biodiversity. Higher productivity levels are expected to reduce the demand for more pastureland, hence releasing grazing areas to meet other agricultural needs or to comply with environmental requirements [45]. Sustainable livestock intensification would also have the potential to mitigate GHG emissions via improved efficiency of production associated with higher slaughter weights and lower age at slaughter; no-till farming; restoration of permanent preservation areas; and by sparing land from deforestation [46]. Other positive outcomes of sustainable livestock intensification include the improvement and restoration of soils, which can help prevent and control erosion and its effects on adjacent water bodies. Additionally, deforestation avoidance and forest restoration would also contribute to generating ecological corridors increasing biodiversity in the region.

There are, however, some barriers to reaching sustainable livestock intensification in the Amazon region. A major one is the difficulty to obtain credit. There are several rural loan programs for small to large producers, with annual interest rates varying between 2.5% and 8%, but few have a clear concern with requirements related to the environmental sustainability of the activity. The Low Carbon Agriculture Program (ABC), created in 2010, is the main financial program in this regard, with a specific line of credit that seeks to reduce carbon emissions by promoting best practices in agriculture. However, neither the ABC Program nor other available credit lines cover costs of compliance with the Forest Code. Therefore, in order to implement sustainable livestock intensification in a sensitive region such as the Amazon biome (and particularly SFX), credit lines should adapt to models that reflect needs other than operationalization of intensification activities, such as restoration and/or offset of permanent preservation areas and legal reserves.

On the other hand, the shift from extensive to intensive livestock production in addition to being costly in its initial stage, can be perceived as financially risky by farmers. However, there are not many alternatives if livestock producers want to stay in business and increase their competitiveness. Forest conversion is no longer a no-risk alternative to replacing degraded pasture. In 2009, slaughterhouses signed a legally binding term with the Pará state government to stop purchasing cattle from farms that deforested illegally [47]. Additionally, the rural environmental registry made it easier to identify transgressors, although the link between monitoring and command and control systems still needs some improvement.

In a survey conducted with farms from the SFX region as part of the implementation of the sustainable intensification project, the absence of technical assistance and skilled workers was shown to be a major barrier to intensification of livestock. Lack of land tenure and environmental regulation were also mentioned as factors in producers' hesitation in investing. The survey also revealed a certain degree of risk aversion to new technologies due to little understanding of the changes being proposed and their results, or related to the scarce knowledge of financial and administrative management of properties.

Lack of incentives and market demand for sustainable products still prevail in the livestock value chain, detaining investments in GAP. Despite the existence of several "green" initiatives and bonus programs, their scale is still very limited. In many cases, sustainability is not very encouraged and valued by retailers, and the current Brazilian economic crisis may limit the ability of slaughterhouses to assume the risks and costs of such initiatives without support from retail, whose biggest concern (shared by consumers) is being able to purchase beef at affordable prices. Another concern regarding the success of intensification strategies is the susceptibility of financial indicators to beef sales price. Market trends indicate that the price of live cattle in Pará state is commonly as much as 18% lower than cattle purchased in southern states in Brazil, reflecting production costs dissimilarities [48]. The long distances required to haul products to and from the Amazon, make the cost of transporting beef and essential items for intensification such as fertilizer, lime and food supplement very high, pushing down the profit margin for SFX producers. If sustainable intensification reaches scale, these production costs likely will be reduced.

5. Conclusions

Overall, the sustainable livestock intensification strategies presented here for the SFX municipality were based on the dynamism of real situations observed in pilot properties, and highlighted the potential for boosting productivity, avoiding deforestation and reducing environmental liabilities in a traditionally underperforming sector. Showing the viability of changing production practices in SFX is very emblematic of the Brazilian Amazon. For years, SFX has been a major deforestation frontier, driven almost exclusively by the expansion of cattle ranching in a continuous and pervasive cycle of land degradation, abandonment and new land conversion.

However, there are a number of challenges that need to be overcome. Upfront costs to farmers are high, and environmentally-aware credit lines are scarce and not easily accessible in a region where land tenure status is commonly unclear; skilled employees, and technical assistance are not readily available. Additionally, contrary to crop farmers, ranchers are not used to a disciplined productive system with a rigid calendar that must be followed at the risk of production loss. Ranchers tend to maintain a certain isolation, their contact with the production chain being generally limited to salt sellers and intermediaries. Significant cultural changes need to occur in a sector that still shows some degree of informality and aversion to new technologies, and that is not used to management practices. This may be a major challenge until farmers are fully convinced of the advantages and profitability of the adoption of the new production system.

Particularly important is the result from pilot farms suggesting the economical infeasibility of the sustainable livestock intensification approach proposed in pasture areas smaller than 150 ha in a region where approximately 80% of the properties fall under that range of pasture size. Another important consideration is that cattle ranching in the region is carried out under precarious conditions, and with high environmental costs. This finding entails a broader discussion on the need of good governance and effective public policies that prioritize lasting support programs that boost sustainable alternative livelihood activities tailored to small producers in the region.

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