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Financial transition and costs of sustainable agricultural intensification practices on a beef cattle and crop farm in Brazil's Amazon

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Abstract

The intensification of Brazil's beef cattle production system can involve different strategies to increase beef production while reducing deforestation in the Amazon biome and mitigating climate change. This study economically evaluates a cooperating beef farm in the state of Mato Grosso, Brazil's Amazon biome over three crop years (2015–16 to 2017–18), transitioning from an extensive grazing system to a semi-intensive system using five sustainable agricultural intensification (SAI) practices. These five practices include (1) grain supplementation for cattle, (2) pasture fertilization, (3) pasture re-seeding, (4) crop–livestock integration (CLI) and (5) irrigated and fertilized pasture that is rotationally grazed. The relative costs of these five SAI strategies used on this cooperating farm are compared. The adoption of SAI strategies increased beef productivity 5.7% (228–241 kg live-weight sold per hectare) and gradually improved net farm income by ~130% over the 3 years of transition (−US\$94.79 to \$29.80 ha^{-1}). Grain supplementation (US\$188 ha^{-1}) had the cheapest cost per hectare, followed by pasture fertilization (US\$477 ha^{-1}) and pasture reseeding (US\$650 ha^{-1}). The most costly practice was in-ground irrigation of fenced rotationally grazed pasture (US\$1600 ha^{-1}) with the second most costly being CLI (US\$672 ha^{-1}). Despite adoption challenges of these SAI practices, past research confirm these five practices can increase beef productivity and profitability while reducing carbon footprint. Regardless of the cost per hectare of each practice, farmer adoption can be improved through education, support and incentives from both the public and private sectors.

Introduction

Agriculture has historically met global demand for food (Tilman *et al.*, 2011). However, future prospects are uncertain as climate change and natural resource exhaustion make feeding the world more challenging (Valin *et al.*, 2014). In this context, Brazil needs to address the challenge of balancing natural resource conservation with agricultural production and expansion. Brazil has the world's largest tropical forest reserve, water resources and biodiversity (VanWey *et al.*, 2013) and significant potential for the production of beef, feed, food, fiber and fuel (Moreira *et al.*, 2016).

The Legal Amazon covers 522 million hectares with 61% in Brazil (Sudam, 2018). Due to low cost of land and labor, and favorable soil and climate, Amazon beef production has expanded (Nepstad *et al.*, 2006; Martha Júnior *et al.*, 2012). Amazon livestock production has been characterized by low investments in technologies, facilities, management and feed supplementation, but guaranteed possession of large tracts of land during initial settlement (Garcia *et al.*, 2017). Legal Amazon beef cattle expansion raises issues and challenges for Brazilian agribusiness (Ruviaro *et al.*, 2014) to increase commodity market revenues while reducing environmental impacts from agricultural production (Strassburg *et al.*, 2014; Cordeiro *et al.*, 2015; Bergier *et al.*, 2019).

Since 2004, Brazil's commercial cattle herd has been the largest in the world and Mato Grosso state is Brazil's beef industry leader (Rosales, 2006) and a major international supplier of beef at 6.8% of the state's total exports (AGROSTAT, 2018). According to IBGE (2017), Mato Grosso's cattle herd of 24.12 million animals was largest among Brazil's states at 17% of national production. Beef cattle (*Bos indicus*, Nelore breed) have contributed significantly to the economic growth of the region, however deforestation, commodity row crops, and poorly managed pastures generate greenhouse gas (GHG) (CO_2, N_2O, CH_4) emissions (Göpel *et al.*, 2018), impact water, soil and air quality, and accelerate biodiversity loss and climate change (Tilman *et al.*, 2011).

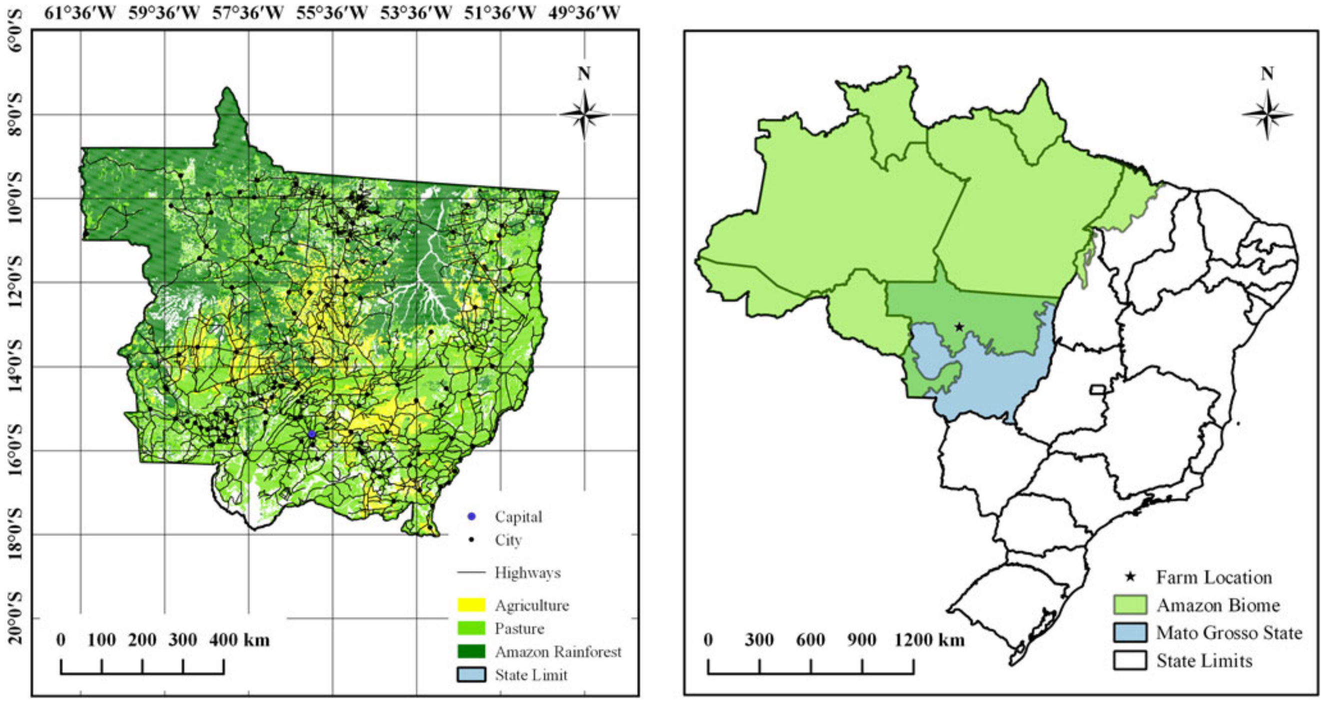

Fig. 1. Location of the cooperating farm in Amazon biome, Mato Grosso, Brazil (IBGE, 2014).

About 28% of Legal Amazon deforestation in Brazil has occurred in Mato Grosso state with 142,714 km^2 of forest lost between 2004 and 2017 (Sudam, 2018). Over the past several years, Brazil's government has established rules and limits to ensure the preservation of the Amazon (Assunção *et al.*, 2015). Initiatives from government, private institutions such as trading companies and slaughterhouses, and farmers investing in technologies to increase productivity all have contributed to more sustainable production (le Polain de Waroux *et al.*, 2017).

The Brazilian Agricultural Research Company (Embrapa) and the Low Carbon Agriculture Program have encouraged reducing deforestation via sustainable beef intensification using degraded pasture recovery, crop–livestock–forest integration (CLFI), no-tillage, biological nitrogen fixing cover crops, reforestation and manure management (Amaral *et al.*, 2012). Such intensification reduces GHG emissions using grain supplementation (Florindo *et al.*, 2017*a*; 2017*b*), pasture improvement (Dick *et al.*, 2015*a*; 2015*b*), sequestering carbon in commercial CLFI timber (De Figueiredo *et al.*, 2017), and rotational grazing (Palermo *et al.*, 2014; Dick *et al.*, 2015*a*). Brazil has recently committed to reducing 36% of its GHG emissions by 2020 and the livestock sector is one of its main targets (Mazzetto *et al.*, 2015).

We hypothesize sustainable agricultural intensification (SAI) of Brazil's beef cattle production system can increase beef production and profitability. However, SAI practices need to be practical to be adopted by farmers. Therefore, our study evaluates the economics of a cooperating farm in Mato Grosso's Amazon biome that recently transitioned over 3 years from an extensive grazing system (industry status quo) to using five SAI practices, including grain supplementation for cattle, pasture fertilization, pasture re-seeding, crop–livestock integration (CLI) and irrigated and fertilized pasture that is rotationally grazed. Our specific research objectives are to (1) evaluate the transition from extensive to more sustainable beef cattle systems on our case study farm in Brazil's Amazon and (2) to compare the relative costs of the five SAI strategies used on this cooperating farm.

Methods

Case study justification and background

The case study of a representative entity from a broader population allows for in-depth knowledge acquisition and general comprehension. Case studies can lay the groundwork for further, more representatively accurate research (Gillham, 2010), especially where the selected case facilitates enough knowledge contribution to be framed as an ideal type (Godoy, 1995; Camelo *et al.*, 2017). We conducted in-depth agronomic and economic data collection over three production years (2015–16 to 2017–18) on and from our case study beef cattle farm and farmers in northwestern Mato Grosso state's Amazon biome. This farm is classified as a large-scale commercial producer with a comprehensive production system (INCRA, 2013). Our case study farm is the most dynamic and complex for meat production in this eco-region because of its management technologies and practices, such as cattle genetics and breeding.

Our cooperating beef farm (Fig. 1) has made recent investments in order to adopt SAI practices to improve productivity and profitability. The technologies adopted are being disseminated to the farmer's community, encouraging other farmers to intensify their production. The dynamism of the region triggered government investments in road paving and railroad construction reducing transportation costs and increasing the competitiveness of the agricultural sector. Our cooperating farm is associated with the Universidade Federal de Mato Grosso's agricultural extension, affiliated researchers, and undergraduate and graduate students.

Cooperating Amazon beef cattle farm data collection

Background information for the farm is summarized in Table 1. The data for this study were collected monthly from July 2015 to June 2018, including land use, resource inventories, predominant soil characteristics (fertility, type and slope), crop and pasture

Table 1. Precipitation, land use and cattle herd and feeding for cooperating farm in Mato Grosso, Brazil's Amazon biome

Parameters	2015–2016	2016–2017	2017–2018
Annual precipitation (mm)	1589	1837	2287
Land and soil			
Land use (% of total farm area)			
Legal forest reserve[a]	82	82	82
Agriculture	18	18	18
Agriculture use (% of total farm area)			
Grass[b]	87	87	82
Crop	13	13	18
Soil type	DRYL; QN[c]	DRYL; QN[c]	DRYL; QN[c]
Slope (%)	8	8	8
Irrigation rate[d] (mm day^{-1})	7	7	7
Animal and feeding information			
Herd			
Breed	Nelore-Angus	Nelore-Angus	Nelore-Angus
Production cycle	Full cycle	Full cycle	Full cycle
Herd composition (%)			
Cows and bulls	37	45	44
Calves and replacements	29	24	24
Stocker cattle	15	17	17
Finishing cattle	19	14	15
Feed source[e] (kg DM head^{-1} day^{-1})			
Pasture[f]	4.25	4.29	4.18
Silage[g]	–	2.21	2.35
Corn meal	1.25	1.5	2.5
Soybean meal	0.45	0.55	0.7
Cottonseed	0.2	–	–
Minerals	0.05	0.05	0.07

[a] Percentage of legal forest reserve did not change since additional crop land was rented in the third year.
[b] About 84% of the pasture area has *Brachiaria* spp. while 16% has *Panicum* spp.
[c] The predominant soil is the dystrophic red-yellow latosol (DRYL), but also part of the farmland has quartzarenic neosol (QN).
[d] Irrigation system was used in a separate rotational grazing area during the dry season only, May to September.
[e] Grain feed supplementation of only stockers and finishing cattle of soybean and corn meal, cottonseed and minerals. Daily feed in kg of dry matter (DM).
[f] Pasture intake estimated at 2% of cattle live weight.
[g] Silage was fed only to finishing cattle.

management including fertilizer application rates, dates and number of operations such as tillage, grazing period and pasture quality. Animal and feeding data included cattle type, breed, numbers and management plus facilities, labor for animal handling and annual livestock costs. Weather data (solar radiation, precipitation, minimum and maximum temperature) were also collected from a weather station set up on-farm (Supplementary Materials, Table S1). The farm operates a full-cycle system where Nelore and Aberdeen Angus cattle are industrial crossbred to raise future replacements. Beef cattle diet is pasture-based with supplemental minerals. Some stocker and fatting phase groups are fed with grain supplements composed of corn grain, soybean meal and minerals.

SAI improvements were made using grain supplementation for cattle, pasture fertilization and re-seeding, integration of livestock with cash crops such as soybeans and rice, and irrigated, fertilized and rotationally grazed pasture with the goal to improve production efficiency and profitability. Information related to timing of fertilizer application, fertilizer types, quantities of nutrients applied and application methods are summarized in Supplementary Materials, Table S2.

Grain supplementation of soybean and corn meal, cottonseed and minerals were only fed to stockers and finishing cattle. Cattle diets changed during different periods of the year due to the quality of the pasture. Concentrated feed supplements and minerals were fed in separate plastic bins and were openly available in pastures and re-filled once a week.

Two SAI practices involved pasture improvements. First, pastures were fertilized with 100 kg ha^{-1} urea (45% nitrogen) applied by rear-mounted fertilizer disk spreaders during the rainy season

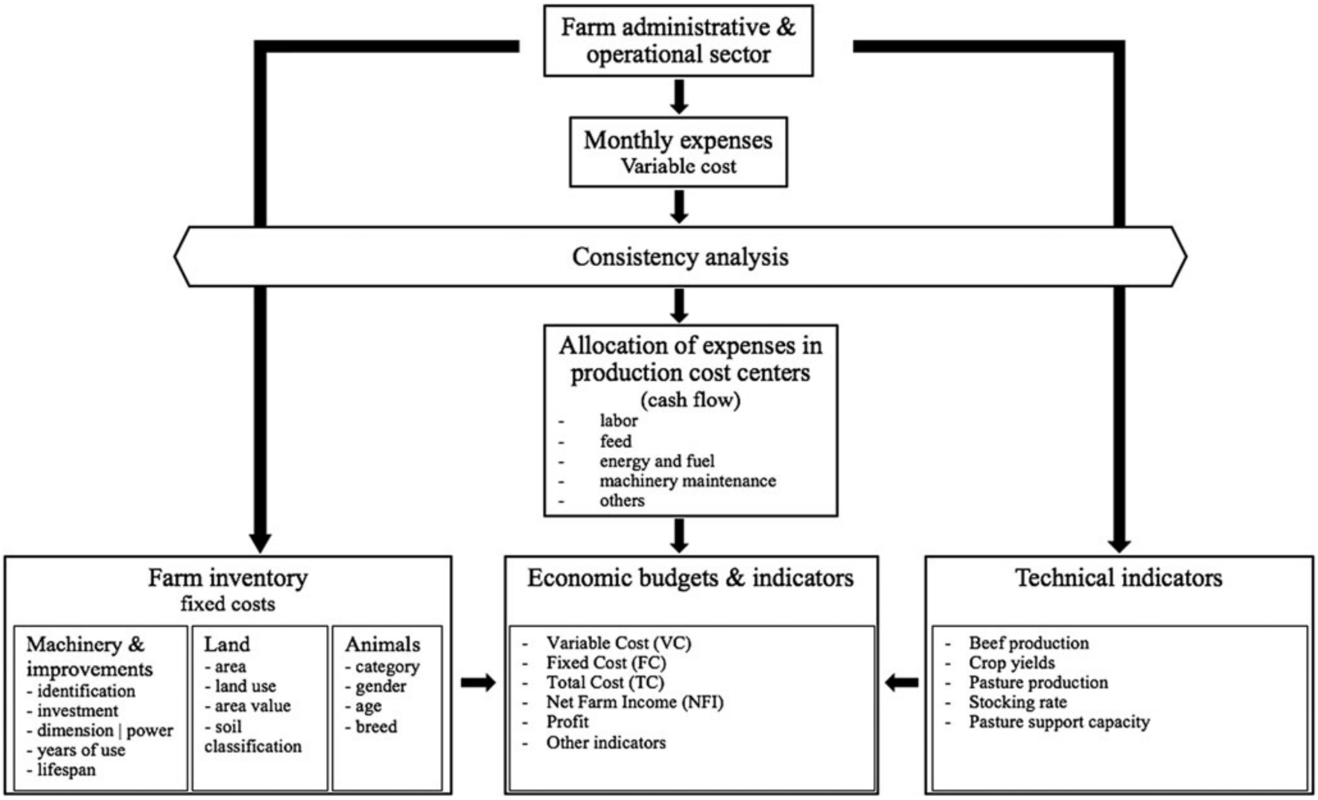

Fig. 2. Schematic diagram of data collection and processing for cooperating farm in Mato Grosso, Brazil's Amazon biome.

(October–March). Second, pasture re-seeding involved desiccating degraded pasture using glyphosate and 2,4-dichlorophenoxyacetic acid (2,4-D). Lime was then applied (1.5 metric tons ha^{-1}) with 120 kg ha^{-1} nitrogen, phosphorus and potassium (6-30-6) and then incorporated with a harrow. This was followed by sowing the tropical pasture grass, *Brachiaria brizantha* cv. Marandú, using a seed spreader which was then disked to incorporate seed.

Integration of crop–livestock was another practice used to improve pasture in the long run. Here soybeans were no-till cropped in degraded pasture areas. Grass was desiccated in the whole area using glyphosate and 2,4-D after applying lime (1.5 metric tons ha^{-1}). Soybeans were no-till seeded with fertilizer (7-37-6 NPK, 300 kg ha^{-1}), and then top dressed with KCl (150 kg ha^{-1}) plus micronutrients. After soybeans were harvested in February, tropical pasture grass, *Brachiaria ruziziensis*, was sown using rear-mounted disk spreaders.

Irrigated, rotationally grazed and fertilized pasture was used during the dry season (April–September) for replacement heifers, stockers and finishing cattle. Irrigation involved water application of 10 mm daily, with water application efficiencies for surface irrigation ranging from 60 to 80%. Irrigated pasture paddocks for beef cattle were also fertilized using the same procedures as for CLI. The cattle were rotationally grazed depending on the height of the pasture, typically moved around twice a week in 15 rotational modules.

Economic evaluation

Economic data including production costs were collected directly from the farm owner and managers. We analyzed the technical and economic indicators using Microsoft Excel® spreadsheets. Capital, sales, cattle and crop inventories, and production processes were also analyzed for the entire production system. Our economic survey methods and types of data collected are diagramed in Figure 2.

Whole-farm budgets included production costs subtracted from farm revenues (beef, cattle and other sales) to derive returns over variable costs (VC) (short-run accounting profit) and net farm income (long-run accounting profit). Whole-farm budgets were also calculated subtracting all revenues and expenses related to commodity crop (soybeans, rice) production in order to better isolate whole-farm impacts of SAI *vs* shifting from rice to soybean production from 2015–16 to 2017–18. In order to calculate farm profitability, production costs must be meticulously calculated (CONAB, 2018) to verify if resources used for production are being adequately paid.

Cost analysis is fundamental to good management, identifying strengths and weaknesses of farm activities to guide better decision making. The cooperating farm's data over all three production years was analyzed by cost center (Table 2), based on comprehensive cost analysis methodology of Matsunaga *et al.* (1976). Each production year was defined running from July 1st from June 31st for the Southern Hemisphere agricultural year. Data collected underwent a consistency analysis, which verified economic data accuracy. Total costs (TC) equal VC plus fixed costs (FC). VC include labor, maintenance of pastures and crops, seed, fertilizer, pesticides, fuel, feed (supplements, minerals), vaccines, medicine, land rent and bank interest on operating loans to finance variable expenses.

VC need to be covered by farm revenues in the short run, else the farm may go out of business. If FC are not covered in the long run, capital cannot be adequately replaced. VC vary annually with

Table 2. Methodology for calculating accounting budget line items used to analyze the agricultural production system of the cooperating farm in Mato Grosso, Brazil's Amazon biome

Accounting budget line items	Accounting and calculation methods
Total revenue (TR)[a]	Total revenue from each farm sale (price × quantity sold)
Variable costs (VC)	Amount of direct expenses dependent on the annual level of production
Fixed costs (FC)	Costs not dependent on the annual level of production such as equipment depreciation, taxes and insurance
Total cost (TC)	TC = VC + FC
Total adjusted cost (TAC)	TAC = TC + remuneration of fixed capital invested in animals, improvements, machinery, pasture and land
Depreciation on capital	(New value of capital item – its salvage value[b])/useful life of capital
Opportunity cost	((New value of capital item – its salvage value)/2) × Interest rate[c]
Return over VC	ROVC = TR – VC
Net farm income	NFI = TR – TC
Net profit (NP)	NP = TR – TAC

[a] TR (total revenue) consists of annual revenue of animals and crops sold, and other revenue such as sale of semen and machinery & equipment.

[b] In the methodology used to calculate the cost of production we use salvage value equal to zero, in order to reduce the subjectivity at the time of the calculations of depreciation and opportunity cost.

[c] Interest rates of 6% is used for the calculation of the opportunity cost of the capital invested in the activity, which is equivalent to the savings interest.

the level of farm production, while FC does not. FC includes equipment depreciation over useful life of capital such as machinery and farm implements (15 years) and structures (20 years), depreciation on non-annual crops and breeding stock, and service animals used for production. Remuneration of fixed capital investment is not included in depreciation (Sartorello *et al.*, 2018).

Total adjusted costs (TAC) equal TC plus remuneration (i.e., 6% interest) that could be earned on fixed capital investments. The percentage of interest is based on Brazilian savings and this reference percentage is the minimum used to judge whether livestock is economically viable. TAC consider the opportunity cost of all capital invested in the business, including both explicit and implicit costs. This better captures the values that the factors of production (machines, implements, improvements, animals and non-annual crops) would generate if used for alternative investments other than farming. Net profit (NP) was calculated as TR minus TAC. Three returns over investment (ROI) measures were also calculated by dividing each profitability measure (ROVC, NFI, NP) by total capital invested (TCI). TCI required to operate the farm include the total value of capital improvements and equipment, as well as pasture establishment costs spent during the first year of an assumed 15-year stand life before re-seeding.

Partial budgets were calculated for each SAI practice. The TC of each SAI practice was divided by the total cooperating farm area that was devoted to each practice. Economic values in Brazilian reals (R$) were converted to US dollars (US$) using the exchange rate on June 4th, 2018 (Banco Central, US$1 = R $3.76). Adoption of SAI practices is expected to diversify and/or increase crop and/or beef yields and profitability measures.

Results

Beef and crop productivity

Beef yield and average daily gain (ADG), cattle stocking density and crop yields are summarized in Table 3. Beef cattle productivity (kg animals sold per ha) was 228 kg ha^{-1} during the first (2015–16) year. Productivity was highest in the second year (2016–17) at 257 kg ha^{-1} but was 6.7% lower in the third year (2017–18) at 241 kg ha^{-1}. ADG of finishing cattle (kg per animal per day) increased steadily (0.476 to 0.511 to 0.531). Herd numbers were highest in 2015–16, which when combined with lower average precipitation and high average temperatures (Supplementary Materials, Table S1), resulted in pasture degradation. Thus, more land was rented in 2016–17 to lower cattle stocking density and silage was purchased to feed animals. Beef productivity increased in 2016–17 and 2017–18, despite herd reductions of 12 and 6% respectively.

There was a 26% reduction in rice yields between the first and second years due to late control of a fungal (*Pyricularia oryzae*) pathogen (Koutroubas *et al.*, 2009). The cooperating farm's average rice yield was 14.9% higher than the Brazilian national average in the first year, yet 7.9% lower in the second year (CONAB, 2018). Soybean yields decreased 13% between the second and third years. In the second year, soybeans were planted in areas previously cultivated with rice, while most soybean areas in the third year were degraded pastures with low soil quality. Also in the third year, some soybean planting was late which reduced yield. The farm's average soybean yield was 28.2 and 35.9% lower in second and third years respectively compared to Brazil's national average for this crop in these years (CONAB, 2018).

Economics of cooperating farm

Economic whole-farm budgets from all crop years are contrasted (Table 4; Supplementary Materials, Tables S3 and S4), showing results per hectare and per head (of all animals). Revenues from crop sales were not enough to initially cover both fixed and variable expenses in the first year after SAI adoption. However after the second and third years, short-run (returns over VC) and long-run (net farm income or NFI) profits were positive. NFI improved from negative returns to positive profitability in the third crop year (US$29.79 ha^{-1}, US$19.07 head^{-1}). NP in the third crop year was 71.2% greater than the first crop year due to only a slight reduction in VC (3.34%) combined with a 59.8% increase in total revenue.

Economic results adjusted for livestock production alone without crops (soybeans, rice) were consistent with combined

Table 3. Beef cattle and crop productivity (2015–18) for cooperating farm in Mato Grosso, Brazil's Amazon

Production indicators	Unit	2015–2016	2016–2017	2017–2018
Beef cattle				
Productivity[a]	kg ha^{-1} yr^{-1}	227.89	256.77	240.64
Live weight at slaughter	kg	460	460	460
Months at slaughter	months	29	27	26
Average daily gain (ADG)[b]	kg per animal per day	0.476	0.511	0.531
Stocking density	head ha^{-1}	2.51	1.77	1.56
	AEU[c] ha^{-1}	2.05	1.59	1.40
Soybean				
Yield	kg DM ha^{-1}	–	2412	2087
Rice				
Yield	kg DM ha^{-1}	2952	2160	–

[a] Live-weight (kg) of animal sold per hectare.
[b] ADG calculated as typical live weight (kg) per animal divided by average days at slaughter.
[c] One AEU (animal unit equivalent) equals 1000 kg of animal live weight.

Table 4. Economic whole-farm budgets for the cooperating farm (2015–2018) in Mato Grosso, Brazil's Amazon

Economic budget line items	2015–16 US$/ha	2016–17 US$/ha	2017–18 US$/ha	2015–16 US$/head	2016–17 US$/head	2017–18 US$/head
Total revenue (TR)	377.67	450.09	497.37	150.34	254.47	318.48
Variable costs (VC)	394.63	400.20	387.91	157.10	226.25	248.40
Fixed costs (FC)	77.83	77.01	79.66	30.98	43.53	51.01
Total cost (TC)	472.46	477.21	467.57	188.08	269.78	299.41
Total adjusted cost (TAC)	565.71	554.81	542.93	225.19	313.65	347.66
Return over variable cost (ROVC)	−16.96	49.89	109.46	−6.76	28.22	70.08
Net farm income (NFI)	−94.79	−27.12	29.80	−37.74	−15.31	19.07
Net profit (NP)	−188.04	−104.72	−45.56	−74.85	−59.18	−29.18

livestock production with these crops albeit with faster pay back (Supplementary Materials, Tables S5 and S6). Adding both of these crops increased TAC 9.9% in the first year, 18.5% in the second year and 21.8% in the third year. Production costs were highest for labor (~25%) followed by crop expenses (~13%) and grain fed (~7%). In all three years, the opportunity cost of capital remuneration was not covered resulting in negative values for NP (Table 4). TCI ranged from US$1747 to $1875 ha^{-1} with long-run return (NFI) over investment turning positive (1.59%) by the third year (Table 5).

Economics of sustainable agricultural intensification practices

The variable and TC per hectare of SAI practices are ranked in Table 6. The least expensive SAI practice was grain supplementation (US$187 ha^{-1}), followed by pasture fertilization (US$476 ha^{-1}) and pasture re-seeding (US$649 ha^{-1}). The most costly practice was irrigation (US$1600 ha^{-1}), followed by CLI (US$672 ha^{-1}). The main cost component is labor making up 23.1 to 25.35% of TAC (Supplementary Materials, Table S4). Labor was followed by crop expenses for CLI (up to 14.6% of TAC) and grain feed for grain supplementation (up to 9% of TAC).

Discussion

Whole-farm sustainable agricultural intensification transition

Beef cattle productivity (kg animals sold per ha) and ADG for our cooperating farm using all five SAI practices were either higher or lower compared to prior studies focusing on just one of these five practices (Supplementary Materials, Table S7). For example, our 11.5% ADG increase from 0.476 to 0.531 kg per animal per day over 3 years was within ADG range of 0.25 to 0.6 kg per animal per day estimated for grain supplementation (Tonello *et al.*, 2011; Fernandes *et al.*, 2016; Guerra *et al.*, 2016) and ADG range of 0.26 to 1 kg per animal per day for pasture improvements (Supplementary Materials, Table S7). However, the ADG on our cooperating farm was lower than 0.581 kg per animal per day for Angus cattle in southern Brazil grazed on fertilized pasture (Ferreira *et al.*, 2011) and lower than 0.75 to 0.81 kg per animal per day for CLI (Salton *et al.*, 2014).

Improved profitability of our cooperating beef farm during transition to SAI is supported by Strassburg *et al.* (2014) who highlight adoption of SAI practices and technologies should increase beef production profitability while also limiting frontier development deforestation and other associated environmental impacts, though see Merry and Soares-Filho (2017). Economic

Table 5. Capital investment and economic ROI indicators for the cooperating farm (2015–2018) in Mato Grosso, Brazil's Amazon

Economic investment and return on investment	2015–16	2016–17	2017–18
Capital investments (US$ ha^{-1})			
Improvements			
House (employees)	113.76	103.64	103.64
Barn and sheds	17.12	15.60	15.60
Feeding	37.68	35.05	35.05
Fence	427.82	389.77	389.77
Corral	61.01	64.84	64.84
Irrigation system (sprinklers)	97.35	88.69	88.69
Others	186.17	173.54	173.54
Equipment	–	–	–
Tractor	139.23	130.75	127.49
Tillage	116.88	108.23	109.46
Fertilizer spreaders	85.58	77.97	77.97
Seeders/planters	9.56	14.86	14.86
Feeders/waterers	14.28	13.01	13.01
Harvest machine	54.47	63.07	63.07
Pasture establishment (15 year stand before re-seeding)	385.76	571.81	598.40
Total capital invested (TCI, US$ ha^{-1})	*1746.67*	*1850.83*	*1875.39*
Returns on investment (ROI, %)			
ROI$_{ROVC}$ = Return over variable cost (ROVC)/TCI	−0.97	2.70	5.84
ROI$_{NFI}$ = Net farm income (NFI)/TCI	−5.43	−1.47	1.59
ROI$_{NP}$ = Net profit (NP)/TCI	−10.77	−5.66	−2.43

results were consistent with several prior studies evaluating implementation of only one or two SAI strategies (Supplementary Materials, Table S7). Prior studies have not contrasted relative costs of all five SAI practices adopted by our cooperating farm.

Improvement in our cooperating farm's beef production may be due to increased average weight gain of cattle as well as herd composition changes (Table 1). In the first year, animals were not fed supplements such as grain, which is a typical management strategy for beef cattle in Brazil (Ferraz and Felício, 2010). Bad weather conditions in 2015–16 (Supplementary Materials, Table S1) resulted in low grass productivity and consequently restricted feed availability. This was compensated over the next 2 years by high-energy intake and high-quality pastures to avoid compromising the compensation capacity of cattle (Creighton *et al.*, 2003).

The cooperating farm's stocking rate in 2015–16 (0.80 AEU ha^{-1}) was greater than the pasture's carrying capacity (0.54 AEU ha^{-1}), resulting in overgrazing, low plant vigor and pasture degradation (Lorena Pedrosa, unpublished data; da Silva *et al.*, 2012). Pasture management entails adjusting animal numbers per hectare (i.e. lower stocking density to reduce grazing pressure), which can improve pasture regrowth and seed production (Cardoso *et al.*, 2017). Animals can also be removed at strategic times to ensure forage species resilience (Pereira *et al.*, 2013).

In order to recover degraded pasture and improve soil quality, our cooperating farm integrated grazed areas with annual crops such as rice and soybeans. Historically, rice enables cultivation even in areas with lower soil quality (Pinheiro *et al.*, 2006). In the future, farm productivity may be further enhanced as some soil quality measures were improved with the addition of annual crops such as rice and soybeans. Soil pH remained in an ideal range (4.6–5.4) which neutralized aluminum saturation and increased base saturation. However, soil disturbance during soybean and rice production decreased organic matter content (Supplementary Materials, Table S8).

Contrasting costs of sustainable agricultural intensification practices

CLI (US$672 ha^{-1}) and irrigation of rotationally grazed pasture (US$1600 ha^{-1}) are the most expensive practices (Table 6) and may not be as practical for adoption by Brazilian beef cattle farmers. For example, only 1.5% of pasture and cropland is integrated in Mato Grosso (Gil *et al.*, 2015). Our results are in line with Peres *et al.* (2014) and Martha Júnior *et al.* (2011) showing that production costs can increase with CLI adoption, deferring economic benefits to the medium and long term. CLI has been demonstrated to be more profitable than extensive pasture and competitive with soybeans (Martha Júnior *et al.*, 2011; Gil *et al.*, 2018). Although irrigated pasture is less prevalent in Brazil, irrigation has great potential to increase pasture yields by 25 to 52% (Antoniel *et al.*, 2016). Our estimated annual cost of $1600 ha^{-1} for in-ground irrigation for permanently-fenced rotational grazing was higher than Soares *et al.* (2015) who estimated US$930 to US$1201 ha^{-1} for pastures irrigated using center-pivot. This was due to higher labor costs of rotating cattle between paddocks (Table 6).

Our cost estimates (Table 6) for grain supplementation, pasture fertilization and pasture re-seeding that were less costly were somewhat consistent with estimates from past studies. Our grain supplementation cost of US$162 ha^{-1} was higher than US $22 ha^{-1} (Pereira *et al.*, 2018) and US$68 ha^{-1} (Florindo *et al.*, 2017*a*), but lower than US$325 to US$332 ha^{-1} (Ruviaro *et al.*, 2016). It was also more expensive than pasturing cattle on soybean crop residues (US$124 ha^{-1}, Pashaei Kamali *et al.*, 2016). Our pasture fertilization cost of US$463 ha^{-1} was between US$437 ha^{-1} calculated by Santana *et al.* (2016) and US$494 ha^{-1} from De Oliveira Silva *et al.* (2018). Our pasture re-seeding cost of US$639 ha^{-1} falls within the ranges of (1) US$410 to $2180 ha^{-1} estimated by Zu Ermgassen *et al.* (2018) and (2) US$619 to $1335 ha^{-1} calculated by Garcia *et al.* (2017), though is greater than US$99 to $510 ha^{-1} from De Oliveira Silva *et al.* (2017).

Adoption challenges for sustainable agricultural intensification

Brazilian beef cattle producers are less likely to invest in the SAI practices we evaluated due to scarcity of labor required for improved techniques as well as financial constraints (Latawiec *et al.*, 2017). Despite the benefits of SAI practices, the most important challenges for farmers looking to adopt these practices are lack of financial resources (Börner *et al.*, 2007), lack of skilled workers and technical assistance, as well as cultural preferences and knowledge (Gil *et al.*, 2015). Another SAI adoption challenge is training people throughout the beef supply chain, from those

Table 6. Sustainable intensification practices and ecological intensification practice variable fixed and TC per hectare for cooperating farm in Mato Grosso, Brazil's Amazon

	Agricultural intensification practice				
	Sustainable				Ecological
Cost category	Livestock supplementation[a]	Pasture fertilization	Pasture re-seeding	Pasture irrigation	CLI
Variable cost (VC)					
Labor	$66.83	$240.49	$277.04	$665.96	$191.21
Maintenance[b]	$4.32	$25.90	$46.62	$104.18	$33.18
Energy	$3.45	$15.51	$60.10	$374.14	$7.75
Diesel	$6.51	$14.15	$50.88	$198.75	$21.27
Pesticide	–	–	$13.95	$23.40	$125.01
Fertilizer and lime	–	$169.32	$128.21	$22.64	$188.98
Crop seeds	–	–	–	–	$67.99
Pasture seeds	–	–	$39.33	$6.10	$10.47
Corn meal	$19.15	–	–	–	–
Soybean meal	$28.26	–	–	–	–
Cottonseed	$15.13	–	–	–	–
Mineral	$27.18	–	–	–	–
Purchased forage	$12.32	–	–	–	–
Total VC (US$ ha^{-1})	$183.14	$465.37	$616.12	$1395.18	$645.86
Fixed cost (FC)					
Capital depreciation					
Tractor	$0.71	$6.15	$14.75	$11.82	$6.08
Tillage	–	–	$53.02	–	$1.55
Fertilizer spreaders	–	$5.13	$4.43	$5.68	$10.29
Seeders/planters	–	–	$1.18	–	$3.57
Feeders/waterers	$1.53	–	–	–	–
Grain processing	$2.35	–	–	–	–
Harvest machine	–	–	–	–	$4.97
Irrigation	–	–	–	$187.00	–
Total FC (US$ ha^{-1})	*$4.59*	*$11.28*	*$73.38*	*$204.50*	*$26.46*
Total cost (US$ ha^{-1})	**$187.73**	**$476.70**	**$649.90**	**$1599.77**	**$672.33**

[a] Only stockers and finishing animals are fed supplemental feed, comprising 48% of the herd.
[b] Maintenance includes machinery and equipment repairs and improvements.
[c] Agricultural and farm land not included in FC due to variable values per hectare.

who directly deal with livestock management to those working for slaughterhouses (McDermott *et al.*, 2010).

Irrigated pasture may be limited by high initial capital investment at ∼$10,000 ha^{-1} for center pivot systems (Soares *et al.*, 2015) similar to ∼$9600 ha^{-1} for the in-ground system used by our cooperating farm. Such investment may not be financially feasible for many farmers. Irrigation can also put strains on limited water resources (Lathuillière *et al.*, 2016), exceeding countries' freshwater availability (Davis *et al.*, 2017). Intensive, well-managed rotational grazing, where cattle are systematically moved at appropriate intervals, controls forage height. This improves the efficiency and persistence of pasture preventing overgrazing, erosion and soil compaction. Eaton *et al.* (2011) found average weight gain of cattle and pregnancy rates were 15 and 22% higher, respectively, for herds using rotational grazing systems in Brazil. Rotational grazing cattle stocking rates (head ha^{-1}) were two to six times greater than for extensive continuous grazing. However, rotational grazing on either rain-fed or irrigated pasture is management intensive and may not be favored by many producers (Gil *et al.*, 2018).

Crop revenues are a critical factor to determining the favorability of CLI, since economic favorability of such integration is very sensitive to prices paid to producers (Martha Júnior *et al.*, 2011; Peres *et al.*, 2014). Forages in rotation with high-value cash crops need to be of high enough value relative to cash crops to make integration favorable (Hoshide *et al.*, 2006). Thus CLI should be adopted in regions with agricultural production suitability and stability. CLI has been shown to improve soil physical and chemical properties, increasing pasture fertility, nutrient cycling and fertilizer efficiency, driven by different needs of rotated crops (Debiasi and Franchini, 2012; Beutler *et al.*, 2016). CLI also increases stability of soil aggregates, soil microbial biomass and diversity, and crop productivity and profitability while reducing economic risk (de Moraes et al., 2014).

CLI economic benefits have been questioned by Brazilian farmers (Gil *et al.*, 2016), due to the large financial investment required in diversified agricultural machinery and implements, road infrastructure and storage structures. This complex system also requires producer knowledge of diversified farm enterprises, technology and commodity markets in addition to potential complex contractual arrangements to insure CLI can take place beyond the farm level involving anything from neighboring farms to regional exchanges coordinated by third-party entities (Asai *et al.*, 2018). CLI also benefits from higher farmer education levels, technical assistance and proximity to Embrapa CLI experiments (Gil *et al.*, 2016).

Pasture improvement via re-seeding requires maintenance fertilization where farmers have adequate training on soil sampling and interpretation of soils analyses to apply optimal amounts of fertilizer (Bogaerts *et al.*, 2017). Pasture fertilization is an efficient SAI practice to increase pasture productivity and forage quality by increasing crude protein content (Venturini *et al.*, 2017; Oliveira *et al.*, 2018). However, Cardoso *et al.* (2016) showed that once nitrogen (N) fertilizer is applied to pasture, it can increase fossil fuel CO_2 and N_2O emissions derived from the manufacture and application of N fertilizer which can increase total greenhouse emissions per animal.

Livestock supplementation is the cheapest SAI practice and can increase production quickly but requires more managerial skills related to livestock feed utilization (Clark *et al.*, 2018). Weight gain of cattle on tropical pastures is typically low and supplemental feed (e.g. soybeans, corn grain, cottonseed) may be needed to supply limiting nutrients such as crude protein (Detmann *et al.*, 2014). Supplementation should be used according to professional recommendations during more responsive animal growth stages such as stockers and finishing so there is less financial risk (Poppi *et al.*, 2018). Inadequate management of low productivity pastures requires supplementation to ensure nutritional balance. This not only improves animal health, but also results in higher productivity (Clark *et al.*, 2018) and lower GHG emissions (Pereira *et al.*, 2018).

Given optimization of sustainable agricultural systems in Brazil are necessary, investments in rural education and credit lines are currently in progress. The Brazilian Federal Government has earmarked US$53.5 billion to agriculture for the 2018–19 crop-year in addition to US$51.6 billion that will be made available as rural credit. Interest rates were reduced from 7.5 to 5.25% per year for producers adhering to the ABC Plan (Low Carbon Agriculture Plan), for projects that finance the recovery of permanent preservation and legal reserve areas, in line with environmental legislation (Maggi and Vaz de Araújo, 2018). Investments are also constantly being made in research centers such as Brazil's Federal Universities and Embrapa as well as rural extension programs sponsored by SENAR (National Rural Learning Service) and other institutions.

These investments have allowed livestock to achieve gains in productivity and also contributed to the growth of agriculture, with emphasis on soybeans (Barros, 2014). Productivity improvements to the whole-farm beef production system are essential to reduce GHG emissions from all relevant sources (Crosson *et al.*, 2011). Brazil has recently committed to reduce GHG emissions 36% by 2020 and the livestock sector is one of the main focal industries for such reductions via intensification (Mazzetto *et al.*, 2015). Lathuillière *et al.* (2018) reported a decline in pasture area from 2000 to 2014, which when combined with increasing cattle population, led to an increase in cattle stocking density in Mato Grosso state: 0.57 head ha^{-1} in 2001 compared to 0.97 head ha^{-1} in 2015. Despite recent improvements in beef system intensification, productivity of Brazil's pastures is only 32 to 34% of its potential. Increasing productivity to 49 to 52% of its potential would meet forage demands until at least 2040, without the need to increase area (Strassburg *et al.*, 2014). Intensification can increase farm revenue 62% and live weight gains 20%, thus reducing the time before cattle are slaughtered (Cepea/Esalq, 2012).

The SAI practices adopted by our cooperating farm can improve productivity and profitability while reducing beef's carbon footprint (Supplementary Materials, Table S7). While these practices are being disseminated locally, other farmers may not be able make such investments. In order to ensure that Brazil's livestock industry develops in a sustainable manner, continued federal government incentives for farmers and investment in agricultural extension education on sustainable livestock systems are required (Zu Ermgassen *et al.*, 2018). Varying types of credit to cover sustainable agricultural practice operating expenses may encourage more producers to adopt these practices through close collaborations between Brazil's beef producers, academic researchers, the Brazilian government and the private sector.

Conclusions

Despite the challenges of adopting five SAI practices, such intensification and diversification improved our cooperating beef cattle farm's net farm income per hectare by ~130% over 3 years. Environmentally, there was recovery of degraded pasture areas. Effective beef cattle farm management and evaluation of production and economic indicators are important to determine if SAI is an appropriate pathway for other Brazilian cattle farmers to follow. In addition to more capital intensive and managerially complex sustainable intensification practices such as irrigated rotational grazing and CLI, it is important to encourage other alternatives that are less costly such as grain supplementation of beef cattle as well as extensive pasture improvements via fertilization and re-seeding.

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