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Climate change mitigation through intensified pasture management: Estimating greenhouse gas emissions on cattle farms in the Brazilian Amazon

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ABSTRACT

Cattle ranching in Brazil is a key driver of deforestation and greenhouse gas (GHG) emissions. The Brazilian government plans to reduce national GHG emissions by at least 36%, partly by reducing emissions in the livestock sector through strategies such as intensification, pasture improvement, and rotational grazing. In response, sustainability programs promoting these practices have begun operation. Though studies have previously investigated aspects of GHG emissions and sequestration in improved pastures, they have not linked improvements with programmatic interventions. We surveyed 40 cattle ranchers located in the Brazilian Amazon biome to investigate how GHG emissions differed between farms participating in livestock sustainability programs with intensified production and farms not participating in these programs. We found that participating farms produced 8.3 kg of CO_2e/kg of carcass weight (CW) less than did non-participating farms, which represents 19% fewer emissions. Farms that had participated in a sustainability program for at least two years showed larger differences in emissions: 19.0 kg of CO_2e/kg CW less for program farms compared with their counterparts, or 35.8% fewer emissions. Key drivers of the total CO_2e/kg CW in all farms were enteric fermentation and manure management. This paper provides farm-level data supporting intensification as a possible strategy to reduce emissions per kilogram of beef produced, and suggests that future research efforts should focus on long-term impacts of intensification and expand metrics for success beyond GHG calculations.

1. Introduction

Brazil is the world's second largest producer of beef—9.68 million tonnes in 2013 (FAOSTAT 2016)—and production is predicted to increase to 11.4 million tonnes by 2025 (MAPA, 2015). As the industry has risen in prominence and economic importance, modern pressures related to social and environmental sustainability have matched pace. In particular, Brazil faces major international pressure to reduce greenhouse gas (GHG) emissions (Ruviaro et al., 2015), of which livestock production contributes roughly 18% to annual totals (MCTI, 2013). Linkages have also been made between the expansion of cattle ranching since the 1970s and increased deforestation. Brazilian cattle herds have nearly tripled since 1970 (IBGE, 2016), in part because of policies promoting agricultural expansion and development activity in the Cerrado (Brazilian savannah) and Amazonian frontier (McAlpine et al., 2009). Though complex, the relationship between cattle ranching and deforestation has created further urgency in the industry to evolve in response. Recent commitments made by the Brazilian national government to reduce GHG emissions by 37% by 2025 (from 2005 levels) (Federative Republic of Brazil, 2015) have further underscored the need to understand the relationship between cattle production and emissions, including emissions attributable

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both to deforestation and to production practices (Cerri et al., 2010). The objective of this paper is to focus on the link between production practices, programs targeting farmer practices, and resultant emissions by asking: "Does the farm-level balance of GHG emissions related to raising cattle differ between farms that do and do not participate in a sustainability program or sustainability certification?"

The economic potential of the cattle sector has spurred desire for innovation in technologies and practices that will increase sophistication and competitiveness in the world market. Traditional cattle-raising practice in Brazil is low input, characterized by large open pastures that are often degraded by unchecked grazing (Cerri et al., 2016). Intensification of cattle production has gained traction as a potential solution to the problem of meeting both increased production and decreased emission goals for a reasonable cost (Palermo et al., 2014). Intensification in Brazil is generally understood to mean "moderate intensification," which uses a system that is still based primarily on pasture-fed cattle. Intensification in this context often includes two sets of strategies: (1) pasture management practices designed to increase quality and quantity of forage, typically using soil inputs and rotational grazing; and (2) the use of feed lots and supplements for the final stages of cattle's lives (Latawiec et al., 2014). The main goals of both strategies include increasing stocking rates and decreasing the age of slaughter, both of which typically yield higher profits for producers (Undersander et al., 2014) and have the potential to decrease emissions from both land use change and enteric fermentation (Dick et al., 2015). Some models suggest that increased quality and quantity of forage through pasture restoration—a key intensification strategy—can potentially decrease GHG emissions per kg carcass weight (CW) by 50%, principally due to reduction in methane emissions (Cardoso et al., 2016).

Cattle intensification strategies are therefore an attractive central component of several new livestock sustainability programs and certification options that were created to induce producers to increase productivity while decreasing environmental impacts. Sustainability programs have made inroads into other sectors such as coffee (Potts et al., 2014), Brazil nuts (Duchelle et al., 2014), and biofuels (Scarlatt and Dallemand, 2011), yet progress in the cattle sector has lagged due to lack of market demand, little or no price premium, and the complexities of assessing livestock operations in comparison with annual crops. There is some evidence that this may be changing (Alves-Pinto et al., 2013).

Key drivers of the future uptake of sustainability programs for cattle are economic viability and impact on environmental outcomes. Reducing carbon emissions is an important environmental outcome linked to intensification programs, which presume that management changes can alter the underlying emissions profile of cattle ranches. Some studies have constructed a useful baseline profile of cattle emissions under typical extensive conditions but do not address how this profile may change under alternative management regimes (Cerri et al., 2016). Those studies that assess different management regimes have typically used Life Cycle Assessment (LCA) approaches to model the full cattle life cycle (Dick et al., 2015) or a stage, such as fattening (de Figueiredo et al., 2016). This paper complements these approaches and fills a gap in the literature by profiling cattle emissions on 40 farms rather than relying on models alone. Our analysis enriches the field by calculating farm emissions under realistic conditions during a typical year of farm operation, including the buying and selling of cattle and partial intensification, which to our knowledge is not reflected in any existing LCA study. This paper also expands the geographic breadth of the field by focusing explicitly on farms within the Amazon biome, considered the new cattle basin of Brazil (Pacheco et al., 2017). Finally, our work explicitly links programmatic interventions, more typically studied from an institutional or policy perspective, to the quantification of emissions.

2. Material and methods

2.1. Description of sustainability programs

We identified sustainability programs that worked with farmers to adopt best management practices for beef cattle in the Amazon biome. We identified four sustainability programs and one sustainability certification program with specific criteria for beef cattle and active operations in the Brazilian Amazon region (Table 1).

Common to all five programs was a focus on improving cattle productivity through increased stocking rates and lower slaughter age, as well as pasture management techniques such as pasture rehabilitation and rotational grazing. All programs provided technical assistance, though this varied widely by initiative. And although all programs were designed for cattle herds raised primarily on pasture, some participating farms also contained confined feeding operations for the finishing stage. Each program had differing requirements and recruitment strategies for identifying farms that would participate in the programs, though generally program staff worked through existing local relationships and networks. All programs supported avoiding further deforestation. All farmers changed their practices in response to program participation, though the magnitude of changes varied by farmer, as some were already experimenting with innovative practices prior to the program. Major changes in practices included rotational grazing, protein supplements in the animal diet, and the use of lime and fertilizer in the grazing area. Two programs additionally included extensive criteria beyond intensification strategies, spanning topics such as social welfare of workers, animal well-being, and environmental factors outside of the pasture area.

2.2. Study sites and farm selection

Our research sampled 40 beef cattle farms in five municipalities in different parts of the Brazilian Amazon using site visits and interviews with the owners and managers (Fig. 1). In Brazil, beef cattle are raised in all 27 states (Latawiec et al., 2014); however, production in the traditional states of the south and southwest has slowed in favor of increased production in the Cerrado and Amazon regions in the central and northern parts of the country (McManus et al., 2016). Despite the smaller contribution of Amazonian beef to overall supply—37% of the total Brazilian herd— as compared with Cerrado-raised beef, we focus here on the Amazonian cattle industry because it has historically been associated with high rates of deforestation and is trending toward a larger share of total Brazilian beef production (Walker et al., 2013). The expanding frontier edge of development and increasing infrastructure in the Amazon region make it particularly vulnerable to continued land use change.

Of the 40 sampled beef cattle farms, we interviewed 19 farmers who were participating in a sustainability or certification program and 21 farmers who were not participating in any such program. All farms in the sample primarily raised beef cattle using pasture-based systems and were located within the Amazon biome. We worked with program staff to connect with producers involved in the sustainability programs of interest; they were able to provide contact information and introductions to farmers. With program staff assistance, we then surveyed approximately the same number of non-program farmers in each study site area. We qualitatively assessed comparability of program and non-program farms at each study site based on size of operation, geographic proximity, and type of operation (i.e., primarily beef cattle raised on pasture, not confined feeding operations only) to ensure that program and non-

Table 1
Summary of the five sustainability initiatives included in this study.

Intervention	Administering organization(s)	Location (municipality, state)	Dates of implementation	Total number of participating cattle farms	Number surveyed	Description of intervention
Novo Campo Project	Instituto Centro de Vida	Alta Floresta, Mato Grosso	2012–present	15 (aim to increase to 300 in next few years)	7	• Technical support and some supplies paid at 50% • About 32 ha intensified per farm
Rondônia Intensification Program	Imaflora, Vida Verde, Marfrig Global Foods	Rolim de Moura, Rondônia	2013–present	4	3	• Technical support covered by program for pilot farmers to intensify about 32 ha
Silvipastoral Program	Instituto de Conservação e Desenvolvimento Sustentável do Amazonas (IDESAM)	Apuí, Amazonas	2014–present	8	4	• Technical support to intensify at least 4 ha and plant trees between intensified areas • Small loan scheme proposed • Focus on milk and beef production
Pecuária Verde Program	Sindicato Rural de Produtores Rurais de Paragominas	Paragominas, Pará	2011–2014	6	4	• Technical support to intensify as many hectares as preferred by farmers • Farm management and animal well-being components
SAN Standard for Sustainable Cattle Production Systems	Imaflora and SAN– Rainforest Alliance certified	Tangará da Serra, Mato Grosso	2011–present	1 (physically two properties under the same owner)	1	• Regular audit and certification (includes social, environmental, animal welfare considerations)

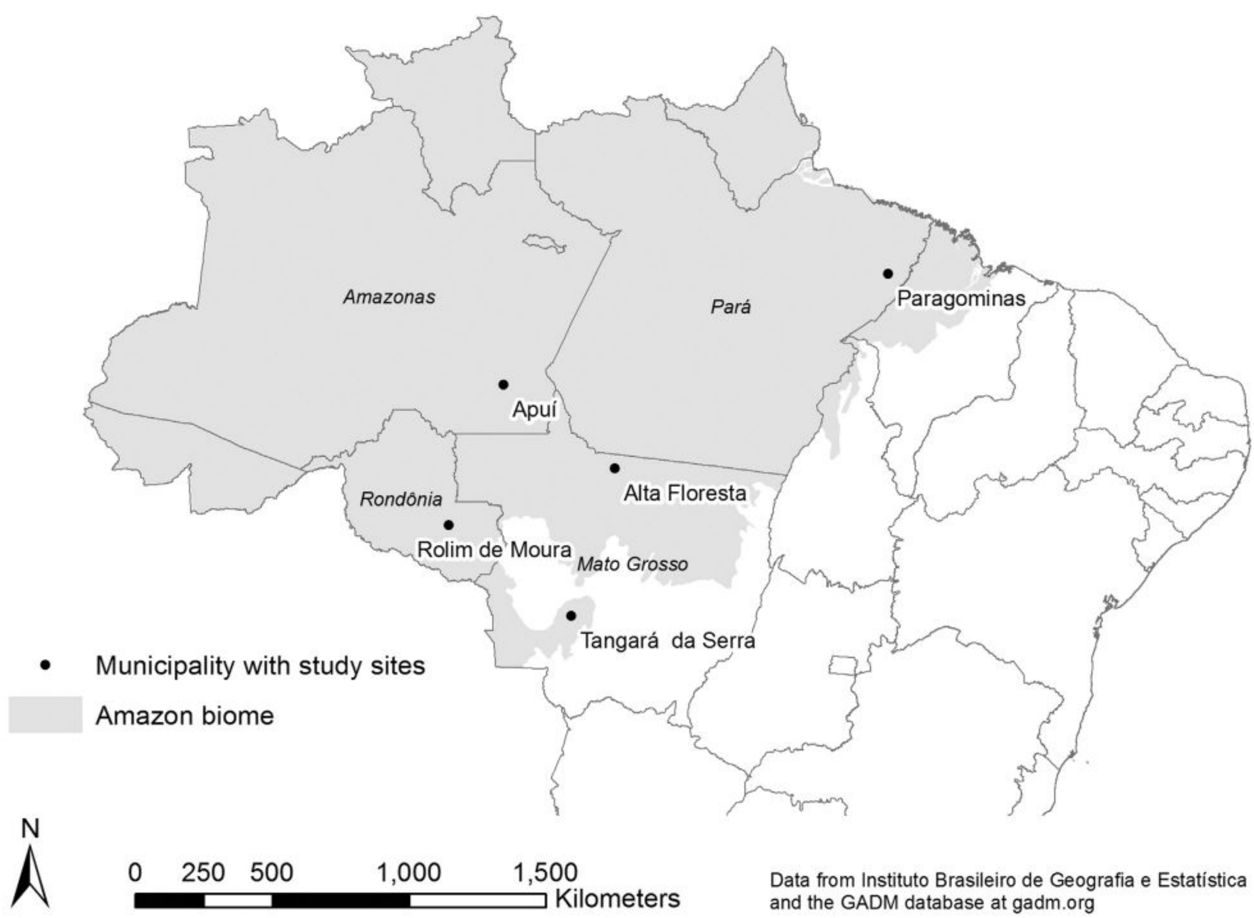

Fig. 1. Municipalities where the surveyed farms were located within the Amazon biome.

program farms were as similar as possible in these respects. We interviewed approximately the same number of participating and non-participating farms in each municipality. The exception was Tangará da Serra, Mato Grosso, where we could not find a non-participating farm comparable to the Sustainable Agriculture Network (SAN)-certified farm. Interviews were conducted with either farm owners or managers, all of whom were involved in day-to-day operations of the cattle portion of the farm.

2.3. Survey development and administration

The owner or manager of each farm was surveyed from June to

July 2015 regarding on-farm practices related to pasture management and beef production. Questions included owner demographics, herd characteristics, fertilizer and pesticide use, pasture characteristics and management, annual production, and anticipated future changes to farm management. The survey questions were designed, first, to solicit enough detail on cattle and pasture operations to calculate a snapshot of GHG emissions in a typical year. Specific metrics were chosen either because they were required inputs to the emissions calculator, or because they reflected a farmer's typical way of measuring their operations, or because they represented a compromise between the two. Questions about changes to management practices over time were included to provide context about the stability of practices as well as the influence of sustainability programs for those farms participating in programs. Basic demographic information was collected because of the possibility that it would reveal differential patterns in management practices among farmers, which could change the interpretation of our results. Surveys were conducted in person and in Portuguese, aided by two native Portuguese speakers from the University of São Paulo. Producers who had no detailed data on hand during the survey were asked to provide the data in follow-up conversations. Therefore, in the months following survey administration, follow-up phone calls with producers were conducted to fill missing data gaps.

2.4. Emissions calculator selection

A few dozen GHG emissions calculation tools are currently available to estimate emissions from agricultural operations or projects. Many are specific to a particular crop, country, region, or user group. Comparative assessments of agricultural GHG tools by Colomb et al. (2013) and Milne et al. (2012) defined key characteristics of available tools, which we used as a starting point in tool selection: geographic focus, scope of emission categories, ease of use, and speed of assessment. To these criteria we added several others: availability of an offline version for use at field sites, manipulability of pre-programmed defaults, and flexibility in reflecting differing cattle management practices.

We selected the Cool Farm Tool (Cool Farm Alliance, 2015) as the best fit for our research needs, given its comparatively detailed livestock sub-module, ease of use, and snapshot-in-time format (i.e., the tool does not require incorporation of a temporal element or the entry of multiple alternative scenarios, as several tools do). The version of the Cool Farm Tool we used is capable of accounting for both annual crops and livestock emissions. Emissions are tailored by climate, location, and soil type. Available modules can account for land use changes, organic and non-organic fertilizer applications, management changes such as tillage or cover cropping, energy use, and transport.

A key strength of the Cool Farm Tool's livestock sub-module is that it allowed us to differentiate among farm practices with respect to livestock lifecycle, pasture management, and feed choice. This flexibility proved to be the most important criterion in our selection process, though given the complexity of modeling livestock operations in contrast with annual crops, it remains less flexible than a custom-designed life-cycle assessment (Crosson et al., 2011). A customized life-cycle assessment, however, would be less comparable to other studies, and would not have the benefit of the more substantial development process that established tools have undergone.

2.5. Scope and assumptions of GHG calculations

Our calculations of GHG emissions focused on activities occurring on pastureland and directly relating to the raising of cattle. We reported total emissions in kilograms CO_2e/kg CW (carcass weight) produced and leaving the farm in a typical year. We included emissions from the production of external inputs such as fertilizer. Specific emissions accounted for included CH_4 emitted from cattle (enteric fermentation) and manure deposited and left on pasture; direct and indirect N_2O emissions from manure deposited and left on pasture and nitrogen fertilizer applied to soil; and CO_2 associated with direct and indirect field N_2O emissions, fertilizer production, pesticide production, and livestock feed production. CO_2 equivalency factors integrated into the Cool Farm Tool are based on IPCC-AR4 standards.

The calculations did not include emissions from land use change, the raising of crops or other livestock on the farm, carbon sequestration from forests on the property, or variation in soil carbon stocks in pastureland. The impact of land use change (particularly deforestation) on total on-farm emissions can be significant; but in most of the municipalities we surveyed, little forest remained. All the data collected reflect each interviewees' reporting of farm practices at the time of the survey (June to July 2015). Our independent variable of interest was whether farms participated in a sustainability program or not.

We included questions on the survey that directly addressed data variables required by the Cool Farm Tool, and transferred these data from the surveys into the calculator. When producers did not directly provide the data needed, we used default values (see Appendix 1). We determined default values based on extensive conversations with project partners in Brazil or average values received during survey administration. Annual total feed for the herd on a given farm was attributed to cattle by life stage based on average weight in each stage. Where the Cool Farm Tool incorrectly assumed that a given management practice was applied over the total farm area (e.g., the application of fertilizer), we adjusted the raw values provided by the survey respondent to force the tool to produce a correct total application. Though we gathered detailed quantity and brand information on pesticides and herbicides used on pasture, the Cool Farm Tool cannot accept this level of detail. Therefore, pesticide and herbicide use is represented as a binary variable in our regression models. Other methods used to fit the data to the Cool Farm Tool involved restricting land area under consideration to pasture area (i.e., excluding forest areas) and adjusting the quality of pasture for those farms participating in a program with a pasture-improvement component.

2.6. Analysis

Survey data and Cool Farm Tool outputs for each of the 40 farms were analyzed using a series of methods. First, descriptive statistics were explored and scatter plots produced to examine any relationships between variables. Difference of means tests were used to analyze the statistical significance of the non-program farm versus program farm differences as well as potential extraneous factors that could have biased the results. Finally, linear regression was used to validate the findings of the difference of means test by including control variables such as location and farm size.

3. Results

3.1. Farm characteristics

Program farms had a mean (±SD) of 3709.5 (±9938.7) head of cattle on 1352.4 (±2805.3) ha of pasture, compared with 1451.4 (±2974.2) head of cattle on 756.7 (±1541.0) ha of pasture on non-program farms (Table 2). The mean number of heads of cattle and pasture area were positively skewed due to two outlier large farms. Program farms reported, on average, a 23% increase in the head of cattle on farm since joining their respective programs with no expansion of land area. Eight out of 19 program farms reported no increase in cattle since joining the program.

Owners of program farms were an average of 5.8 (±3.6) years older than owners of non-program farms. The number of years the farm had been owned was 3.6 (±3.1) years longer for program farms. Non-program farms reported having last cleared forest an average of 14 (±9.4) years ago, and program farms 18.5 (±7.8) years ago. None of the above stated differences between program and non-program farms were statistically significant; however, number of head of cattle, pasture area, and years farm owned were included in the subsequent multivariate regression analyses since the differences were not approximately zero.

The slaughter weight of animals was slightly higher for females on non-program farms—200.5 (±14.5) kg compared with 198.92 (±19.7) kg—but lower for males, 266.8 (±29.1) kg compared with 275.4 (±18.5) kg (Table 2). The average slaughter age for females was 23.5 months on program farms, compared with 26.9 on non-program farms. The average slaughter age for males was 27.3 for program farms and 30.7 for non-program farms. The difference in slaughter age was statistically significant at a 95% confidence level for males and at a 90% confidence level for females.

3.2. GHG emission results per kilogram of beef produced

On average, GHG emissions from beef production were lower on program farms at 36.4 (±14.6) kg of CO_2e/kg CW produced than on non-program farms at 44.7 (±21.4) kg of CO_2e/kg CW produced—a difference of 8.3 (±5.9) kg (Table 3). This represents a reduction of 18.6% fewer emissions per kilogram of CO_2e/kg CW produced; this difference was not statistically significant.

To verify whether emission outcomes were influenced by other explanatory factors, such as location, size of the farm, and years the farm was owned, a series of linear regressions were conducted. These control variables were selected to try to isolate the effect of program participation from technical sophistication and differential adoption of new practices by generation. Including all 40 sampled farms and control variables, we estimated our first model:

$$Y_i = \beta_0 + \beta_1 P_i + \beta_2 HEAD_i + \beta_3 HA_i + \beta_4 YR_i + \varepsilon_i$$

where Y_i is the kilograms of CO_2e/kg CW produced for a given farm, P_i is a dummy variable for the program participation status of the farm, $HEAD_i$ is the annual stocking rate of cattle, HA_i is the hectares of pasture land, YR_i is the years of ownership of a farm, and ε_i is a heteroskedasticity-robust error term. In this model, farms participating in programs contributed an average of 9.9 fewer kilograms of CO_2e/kg CW when compared with non-program farms; however, this was not statistically significant at the 90% confidence level.

To test whether results were impacted by locational differences, we estimated a second model, controlling for location:

$$Y_i = \beta_0 + \beta_1 P_i + \beta_2 \lambda_i + \varepsilon_i$$

where λ_l is a vector of location fixed effects. The coefficient reduced to 7.4 fewer kilograms of CO_2e/kg CW produced, which was not statistically significant ($p < 0.1$). When taking into account farm characteristics, the coefficient on program participation resulted in a slight increase in the emission differences, whereas the coefficient on the regression controlling for locational differences resulted in a slight decrease in the emission differences.

Because these differences were minimal, and not statistically significant, the descriptive difference of 8.3 kg is believed to accurately represent the program difference, despite other explanatory factors. A regression that included both farm characteristics and location was not possible because of the small sample size, which restricted our controls to a maximum of four variables.

When restricting the data to two locations, Paragominas and Alta Floresta, where programs had been implemented for more than two years, a third model was estimated:

$$Y_i = \beta_0 + \beta_1 P_i + \beta_2 AF_i + \beta_4 YR_i + \varepsilon_i$$

where all variables were as defined in the first model, plus AF_i, a dummy variable denoting whether a farm was in Alta Floresta. In this model, the average difference was 19.0 kg of CO_2e/kg CW produced, which was statistically significant ($p < 0.05$) (Table 3). This difference equates to 35.8% fewer kilograms of CO_2e/kg CW from program farms. When holding constant the number of years that a farm had been owned and its location in a linear regression analysis, farms participating in a program in one of these locations had on average of 21.7 fewer kilograms of CO_2e/kg CW produced compared with non-program farms in the same location (Table 4).

The coefficient was statistically significant ($p < 0.05$). Non-program farms in Paragominas and Alta Floresta had a median kilogram of CO_2e/kg CW produced higher than the median for all farms, whereas program farms in these two locations also had a slightly higher median than all farms (Fig. 2).

The location with the greatest average difference between program and non-program farms was Alta Floresta (Fig. 3). Farms that participated in Pecuária Verde, in the state of Pará, emitted 30.0 (±16.8) kg of CO_2e/kg CW on average, which was the lowest average among the eight groups of program and non-program farms across the four locations (Fig. 4). The single observation in Tangará da Serra, the SAN-certified sustainable farm, had a per-kilogram output substantially lower than the averages of other groups of farms at 19.7 kg of CO_2e/kg CW; however, there were other individual farms in the sample that had estimated emissions lower than this figure.

3.3. GHG emissions per hectare of pasture

On average, program farms had 2.25 (±0.9) animals per hectare,

Table 2
Comparison of non-program and program farms.

	Non-program (SD)	Program (SD)	Difference (SE)	t-score (of difference)	Confidence interval
Number of head of cattle	1451.4 (2974.2)	3709.5 (9938.7)	−2258.1 (2271.0)	0.994	(6855.48, 2339.285)
Pasture area (ha)	756.7 (1541.0)	1352.4 (2805.3)	−595.7 (706.4)	−0.843	(-2025.779, 834.312)
Owner age (years)	51.3 (12.2)	57.1 (9.8)	−5.1 (3.6)	−1.606	(-9.910, 2.742)
Years owned farm	18.1 (10.4)	21.6 (9.3)	−3.6 (3.1)	−1.147	(-9.910, 2.742)
Last clearing of forest (years ago)	14.0 (9.4)	18.5 (7.8)	−4.5 (3.0)	−1.518	(-10.608, 1.541)
Slaughter age in months (female)	26.8 (5.5)	23.5 (3.2)	3.4 (1.9)	1.816*	(-0.523, 7.384)
Slaughter age in months (male)	30.7 (5.9)	27.3 (2.6)	3.4 (1.6)	2.053**	(-0.004, 6.774)
Slaughter weight in kg (female)	200.5 (14.5)	198.9 (19.7)	1.6 (7.8)	0.202	(-14.781, 17.939)
Slaughter weight in kg (male)	266.8 (29.1)	275.4 (18.5)	−8.6 (9.0)	−0.958	(-27.143, 9.883)

Table 3
GHG emission outcomes for program and non-program farms.

	Non-program (SD)	Program (SD)	Difference (SE)	t-stat (of difference)	Confidence Interval
GHG/kg (all farms)	44.7 (21.4)	36.4 (14.6)	8.3 (5.9)	1.418	(-3.549, 20.156)
GHG/kg (farms in locations 1 and 4)	53.1 (27.8)	34.1 (12.8)	19.0 (9.5)	2.005**	(-0.990, 38.943)
Fertilizer emissions/kg	1.1 (3.4)	0.8 (1.2)	0.2 (0.8)	0.266	(-1.452, 1.891)
Nitrogen emissions/kg	1.8 (1.3)	1.3 (0.8)	0.5 (0.4)	1.549	(-0.167, 1.25)
Pesticides emissions/kg	0.05 (0.09)	0.07 (0.1)	-0.03 (0.03)	-0.793	(-0.093, 0.040)
Enteric fermentation/kg	33.0 (15.7)	26.7 (13.0)	6.2 (4.6)	1.358	(-3.051, 15.492)
Manure emissions/kg	8.0 (6.7)	6.7 (5.9)	1.3 (2.0)	0.653	(-2.760, 5.386)

N.B. Total GHG/kg CW is derived from emissions associated with fertilizer, nitrogen, pesticides, enteric fermentation, and manure per kilogram.
t-scores significant at 0.1 level are marked with *, 0.05 at **.
Location 1: Alta Floresta, Location 4: Paragominas.

Table 4
Regression coefficients of program participation on kg of CO_2 per kg CW produced and per hectare of pasture.

	Kg of GHG per kg CW produced			Kg of GHG per ha of pasture area		
	All farms adjusted for control variables	All farms w/controls and location effects	Alta Floresta and Paragominas only	All farms with controls	All farms w/controls and fixed effects	Alta Floresta and Paragominas only
Farm participating in program	−9.859 (5.696)	−7.386 (6.693)	−21.732** (9.653)	−510.369 (857.315)	−419.643 (690.150)	111.099 (682.293)
Number of cattle	−0.001 (0.001)			0.464** (0.232)		−0.645 (0.385)
Pasture area (ha)	0.002 (0.003)			−1.220 (0.781)		
Years farm owned	0.858* (0.297)		0.901 (0.621)	72.057** (35.011)		74.914** (35.199)
Location 1		23.522*** (5.343)	6.649 (10.001)		−3893.981*** (560.307)	863.896 (739.348)
Location 2		13.609 (6.873)			−2735.864** (1292.18)	
Location 3		18.368*** (6.967)			−7065.245*** (644.257)	
Location 4		11.788 (7.976)	–		−5318.664*** (744.443)	–
Location 5		–			–	
Intercept	29.254 (6.398)	26.586 (6.693)	29.769 (15.118)	3432.770 (1139.965)	9445.543 (690.150)	3510.026 (1125.41)
R squared	0.26	0.13	0.39	0.18	0.41	0.30
N	40	40	19	40	40	19

N.B. Standard errors are given in parenthesis; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; Location fixed effects are labeled as follows: Location 1: Alta Floresta, Location 2: Rolim de Moura, Location 3: Apuí, Location 4: Paragominas, Location 5: Tangara da Serra; Location 5 is omitted from columns 2 and 5 for collinearity; Location 4 is omitted in columns 3 and 6 for collinearity.

compared with non-program farms with 1.92 (±1.4) animals per hectare. Similarly, emissions per hectare on program farms was slightly higher at 4552.2 (±2106.6) kg of CO_2e/ha/yr, compared with non-program farms at 4483.5 (±3397.2) kg of CO_2e/ha/yr (Table 5), yielding a difference of 67.8 kg of CO_2e/ha/yr. When controlling for number of cattle, pasture area, and years that a farm had been owned in the linear regression, program farms emitted on average 510.4 kg of CO_2e/ha/yr less than non-program farms (Table 4), which was not a statistically significant difference ($p < 0.1$). When controlling for location, the coefficient reduced to 419.6 kg less.

When restricting the data to Alta Floresta and Paragominas, where programs had been implemented for more than two years, program farms emitted 111.1 more kilograms of CO_2e/ha/yr on average compared with their counterparts, when controlling for number of head of cattle, years farm owned, and location (Table 4), which was not statistically significant ($p < 0.1$).

3.4. Total GHG emissions

The median total emissions per year for program farms was 2081.6 tCO_2e, compared with non-program farms at 2512.4 tCO_2e (Table 5). Across all farms in the sample, 74% of total emissions were from enteric fermentation, 22% from manure, 2% from feed (production and transportation emissions), 2% from fertilizers, and less than 1% from pesticides (Fig. 4).

4. Discussion

4.1. Understanding emissions results per kilogram of product produced

The results indicate that, on average, farms with some area of intensification experienced reduced emissions of kg CO_2e/kg CW produced as compared with farms with no intensification, although not at statistically significant levels. Furthermore, farms that were participating in programs that had been established for more than two years showed even greater emission reductions per kilogram of beef than farms in more recently established programs; these differences were statistically significant. We hypothesize that the difference is due to some combination of level of technical assistance and program maturity (years in operation), but we cannot substantiate either claim with our current data set.

We analyzed farms participating in the Pecuária Verde (Paragominas) and Novo Campo (Alta Floresta) programs as a subset because of the programs' similarity in age and how they function and interact with ranchers, which includes more extensive and

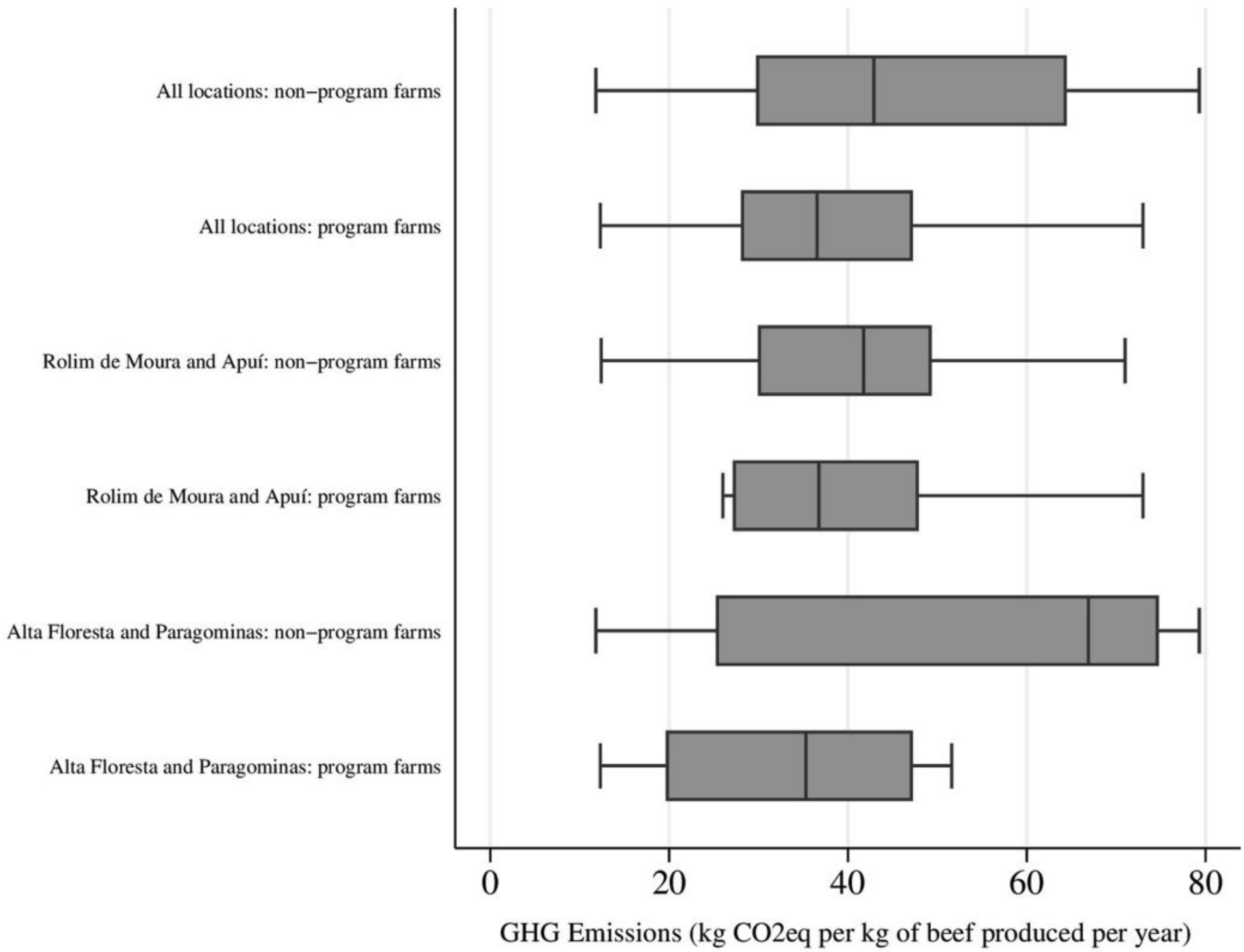

Fig. 2. Box plots of kilogram of CO_2eq/kg CW produced per year for all farms, farms in locations where the program has been implemented for less than two years (Locations 2 and 3), and farms in locations where the program has been implemented for more than two years (Locations 1 and 4) by program participation. Notes: Location 1: Alta Floresta, Location 2: Rolim de Moura, Location 3: Apuí, Location 4: Paragominas.

intensive interaction. It is uncertain whether program age or some other distinctive feature of these programs might explain the better performance of Pecuária Verde and Novo Campo in reducing GHG emissions.

The farms in our sample's youngest program, IDESAM's project in Apuí, had been implementing intensification practices for less than one year. Results from intensification strategies may not appear immediately, given how recently many of the farmers adopted these practices. Many of the farms in Apuí applied fertilizers and divided their pastures just before the data were collected; thus they did not yet have updated production numbers to share. Therefore, their emission values are likely inflated, negatively impacting the GHG balance because fertilizer inputs are included but increased stocking rates have not yet been realized (Fig. 3).

Farms participating in programs had reduced slaughter age and increased stocking rates than did non-participating farms. Although there were, on average, more cattle per hectare on program than non-program farms, there was only a slight, not statistically significant increase in per-hectare emissions. Improvement in forage quality, as modeled by the Cool Farm Tool, accounts for some of the per-kilogram emission differences, presumably because the higher quality forage is believed to increase digestibility and therefore lower emissions. Increased productivity also accounts for a portion of the emission differences between the program and non-program farms. As program farms increase the size of their herds and produce more kilograms of beef per year on the same amount of land, per-kilogram emissions tend to decrease while emissions per hectare increase. We would therefore expect program farms to have slightly higher emissions per hectare due to intensification. Indeed, this is borne out for the locations where a program has been implemented for more than two years (Table 4, column 6). This difference, however, is not statistically significant. When all sample farms are included, program farms actually had fewer emissions per hectare than their counterparts (Table 4, columns 4 and 5). Again, the difference was not statistically significant. Possible explanations for the deviation in trend are the relatively small difference in number of cattle head per hectare between program and non-program farms and the relative youth of some of the programs (e.g., additional cattle may be phased into a farm's herd slowly over a period of years, and this process may not yet be apparent in the data).

This difference underscores the importance of choosing an appropriate metric for analysis when looking at program outcomes. Per-kilogram estimates are useful in understanding how a farmer producing at a certain level can expect intensification practices to increase the efficiency of production relative to emissions. On the

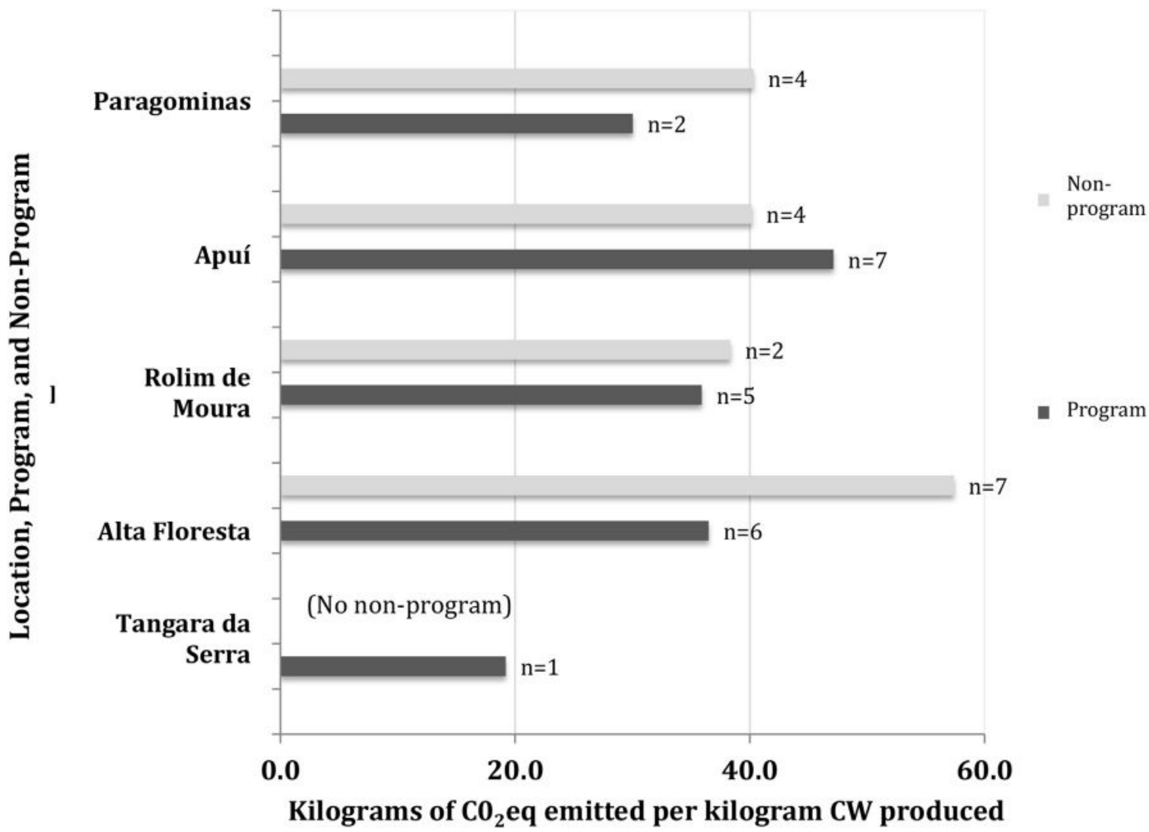

Fig. 3. Kilogram of $C0_2$ emitted per kilogram CW produced by location and program status.

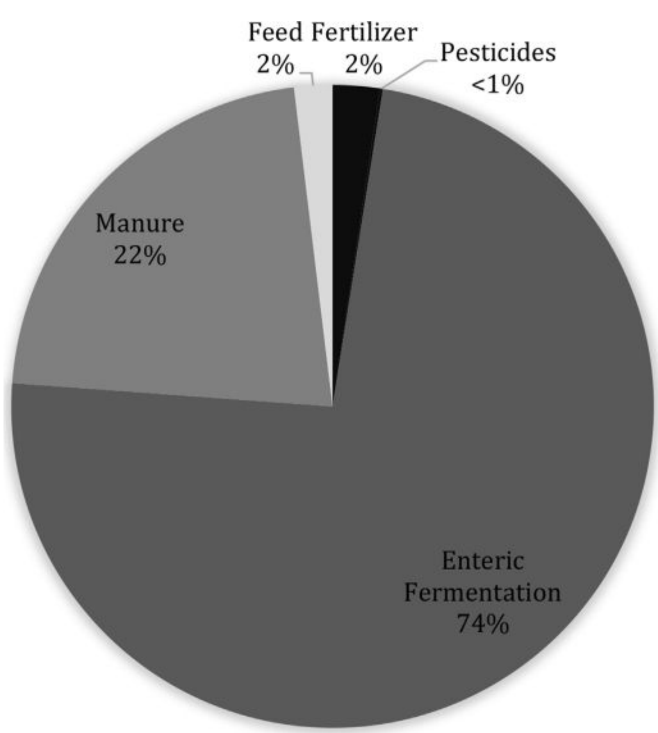

Fig. 4. Sources of total GHG emissions for all farms in sample (n = 38).

other hand, per-hectare estimates are more useful for understanding how total emissions could vary according to land use change scenarios.

4.2. Comparison to previous studies

As authors of similar carbon footprint studies have noted, comparison of results across studies is difficult due to variability in boundaries of the analysis (de Figueiredo et al., 2016). However, a cursory review places our results within a reasonable range of others in the literature. Over a 12-year period, Dick et al. (2015) modeled emissions of 45.05 kg CO_2e/kg CW in an extensive (low-input, traditional) system, versus 18.32 kg CO_2e/kg CW in an improved system. The improved system has a substantially lower footprint here than in our work (36.4 kg CO_2e/kg CW), but the extensive system result is very close to ours (44.7 kg CO_2e/kg CW). In contrast, Ruviaro et al. (2015) modeled seven management systems along an intensity gradient, with the least intense resulting in 85.2 kg CO_2e/kg CW and the most intense in 36.6 kg CO_2e/kg CW. In this case, it is the intensified system that mostly closely parallels our results. As Cardoso et al. (2016) point out, these two studies appear to use very similar IPCC-based methods, yet they arrive at starkly different results—Cardoso et al. (2016) found results in between the two extremes, again within range of ours at 58.3 kg CO_2eq/kg CW for the degraded pasture and 29.4 kg CO_2eq/kg CW for the most intensified pasture.

Despite the similarity of our results to these studies, aspects of the system boundaries used in the studies are often unclear, and so the comparability of results should not be overstated. Previous studies focusing on carbon emissions by management strategy have most commonly used an LCA approach, which produces a picture of emissions over a period long enough to follow cattle through a full life cycle. In contrast, a major contribution of this paper is its representation of emissions in a typical year on 40 real farms. Boundary issues proliferate here, due to the common

Table 5
GHG emissions summary by carcass weight produced, area, and total annual farm emissions for all program and non-program farms aggregated together.

	GHG emissions (kg of CO_2e/kg CW produced/yr)	GHG emissions (kg of CO_2e/ha/yr)	Total GHG emissions (tCO_2e/yr)
Program farms (n = 19)			
Mean	36.4	4552.2	8754.0
Median	35.3	4928.4	2081.6
Standard Deviation	14.6	2106.6	25,670.5
Non-program farms (n = 21)			
Mean	44.7	4483.5	3968.7
Median	42.9	3873.9	2512.4
Standard Deviation	21.4	3397.2	9167.6
N.B. Total emissions for program farms is positively skewed due to two outliers.			

occurrence of farms that only birth cattle or only fatten cattle in addition to full life cycle farms. Additionally, it is unclear in existing studies whether improved or intensified scenarios assume intensification of the entire pasture area. This could be a major source of deviation between our results and those of LCA studies, because we modeled all pastures on a farm as an integrated system that typically included both intensive and extensive pastures. We observed wide variation in percentage of pasture lands intensified on a given farm, typically due to economic constraints—percentage intensified ranged from 3% to 100%, with a median value of 17%. Because it is atypical to intensify 100% of available pasture, LCA studies that presume this condition may overstate the emissions savings of intensification when presenting findings on a whole-farm basis.

4.3. Practical applications for program development

For farmers, adopting intensified management represents a departure from the traditional open-pasture management that has historically been used in the Brazilian Amazon. All intensification programs provided technical training to farmers on intensified rotational management. Yet very few technicians in Brazil are capable of training farmers to adopt these practices (Professor Moacyr Corsi, pers. comm. July 2015). The intensity and quality of the training that farmers receive are critical to the programs' achieving their performance goals. The advantages conferred by participating in more established programs (in existence at least two years) and with a longer period of assistance (at least two years) may help to explain why the production increased at farms in the longer established Pecuaria Verde and Novo Campo programs. This implies a need for steady funding streams to maintain adequate technical assistance until intensification is fully implemented.

Herd size for program ranchers increased in the time since joining the program. Farmers increased their stocking rates on average by 23%, while reducing the slaughter age by 3.4 months. One goal for all of the programs was to help producers increase beef production, and these results indicate the positive progress toward that goal. Despite the evidence of increased stocking rates and decreased slaughter age, significant challenges to more widespread adoption remain due to lack of qualified technical assistance (de Figueiredo et al., 2016). Movement toward this goal is still warranted, however, particularly given recent research substantiating cost savings alongside emissions savings for certain kinds of intensified systems (Florindo et al., 2017).

4.4. Implications for deforestation

Although each program had different specific requirements for participation, a primary goal of each was to increase production on land that is already pasture to prevent future deforestation. Because our model's scope only included emissions directly related to ranching operations at a specified moment in time, we did not account for emissions associated with deforestation. However, the vast majority of farmers in our sample indicated no interest or need for future deforestation activity on their properties, giving the issue little weight at the level of individual farmers and existing cattle ranches in the studied areas. Several studies hypothesize potential carbon savings from avoided deforestation as a result of improved livestock practices in Brazil, either focused on voluntary certification schemes (Alves-Pinto et al., 2013) or economic policies (Cohn et al., 2014). Realizing these savings requires addressing the structural causes of deforestation through options such as more attractive financing for ranchers interested in intensifying their operations, improved extension services, and greater monitoring and enforcement of environmental regulations to prevent a rebound effect; all would allow intensification programs to contribute to avoided future deforestation (de Gouvello, 2010).

4.5. Methodological and analytical considerations

LCA methodology is useful and dominant in the literature on carbon emissions footprints for livestock, but a weakness of this approach is its inherent customization and the difficulty of comparing LCAs with different functional units (de Vries and de Boer, 2010). Third-party calculators offer an alternative method that, although limited in customization, allows for easier comparability across studies and potential use by a wider range of non-experts or experts executing rapid assessments in the field. A secondary outcome of this paper, therefore, is an improved understanding of how different off-the-shelf GHG emissions calculation tools can be used to capture emissions from a range of livestock practices. We initially tested the EX-Ante Carbon balance Tool (EX-ACT) (FAO, 2015) developed by the Food and Agriculture Organization of the United Nations, and World Resources Institute's emissions calculator (World Resources Institute, 2014). We decided, however, to use the Cool Farm Tool for several reasons: it was best able to calculate on-farm emissions using our data relative to the available tools; it was best able to incorporate the different feeds for the different life stages; and its snapshot-in-time mode and user friendliness. Despite these reasons, using the Cool Farm Tool entailed trade-offs, which indicates the need for improved tools that use local datasets, provide flexibility in capturing the different stages of animal lives, and reflect multiple management regimes within a farm.

One of the most pressing needs for future calculator development is a more robust method for incorporating potential carbon sequestration benefits from improved pasture management. Studies show increased carbon sequestration in improved pastures rather than in degraded pastures (Braz et al., 2013), which could reduce the overall emissions from ranching operations. Research has not been conclusive, however, and the magnitude of soil organic carbon (SOC) stock changes may vary substantially by soil type, even in the same region (Maia et al., 2009). Degradation of pastureland does not necessarily result in changes in carbon in the soil and biomass (Müller et al., 2004), and existing evidence indicates that factors such as clay content may play more of a role in soil carbon changes than management (Hughes et al., 2002). Many studies rely on models such as Century and RothC, which are useful for deriving general patterns of SOC but should be augmented by field samples that can more precisely measure changes based on management (Cerri et al., 2007). One of the biggest challenges in the existing literature is that studies examine different suites of management practices, so it is difficult to compare across studies. Longitudinal studies examining soil carbon stocks over time are rare and needed, given the wide variation in stocks based on factors such as soil type and land use history, which make even carefully selected chronosequences imprecise (Fearnside and Barbosa, 1998). The Intergovernmental Panel on Climate Change (IPCC) has selected default values for carbon sequestration in grasslands that are incorporated into one tool, EX-ACT. Developers of other tools should consider incorporating IPCC defaults as well, though region- or soil type-specific default factors would be better. Evidence from Maia et al. (2009) suggests under conditions like those of our study—oxisols in Brazil with a range of management regimes—soil organic carbon stocks could increase by a factor of 1.19 ± 0.07 under improved pasture management as compared to native vegetation, while nominal management would decrease stocks by a factor of 0.99 ± 0.08. Studies like these suggest that we might expect significant SOC gains or losses depending on management, underscoring the need for corroborating research.

Nearly as pressing is a need for calculators that can reflect several pasture management regimes per farm. Because livestock often rotate between pastures under different management regimes at different life stages, calculators assuming a single regime are inadequate and force the use of loosely defined average conditions for an entire farm. Emerging research suggests that dry matter intake digestibility, which directly relates to pasture quality, is a key driver of enteric fermentation (Ruviaro et al., 2015). For example, in our sample, all program farms contained both intensified and non-intensified areas. We observed a range of pasture quality conditions in different farm areas, yet these differences could not be reflected with precision in existing tools. Given these reasons, our estimates are likely negatively biased.

The current suite of available calculators does not reflect the emission benefits of reducing animal slaughter age, another key recommendation for inclusion in future calculators. GHG emissions increase as animals eat more (Shibata and Terada, 2010). Animals will have lower emissions if they are slaughtered at younger ages and remain at heavier weights for less time. Demarchi et al. (2003) estimated that reducing average slaughter age for steers could reduce methane emissions by 10%. Animal lifespans were reduced significantly on program farms in our sample, but the Cool Farm Tool does not reflect the potential emission savings from this reduction. Reflecting carbon benefits of reducing cattle slaughter age would improve the ability of off-the-shelf GHG emissions calculators to calculate ranching-related emissions.

5. Conclusion

Our research uses information gathered through interviews with farmers participating in sustainable intensification ranching programs to model the impacts on per kilogram emissions between program farms and non-program farms. It shows that program farms have lower per-kilogram emissions than do non-program farms, and that farm performance is greater among farms that are part of longer established programs. These differences were statistically significant for farmers who participated in the longer established programs. Further, this research outlines some of the important limitations of using off-the-shelf calculators for looking at emissions from ranching operations.

Limitations of the research include: small sample sizes in each study location, which constrains the potential for causal inference; imperfect matching between program and non-program farms; and the infancy of the programs, which may mean that the full life cycle of the herd is not complete and results are therefore not representative of eventual program performance. We relied upon farmer recollections and records to measure inputs and outputs of farm operations rather than field measurements, and our results therefore suffer from the imprecision of human memory and other biases. Further, this study presents a snapshot of GHG emissions at a point in time, which means that temporal changes in management and land use occurring over more than the span of a year are not accounted for.

Recommendations for further research include returning to the farms in subsequent years to understand how per-kilogram emissions change as farmers spend more time in programs and continue to implement the practices once program funding ends, and incorporating field measurements. More studies modeling emissions from real farms are needed to balance the existing literature on LCA-derived emissions estimates, to ground-truth both kinds of studies. Our work also highlights the need for future studies to define the boundaries of analysis more explicitly with regard to animals that do not complete a full life cycle on the observed farm, to aid in comparability across studies.

In addition, this research highlights the need for off-the-shelf GHG emissions calculators to better capture mitigation impacts of a variety of livestock-raising practices when measuring ranching rather than crop agriculture operations. Incorporating animal age structures and dividing the farm into different management areas would be essential for keeping track of changes in the cattle sector around the world. Furthermore, being able to reflect the effects of emissions savings from improved pasture management would be an important step for accurately reflecting the environmental impacts of ranching operations.

Though GHG balance is a critical metric linking management practices to impacts of prime interest to policymakers, it does not present a full picture of environmental performance. Intensification of cattle operations likely influences the pasture ecosystem and related ecological functions such as water quality, biodiversity, and nutrient cycling. On-farm research exploring the effect of intensification programs on these functions would complement GHG models and present policymakers with more information about the long-term effects of programs.

The results of this research are an important stepping-stone to understanding how on-farm practices can make the biggest impact on GHG emissions from livestock. With increasing attention on climate change mitigation, it is imperative that the global increase in demand for beef does not drive unmanageable increases in emissions related directly to farming practices. Our hope is that further studies can build on the data collected from individual farms and illuminate the strengths, weaknesses, and importance of intensification programs in Brazil.

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Appendices

Appendix 1. Default values used in Cool Farm Tool calculations.

Input parameter	Value
Calf birth weight	33 kg
Cattle weight after one year	210 kg of live weight
Length of cow productive phase	96 months
Corn-to-soy ratio of supplemental feed	70:30
Percentage of animal weight consumed in pasture per day (no supplemental feed)	3.5% of live weight
Percentage of animal weight consumed in pasture per day (if supplemental feed)	2.5% of live weight
Percentage of cows giving birth each year	80%
Length of finishing phase (unless otherwise specified)	2.5 months
Mean annual temperature	WorldClim data (Fick and Hijmans 2017)
Soil characteristics	FAO Soil Map of the World

Appendix B. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.06.130.

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