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Sustainable intensification in the Brazilian cattle industry: the role for reduced slaughter age

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Abstract
The cattle industry in the Brazilian Amazon causes vast deforestation while producing at only one-third of the sustainable capacity. Slaughtering cattle at a younger age directly increases production per hectare per year, all else equal, and provides a potential path for sustainable intensification. Here we show that slaughter age is decreasing in the Amazon biome, but this increase in productivity varies across space and throughout the cattle supply chain. We characterize the properties and municipalities that have reduced slaughter age, providing insights into the incentives and barriers to this form of intensification. Most notably, reductions in slaughter age occurred in regions with low remaining forest cover and on properties with little current deforestation, suggesting that ranchers intensify via slaughter age as an alternative to deforestation. We then estimate how changing production practices to reduce slaughter age can reduce enteric methane emissions, accounting for production of additional feed. Our results indicate that reducing slaughter age through improved pasture and feed sources are a path to lower global GHG emissions from cattle production, particularly as beef is increasingly produced in developing countries with historically higher emissions. Yet in the Amazon, deforestation remains the leading source of GHG emissions, necessitating that any effort to reduce slaughter age must be coupled with strict enforcement of zero-deforestation policy. Our findings demonstrate the potential of policy limiting deforestation as a means to reduce both emissions from deforestation and enteric emissions from cattle.

1. Introduction
The question of sustainable intensification is critically important in the Brazilian Amazon. In the last thirty years, 780 000 km\textsuperscript{2} of the Amazon has been cleared, with the majority of clearing done for cattle ranching (Global Forest Atlas 2002, Nepstad \textit{et al} 2014, INPE—Brazilian National Institute of Spatial Research 2020). This threatens countless species of plants and animals, is the cause of nearly half of carbon emissions in Brazil, and has led to a longer dry season (Wearn \textit{et al} 2012, de Castro Solar \textit{et al} 2015, Azevedo \textit{et al} 2018, INPE—Brazilian National Institute of Spatial Research 2020). Yet ending production entirely would risk the livelihoods of the millions of farmers in the region (Angelsen and Kaimowitz 2001, Walker \textit{et al} 2013, Nepstad \textit{et al} 2014, Vale 2017, Rajão \textit{et al} 2020).

Sustainable intensification offers an avenue to slow deforestation and carbon emissions from the sector while continuing to support household incomes (Cohn \textit{et al} 2014, Strassburg \textit{et al} 2014). We study cattle age at slaughter, an overlooked dimension of sustainable cattle intensification. Shorter time to slaughter increases productivity by

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allowing ranchers to produce more head per hectare per year. All else equal, a rancher that rears, finishes, and slaughters animals in two years instead of four would be able to produce twice as many animals over the same length of time using the same land area. Because decreasing the time needed to bring an animal to slaughter weight requires significant investment and changes in production practices, younger slaughter age may also be a signal of increased productivity across a multitude of dimensions.

We provide the first characterization of slaughter age as a measure of cattle productivity, using data on cattle movement to show how slaughter age varies in the Brazilian Amazon. Understanding where, by whom, and why slaughter age is decreasing improves our understanding of sustainable production in a way that is quickly actionable for policy. Slaughter age could be used by researchers, extension agents, and industry leaders to measure and support sustainable intensification. We demonstrate the feasibility using a census of cattle sale for slaughter from the Guide to Animal Transport (GTA) in the states of Mato Grosso (MT), Pará (PA), and Rondônia (RO) from 2013 to 2018. The GTA is a federal database tracking livestock vaccinations, health standards, and movement between properties and slaughterhouse. We use big data and machine learning to match GTA transaction data to property boundaries and land-cover maps of 45,000 properties, allowing us to analyze the links between slaughter age, supply chains, and deforestation.

We profile the properties that sell younger animals for slaughter. Our results suggest that intensification is being used as an alternative to deforestation. Properties that sell younger animals had less deforestation before and during the period and were connected to zero-deforestation slaughterhouses. These properties also sell high volumes of cattle and are well-connected to slaughterhouses. Moreover, slaughter age is lower in municipalities with high allocation of agricultural credit and higher soy production. Our results suggest that the strategies needed to achieve reduced slaughter age have high start-up and operational costs, and these costs are a barrier to slaughter age reduction for smallholders and cash-constrained ranchers operating a traditional, pasture-based system.

We then quantify the reduction in enteric emissions due to reductions in slaughter age. Cattle production is responsible for over 70% of global emissions from livestock, which as a whole emit 5.6–9.3 billion metric tons (Gt) of carbon dioxide equivalent per year (Herrero et al. 2016, United Nations Food and Agriculture Organization 2020, Cusack et al. 2021, Xu et al. 2021). Worldwide, 40% of cattle emissions are from enteric emissions of methane produced as a byproduct of digestion. Production in developing countries yields two to three times more greenhouse gas (GHG) emissions per kilogram of meat produced than in North America and western Europe, largely due to higher enteric emissions per head (Herrero et al. 2013, Cusack et al. 2021). Meanwhile, global demand for beef is rising, and 80% of production is expected to come from these high-emissions developing countries by 2029 (OECD/FAO 2020). Reducing cattle age at slaughter through consistent nutrition and high growth rates has the potential to reduce emissions from cattle (Bustamante et al. 2012) by reducing the lifetime over which an animal produces methane (Herrero et al. 2016). Additionally, many of the strategies that bring an animal to slaughter weight faster have themselves been shown to reduce GHG emissions (e.g. faster weight gain due to improved pasture varieties and rotational grazing) (Herrero et al. 2016, Vale et al. 2019, Cusack et al. 2021). Empirical evidence is mixed, but suggests that some methods of intensification may reduce GHG emissions (Demarchi et al. 2003, Mazzetto et al. 2015, Bogaerts et al. 2017). We expand on this existing work by modeling methane production across different feed and slaughter regimes, demonstrating the potential for younger slaughter age to reduce emissions in the Brazilian cattle sector.

The total effect of reduced slaughter age on GHG emissions depends on the relationship between intensification via slaughter age and deforestation. Whether an increase in productivity will necessarily decrease deforestation is still an open question. Borlaug’s hypothesis suggests that increased productivity reduces land required to produce food, decreasing deforestation, while Jevon’s paradox posits that increased productivity increases the value of cleared land, increasing deforestation (Hertel 2012). Empirical results support both, suggesting that the direction of the relationship depends on the context (Angelsen and Kaimowitz 2001, Angelsen 2010). A causal analysis of the effect of slaughter age on deforestation is beyond the scope of this paper, but our results are in line with work in Brazil that found that intensification is a substitute for deforestation (Assunção et al. 2017, Koch et al. 2019, Moffette et al. 2021). If this were the case, then our estimates of the reduction in enteric emissions would be relatively representative of the total effect on GHG emissions.

The remainder of the paper proceeds as follows. First, we describe the Brazilian cattle sector and potential paths forward for intensification. We then quantify changes in slaughter age across the Amazon and model the property- and municipal-level traits that are correlated with reductions to characterize where and by whom intensification occurred. We then estimate the potential effects of this reduced slaughter age on enteric emissions, providing insight into the environmental implications of younger slaughter. We close with a discussion of policy implications of our findings.
2. Curbing deforestation is tied to productivity

The Brazilian federal government leads the world in efforts to reduce deforestation under the Plan to Control Illegal Deforestation and for Recuperation of Native Vegetation (Portuguese acronym PPDAm), including the 2012 Forest Code, the Priority Municipalities List, and credit regulations and initiatives (Assunção et al 2015). Additional monitoring and enforcement occurs through supply chain sustainability initiatives such as the Soy Moratorium and Zero-Deforestation Cattle Agreements (CA). Despite a period of declining deforestation following policy pressure, deforestation was not eradicated, and has spiked in recent years (United Nations Food and Agriculture Organization 2010, Assunção et al 2017, INPE—Brazilian National Institute of Spatial Research 2020).

In addition to command and control methods to slow deforestation, policymakers are increasingly interested in promoting sustainable cattle production methods that do not rely on clearing for pasture. Research finds that productivity can be motivated directly through financial mechanisms (Ermgassen et al 2018) or indirectly through mechanisms such as electrification (Assunção et al 2017) or environmental policies restricting clearing (Koch et al 2019, Moffette et al 2021). The Brazilian government has established larger-scale sustainable agriculture programs, including the Low Carbon Agriculture (Portuguese acronym ABC) plan in 2010, which made low-interest credit available to fund programs that reduce GHG emissions or sequester carbon (Russell and Parsons 2014, Newton et al 2016).

3. Cattle productivity in the Amazon continues to lag, but efforts to intensify are increasing

Cattle ranching in the Amazon is historically unproductive, with an average stocking density of one head per hectare, or one-third of its sustainable capacity (Ermgassen et al 2018). Moreover, animals are commonly slaughtered at 48 months, twice as long as can be achieved in a high turnover system (Embrapa 2018). Animals are kept in pasture until slaughter (‘grass-fed’), with low investment in pasture leading to widespread pasture degradation (Bustamante et al 2012, Cohn et al 2014, Strassburg et al 2014, Ermgassen et al 2018, Feltran-Barbieri and Féres 2021). Consistent nutrition is the most important factor in producing high-quality, high-turnover beef, and this low-input pasture production is vulnerable to variation in nutritional availability due to the rainy and dry seasons (Embrapa 2018). Regional climate change is lengthening the annual dry season, further threatening the viability of low-input, pasture-based production methods (Khanna et al 2017, Leite-Filho et al 2019).

Some ranchers are intensifying using techniques such as supplementing pasture with feed or mineral salt and reforming pasture using improved varieties, fertilizers, silvo-pastoral systems, or intercropping with leguminous crops. Ranchers also increasingly finish cattle in a feedlot, where the animals put on additional weight before slaughter (‘grass-fed, grain-finished’) (Bustamante et al 2012, Millen and Arrigoni 2013, Vale et al 2019). Agroforestry—tree-based management strategies that re-integrate trees with livestock and agriculture—may increase pastoral capacity (the number of head that can be kept and fed on a given land area) (Ermgassen et al 2018). These methods deliver better and more consistent nutrition resulting in more rapid weight gain (Millen and Arrigoni 2013, Dos Reis et al 2020, Cusack et al 2021). Cattle raised using these production methods reach slaughter weight earlier and are typically slaughtered between 24 and 36 months rather than 36 to 48 months (Millen and Arrigoni 2013). Vale et al (2019) find that cattle raised in intensified pasture systems gain twice as many kilograms per day with a life cycle of 30 months, compared to a 46-month cycle on traditional pasture. These practices, particularly the use of grain-finishing on feedlots, also lead to animals with more tender meat and greater marbling (intra-muscular fat), making them more profitable to slaughter at younger ages (Embrapa 2018).

While the high-turnover production resulting from these modern methods yields higher profits (Millen and Arrigoni 2013), the necessary changes to production techniques require significant up-front investment (da Cunha et al 2014, Barbieri et al 2016, Ermgassen et al 2018). Ranchers in the Amazon are frequently credit constrained, which helps explain why extensive, low-input low-turnover production is still common in the Amazon (Assunção et al 2017, Koch et al 2019, Jung et al 2021), and why we estimate that a third of male head were still slaughtered at more than 36 months in 2018.

4. Slaughter over 36 months fell by 14% over 5 years

We analyze cattle movement for slaughter using the Guide to Animal Transport (GTA) in the states of Mato Grosso (MT), Pará (PA), and Rondônia (RO) from 2010 to 2018. The GTA is a federal database tracking livestock vaccinations, health standards, and movement between properties (including for slaughter), and it records the age of an animal in increments of twelve months. It has been established as a reliable source of data on cattle transactions and has been used to analyze the Brazilian cattle industry (Klingler et al 2018, Rajão et al 2020, Skidmore et al 2021). We focus on transactions of male animals and assume that all males are steers, but we discuss
transactions of cows in appendix section A.4. This amounts to over 700,000 sales of over 28 million animals by 90,000 properties.

We estimate that 32% of head were still slaughtered at more than 36 months in 2018, down from 37% in 2013. Figure 1 shows that Mato Grosso and Rondônia saw significant decreases in slaughter over 36 months between 2013 and 2018. In Mato Grosso, the share of slaughter over 36 months fell from 27% to 18%; in Rondônia, it fell from 46% to 25%. Both states also saw rapid increases in the percent of head slaughtered between 13 and 24 months. On the other hand, patterns of slaughter age in Pará did not change significantly between 2013 and 2018. Half of cattle in Pará were slaughtered after 36 months both in 2013 and in 2018 with no clear trends over the period.

5. Characteristics of properties selling cattle less than 36 months

We provide the first characterization of property-level productivity in terms of slaughter age to help describe the differences in slaughter age we find across the states. We employ a series of linear regression models of the form:

\[ Y_i = \alpha + \beta X_i + \epsilon_i, \]

where \( Y_i \) is the property percent of head slaughtered under 36 months and \( X_i \) is a series of property characteristics. All explanatory variables are standardized to have a mean of zero and a standard deviation of one, so coefficients can be interpreted as the percentage point difference in head slaughtered under 36 months with a one standard deviation higher value in the explanatory variable. For example, a coefficient of 0.01 would show that a one standard deviation increase in \( X \) is accompanied by 1% more head slaughtered under 36 months.

We estimate this as a series of simple linear regressions including each \( X_i \) individually and as a multiple linear regression where \( X_i \) takes the form of a vector of property characteristics. We employ inverse probability weights using municipality as the level of weighting. We also cluster standard errors at the municipal level. In the appendix, we include state fixed effects, \( \gamma_s \), to control for underlying differences in the three states. We omit these in the main text as many of the characteristics of interest are significantly different across states, as we will discuss.

Figure 2 and appendix table 2 show the results of individual regression models and the combined model. The proportion of head sold under 36 months was significantly higher on properties that (1) had less deforestation before the study period (2004–2009) (combined model \( \beta = -0.008 \)); (2) sold a larger number of animals for slaughter (\( \beta = 0.039 \));
Figure 2. Coefficients of the relationship between property characteristics and percent of head slaughtered under 36 months. Explanatory variables are normalized to have a mean of zero and standard deviation of one. Coefficients can be interpreted as the percentage point difference in head slaughtered under 36 months with a one standard deviation higher value in the explanatory variable. Observations are at the property level. Included properties are matched to property maps. Standard errors are clustered at the municipal level. Bars correspond to the 95% confidence interval.

(3) sold a higher percent of animals directly for slaughter ($\beta = 0.039$); (4) sold to slaughterhouses that monitor for deforestation ($\beta = 0.019$); (5) were located closer to slaughterhouses ($\beta = -0.030$) and (6) were located farther from the deforestation frontier ($\beta = 0.013$).

Properties selling younger cattle also had significantly less deforestation during the sales period (2013–2018) in the individual model (figure 2). We omit this variable from the combined model due to the high correlation with whether the property had deforestation before the sales period. We focus on deforestation between 2004 and 2009, as this measures a longer-term transition away from deforestation and toward intensification.

There is also correlation between patterns of deforestation and distance to the forest frontier, as longer-established areas (further from the frontier) have less remaining forest to clear, and deforestation remains the most active closest to the frontier. However, when we include both deforestation and distance to the frontier in the combined model, the coefficients on both variables remain statistically significant and of relatively similar magnitudes.

A property’s stocking density (the number of animals sold for slaughter divided by property area) was marginally significant in the individual model, but it was significant after controlling for other property characteristics. A property’s distance to a slaughterhouse was not significant after controlling for state fixed effects, although all other coefficients were robust to this inclusion. We find that whether the property had remaining forest at the start of the study period or the property’s total area were not correlated with the proportion of slaughter under 36 months.

These results characterize the properties that sell younger animals as large operations that are readily connected to slaughterhouses, both geographically and in the supply chain. Moreover, they have traded deforestation for intensification, as evidence by their relationship with zero-deforestation supply chains and that they had slowed deforestation even prior to the passage of strict anti-deforestation policy. The overall profile of properties with younger slaughter mirrors that of properties without deforestation characterized in Skidmore et al (2021).

6. Slaughter age is lowest in municipalities with high crop agriculture and credit uptake

Next, we consider patterns of slaughter age across municipalities. Figure 3 maps the proportion of head
slaughtered at less than 36 months by municipality. We divide municipalities into quintiles and use diagonal grid-lines to indicate municipalities in the bottom 10% of production as their averages are more influenced by individual sales. As before, we see that Mato Grosso and central Rondônia are both leaders in young slaughter.

To better understand the regional characteristics that support young slaughter, we estimate a series of regression models of the form:

$$Y_m = \alpha + \beta X_m + \epsilon_m.$$  \hfill (2)

The model and procedure are identical to equation (1), except we now estimate the percent of slaughter under 36 months, $Y_m$, and the characteristics, $X_m$, at the municipal level. We again estimate a model with state fixed effects, $\gamma_s$, in the appendix.

Figure 4 and appendix table 3 shows the coefficients of the series of simple linear regressions and the combined model. The proportion of head sold...
under 36 months was significantly higher in municipalities that (1) had more crop agriculture (particularly soy) (combined model $\beta = 0.088$); (2) received more credit per hectare of pasture ($\beta = 0.032$) and (3) had higher stocking density ($\beta = 0.054$). Municipalities with less remaining forest had younger slaughter age, although this is not statistically significant after controlling for the other three characteristics.

These results help explain why Mato Grosso and Rondônia have more young slaughter while Pará lags behind. Figure 5 shows the distribution of these municipal characteristics by state, while figure 6 shows the distribution of the property characteristics by state. Both Mato Grosso and Rondônia are considered the 'old frontier'—areas of the Legal Amazon that were settled first and are now highly deforested with developed agricultural supply chains (Nepstad et al 1997). The properties in our sample, as well as the municipal traits that we find are related to young slaughter, reflect that. In Mato Grosso, which has the highest overall proportion of slaughter under 36 months, municipalities have high levels of soy production. Properties had little deforestation from 2004–2009, sold high volumes of cattle for slaughter and had low distances to slaughterhouses. In Rondônia, which saw a sharp increase in the slaughter under 36 months, municipalities had high credit and high stocking density. Properties also had little deforestation, but had high stocking density and were close to slaughterhouses.

In contrast, the profile of municipalities and cattle-producing properties in Pará are very different. Municipalities had higher remaining natural vegetation and low levels of soy production, credit, and stocking density. Properties had more deforestation from 2004 to 2009, lower stocking density, and were farther from slaughterhouses.

Notably, these traits do not fully explain the differences in slaughter age between the states. Dummy variables denoting whether a property is located in Pará ($\beta = -0.164$) and Rondônia ($\beta = -0.072$) are both significant in the property-level regression with fixed effects (appendix table 2). Thus, there remains a difference between the states that we do not account for here.

Higher turnover production systems lower enteric emissions

We quantify the effect of changes in slaughter age on enteric emissions of GHG by steer. We follow the IPCC Lifecycle Assessment Model methods and include emissions from enteric methane and feed production (converted to methane-equivalents). We do not include emissions from land use change in the model, as the relationship between reduced slaughter
Figure 5. Distribution of municipal characteristics by state. Observations are at the municipal level. Horizontal line represents the sample mean. Natural vegetation and soy are measured as a percent of municipal area, municipal credit is in reais, and stocking density is in head per hectare.

Figure 6. Distribution of property characteristics by state. Observations are at the property level. Horizontal line represents the sample mean. Included properties are matched to property maps. Deforestation is measure as a percent of property area, property area is measured in hectares, stocking density is measured in head per hectare, and distance to slaughterhouse is in kilometers.
age and deforestation is not clear. Thus, we effectively assume that all confinements are constructed and feed is produced on previously cleared land. (Full details on emissions calculations and on emissions of cows and bulls are provided in appendix section A.1.) We similarly do not include emissions from manure. While this is a shortcoming to estimate total reductions in GHG in the Brazilian context, enteric emissions make up the majority of GHG emissions from cattle in many other regions. If intensification were to drive further deforestation, then total GHG emissions may be higher than what we estimate here. However, our results and those of previous studies suggest that, in this context, intensification may be an alternative to deforestation or a response to land constraint (Koch et al. 2019, Moffette et al. 2021). Reducing slaughter age may also alleviate local land constraint by reducing the total land needed for grazing (due to increased use of grain-finishing in confinements), in turn increasing the available land for crop production. In this case, the total GHG emissions would be similar to the enteric emissions.

Figure 7 graphs the daily methane emissions made by a steer under a series of feed and slaughter regimes, where the horizontal axis represents animal lifespan. A steer raised in pasture from weaning (age 12 months) until slaughter (48 months) emits 201.83 kg of methane during their lifetime. Conversely, an animal raised on pasture and slaughtered at 36 months has lifetime methane emissions of 151.23 kg. This reduction is entirely due to the reduction in enteric emissions from a shorter life cycle and is achieved through improvements in pasture.

The reductions are more stark when we consider grain finishing. A steer that is grain-finished for three months and slaughtered at 24 months would emit only 72.71 kg of methane per lifetime. These emissions reductions are due to the reduced life cycle as well as the easier digestibility of corn and soy. We account for the carbon costs of producing corn silage fed in confinement using the estimates in Cardoso et al. (2016), assuming that animals are fed corn silage grown and processed within 50 km. This is a reasonable assumption as many confinement operations grow their own grain on-property (Compre Rural 2020). Additionally, Cederberg et al. (2011) estimate that fossil-fuel related emissions account for only 2.5% of the emissions from Brazil’s cattle industry, even including the emissions from export to Europe. We similarly estimate the emissions of a ‘super-modern’ steer that is entirely grain-fed after weaning and slaughtered at 18 months, comparable to the cattle industries in the United States. This ‘super-modern’ steer would have lifetime methane-equivalent emissions of only 54.15 kg. However, there are numerous environmental and ethical implications of such a system that are not captured in GHG emissions alone (Burkholder et al. 2007, Ribaudo et al. 2011, Raff and Meyer 2021).

8. Discussion

Slaughter age is decreasing in the Brazilian Amazon, indicating an overall shift toward an intensified, and potentially lower-carbon, production system. Across the region, slaughter over 36 months fell by 14% from 2013 to 2018, but the changes were led by old-frontier regions in Mato Grosso and Rondônia.

There is local and international demand for both increased productivity and decreased deforestation in the Amazon. Notably, we find that reductions in slaughter age occur on high-volume ranches with less deforestation both before and during the period. This supports existing evidence that ranchers in Brazil pursue intensification as an alternative to deforestation, whether driven by true land scarcity (Angelsen...
and Kaimowitz 2001, Kaimowitz and Angelsen 2008, Phalan et al 2016, Garrett et al 2018) or artificial scarcity due to zero-deforestation policies (Koch et al 2019, Moffette et al 2021). Zero-deforestation policy could therefore yield two-fold gains for climate change by slowing both enteric emissions and deforestation emissions.

Our results support previous findings that start-up costs are a barrier to entry for cash-constrained and smallholder producers (da Cunha et al 2014, Barbieri et al 2016, Gibbs et al 2016, Gil et al 2016). Embrapa (2018) argues that choosing whether and how to adopt a system that finishes animals under 36 months requires an analysis of the economic benefits that create an additional barrier to adoption for many producers. They suggest the transition to modern production can rarely be achieved without a consultant, thereby adding to the cost of intensification and leading ranchers to ultimately stay with the status-quo. Our results support this hypothesis, as we find that slaughter age is lower on properties selling high volumes of cattle, those that sell more cattle directly to slaughterhouses, and those that sell to the major CA slaughterhouses. Moreover, slaughter age is lower in regions with higher allocations of agricultural credit.

Financial incentives, particularly credit, may be a second viable policy mechanism to support sustainable production methods and reduce enteric emissions. Brazil’s ‘ABC’ loans for low-carbon production provide a policy model to promote adoption of techniques that lower GHG emissions and promote faster weight gain (EMBRAPA 2013). Indeed, such policies to improve pasture quality, which already show promise as a means to reduce deforestation while bolstering the cattle industry (Feltran-Barbieri and Féres 2021), could provide a further ‘win’ by reducing enteric emissions. Given the high cost of adopting new production techniques as well as the significant training and education needed for some methods, we believe that smallholders would benefit from additional financial and technical assistance to achieve modern production practices.

Slaughterhouses can provide financial incentives for younger animals. Such incentives have already been developed in Brazil, as in 2013, the world’s largest meat-packer, JBS, began offering premia based on animal age and fat content with the program Boi no Ponto (Equipe BeefPoint 2014). Marfrig and Minerva created similar bonuses in 2015 and 2018, respectively (Carne Certificada Hereford 2015, Compre Rural 2018). This policy was likely driven by requirements from China and the European Union that cattle be slaughtered at 30 months or less (Ministry of Health of the People’s Republic of China 2015, Food Safety and Inspection Service 2020, Leon 2020).

In the Amazon, there is a risk that increased demand for feed could cause deforestation to increase as slaughter age falls. For this reason, all incentives to reduce slaughter age should be paired with continued or heightened enforcement of zero-deforestation policies. Given that cattle production is the leading driver of deforestation in the Amazon (Global Forest Atlas 2016), the industry’s main potential contribution to reducing carbon emissions is achieving zero-deforestation production.

Additionally, though beyond the scope of this paper, it is important to consider the animal welfare implications of transitioning from pasture-based production to use of feedlots. While confinements may improve access to water and shade, feedlots that are overly crowded may have deleterious effects for animal health (Macitelli et al 2020).

As global beef demand and the cattle industry in other developing countries grow, the pressure for sustainable productivity increases. Investment in land that is already cleared to achieve high growth and earlier slaughter offers a path to sustainable low-carbon cattle production. Here we show this effort can be documented using current data and supported using targeted policies.

**Data availability statement**

Data on cattle movements and slaughter age come from the Guide to Animal Transport (GTA), which is a federal database tracking livestock movement. We are unable to share the set of GTA records as we have compiled them as this contains potentially sensitive information for individuals and violates the terms of our IRB. However, other researchers could also download individual GTA records as we do here and compile a similar dataset.

Property boundaries come from the Rural Property Registry (CAR), INCRA, and Terra Legal. As with the GTA, we are unable to share these but they can be obtained by other researchers.

Slaughterhouse locations come from maps produced by the Image and Geoprocessing Lab (LAPIG) and Imazon. In cases of slaughterhouses that appear in the GTA but neither of these sources, we assume it is located in the centroid of urban areas in the listed municipality.

Data on deforestation come from PRODES-Amazon.

Data on soy come from land cover maps in Mabbiomas version 5.

Municipal herd size comes from the Brazilian Institute of Geography and Statistics (IBGE).

All code to clean and merge data files and conduct the statistical analyses are able to be shared upon request.

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Appendix

A.1. Enteric emissions calculation

Here, we describe the calculations used the estimate the difference in lifetime enteric emissions between cattle slaughtered using a reduced slaughter age and finished in feedlots and cattle slaughtered at the traditional slaughter age and grass-finished. We follow the Tier 2 guidelines for enteric emissions calculations detailed in IPCC (2019) to the following gross and daily emissions equations (Mangino et al 2003):

\[
\text{Gross energy (GE) (MJ day}^{-1}) = \frac{\text{NE}_{\text{m}} + \text{NE}_{\text{s}} + \text{NE}_{\text{NE}} + \text{NE}_{\text{p}}}{\text{DE/100}}. \tag{3}
\]

Daily methane-equivalent emissions

\[
(\text{kg head}^{-1} \text{day}^{-1}) = \frac{\text{GE} \times Y_m}{55.65 \text{ MJ kg}^{-1} \text{ CH}_4}. \tag{4}
\]

For further details on relevant constants, see Mangino et al (2003), IPCC (2019), and Paustian et al (2006). Calves are assumed to have zero enteric emissions while milk-fed (Paustian et al 2006, IPCC 2019). We assume that in traditional systems calves are weaned at 12 months (140 kg), and in modern systems at 8 months (140 kg). Animals are sent to finishing at 360 kg, and steers/bulls are slaughtered at 600 kg while heifers are slaughtered at 480 kg (Millen and Arrigoni 2013). We assume that heifers are not engaged in active milking or breeding, and cattle are not used for work. Cattle in modern systems are finished in feedlots (grass-finished) for three months, and spend the remainder of their lives in pasture (except where otherwise specified).

Cattle kept in feedlots or confinements are assumed to have a methane conversion factor (\(Y_m\)) of 0.03, whereas cattle fed via large grazing have a methane conversion factor of 0.065. The digestibility of feed (\(DE\)) is assumed to be 0.85 in feedlots and 0.6 in pasture. Calves gain 0.9 kg day\(^{-1}\), and young cows gain 0.3 kg day\(^{-1}\) until fully grown. Using this, we calculate lifetime emissions for both heifers and steer; grain-finished and grass-fed; and slaughtered at 24, 36, and 48 months. We also calculate lifetime emissions for a ‘super-modern’ steer that is weaned at 8 months and grain-fed until slaughter at 18 months\(^5\). We then expand on the Tier 2 calculations by creating a dynamic program to calculate lifetime enteric emissions considering daily weight gain and different feed regimes.

Lifetime methane-equivalent emissions are the sum of daily enteric emissions over the lifetime and emissions used in the production of supplemental feed for animals finished on corn silage in a feedlot. The composition of feed concentrate used in confinement may vary, but corn and corn silage are the primary components and typically account for more than 75% of concentrate by weight (Cesar et al 2005). An animal’s daily consumption varies with the composition of the concentrate, but is typically between 2 and 4% of the animal’s body weight (Henrique et al 2007, Moreira et al 2009). We follow the advice of a well-known Brazilian agriculture newspaper and forum, Compre Rural, which advocates feeding corn silage at a rate of 3% of body weight per day (Compre Rural 2020). We estimate one kilogram corn silage production generates 0.03 857 kg CO\(_2\) equivalent (Cardoso et al 2016). For generalizability, we calculate emissions effects of feed regimes for cattle kept in confinement fed 100% corn silage and a 1:2 ratio of soy and corn silage. Therefore, total lifetime methane-equivalent emissions for a modern animal (steer, cow, and bull) are:

\[
\text{Lifetime emissions kg head}^{-1} = \frac{1}{25} \times 0.03857 \times \sum_{t=631}^{720} \text{[Daily weight,} \times 0.03] \tag{5}
\]

(For what we refer to as a ‘super-modern’ steer kept in confinement for 10 months, the emissions costs of feed are summed from 241 to 540 days.) Lifetime emissions for different sexes, slaughter ages, and feed regimes are reported in table 4.

It should be noted that these calculations yield the head-equivalent lifetime carbon savings, not changes in the total emissions by cattle ranchers in the Amazon. It is possible that ranchers adopting reduced slaughter age are changing their behaviors in some other way, such as driving fewer miles to check on cattle in pasture, driving more frequently to town to purchase inputs, or moving more cattle overall. As such, we consider this to be a baseline estimate for the carbon savings generated by reducing slaughter age. Future research should dig into how technology complementarities may increase or decrease these savings.

Additionally, we calculate carbon costs of producing and sourcing feed, but we do not calculate the carbon impact of the conversion of land to corn production. While this simplification is reasonable at the level of the individual animal or even property, it is increasingly problematic when aggregating up to the municipal or state level. Evidence regarding the effect of land conversion for crop production is inconclusive (Carvalho et al 2010, Sanderman et al 2018). Overall, research suggests that land use

\(^5\) Note that for this regime we assume a constant growth rate from weaning to slaughter.
change from native vegetation to some other land use (such as pasture or crops) may reduce carbon sinking, particularly when land is cleared using slash-and-burn. Change from pasture (especially degraded pasture) to crops may increase carbon-sinking on these properties. In the Amazon during our period, new cropland was primarily converted from pasture, not native vegetation (MapBiomas 2020), so the carbon-sinking implications of land conversion are less clear. For these reasons, we do not calculate the carbon effect of land-use change driven by intensification. We consider this to be a first step toward estimating the carbon impact of reduced slaughter age until work is developed to better estimate the effect of land-use change on carbon sinking versus sourcing in the region. Immediate policy implications are for policymakers to support necessary conversion to cropland particularly on degraded pasture and to encourage good land-management practices to promote soil carbon sinking.

Similarly, we do not estimate the effects of differential manure management practices resulting from an increase in the share of animals that are finished in confinement. Manure lagoons create anaerobic environments wherein dung and urine produce methane during decomposition (IPCC 2019, Mitloehner 2020). Evidence from the field suggests that these lagoons are in no way universal fixtures of confinement operations in the Amazon. Additionally, methane production in lagoons is highly seasonal and varies across space (IPCC 2019). For these reasons, we interpret our estimates as an upper bound of the effect of reduced slaughter age on enteric emissions production, conditional on manure management practices.

Future work could explore the trade-offs between investment in intensification technologies necessary to decrease slaughter age and the overall carbon savings yielded from such changes. This would provide policy recommendations for supporting ranchers as they make this transition. Additionally, researchers could quantify how ranchers who do decrease slaughter age increase their overall slaughter. In other words, does an increase in intensification lead to an increase in overall supply (and thereby wash out the climate benefits of these changes)?

Further, cattle in the Amazon are subject to highly seasonal weight gain and weight loss. In the dry season, cattle are known to lose large amounts of weight due to feed constraints. They then regain this weight in the wet season, causing what is commonly known as an ‘accordion effect.’ There is evidence that this effect is exacerbated by global climate change (Skidmore 2020). We do not account for this in our calculations of lifetime emissions, and future work should do so.

We approximate changes in total emissions based on changes in slaughter age in each of the three states, holding slaughter volume constant at the period mean (table 1). We assume that cattle in the 13–24 month age bin were slaughtered at the upper end of the bin (i.e. 24 months), were raised on pasture, and were finished on grain for three months; we similarly assume that animals in the 25–36 month bin were slaughtered at 36 months but were raised on pasture. We assume that animals slaughtered over 36 months were slaughtered at 48 months, maintaining a twelve-month span between bins. This approach follows Vale et al (2019) and Millen and Arrigoni (2013), both of whom find unimproved pasture systems finish an animal around 48 months. Our assumptions provide the best approximation of emissions if cattle ages are evenly distributed within an age bin, although the exact change in emissions may be higher or lower than our estimates depending on the true distribution within the bins. Global warming potential values are derived from the Environmental Protection Agency (2020) Greenhouse Gas Equivalencies Calculator, which estimates one kilogram of methane as being equivalent to 0.025 metric tons of carbon dioxide equivalent (Cardoso et al 2016).

We calculate a reduction in lifetime methane emissions of 28 192 metric tons of methane-equivalent in Mato Grosso for cattle slaughtered in 2018 compared to cattle slaughtered in 2013, 13 250 metric tons in Rondônia, and 4176 metric tons in Pará.

### A.2. Relationship between stocking density and slaughter age

There is not a strong statistical correlation ($\rho = -0.06$) between slaughter age and stocking density. The lack of relationship between the two may be driven by extreme values in stocking density.
Table 2. Regressions of the relationship between property characteristics and percent of head slaughtered under 36 months.

|                          | (1)       | (2)       | (3)       | (4)       | (5)       | (6)       | (7)       | (8)       | (9)       | (10)      | (11)      | (12)      |
|--------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                          | Combined  | Individual models |
| No forest 2009 (0/1)     | −0.002    | −0.001    | 0.002     |           |           |           |           |           |           |           |           |           |
|                          | (0.002)   | (0.002)   | (0.002)   |           |           |           |           |           |           |           |           |           |
| Defo 2004–2009           | −0.008∗   | −0.009**  | −0.016*** |           |           |           |           |           |           |           |           |           |
|                          | (0.005)   | (0.004)   | (0.002)   |           |           |           |           |           |           |           |           |           |
| (Log) head for slaughter  | 0.039***  | 0.029**   | 0.060***  |           |           |           |           |           |           |           |           |           |
|                          | (0.007)   | (0.007)   | (0.003)   |           |           |           |           |           |           |           |           |           |
| Stocking density         | 0.000     | 0.001     |           | 0.008∗    |           |           |           |           |           |           |           |           |
|                          | (0.001)   | (0.001)   |           | (0.005)   |           |           |           |           |           |           |           |           |
| Pct direct sales         | 0.039***  | 0.050***  |           | 0.050***  |           |           |           |           |           |           |           |           |
|                          | (0.005)   | (0.006)   |           | (0.005)   |           |           |           |           |           |           |           |           |
| Sells to the CA (0/1)    | 0.019***  | 0.013**   |           | 0.044***  |           |           |           |           |           |           |           |           |
|                          | (0.006)   | (0.006)   |           | (0.003)   |           |           |           |           |           |           |           |           |
| Dist to slaughterhouse   | −0.030*** | −0.005    |           | −0.043*** |           |           |           |           |           |           |           |           |
|                          | (0.010)   | (0.010)   |           | (0.004)   |           |           |           |           |           |           |           |           |
| Dist to forest frontier  | 0.013*    | 0.016**   |           |           | 0.018***  |           |           |           |           |           |           |           |
|                          | (0.007)   | (0.006)   |           |           | (0.002)   |           |           |           |           |           |           |           |
| PA                       | −0.164*** |           |           |           |           | 0.001     |           |           |           |           |           |           |
|                          | (0.018)   |           |           |           |           | (0.002)   |           |           |           |           |           |           |
| RO                       | −0.072*** |           |           |           |           |           | 0.001     |           |           |           |           |           |
|                          | (0.019)   |           |           |           |           |           | (0.002)   |           |           |           |           |           |
| Defo 2013–2018           |           |           |           |           |           |           |           | −0.013*** |           |           |           |           |
|                          |           |           |           |           |           |           |           | (0.002)   |           |           |           |           |
| (Log) property area      |           |           |           |           |           |           |           |           |           |           |           | 0.001     |
|                          |           |           |           |           |           |           |           |           |           |           |           | (0.002)   |
| Observations             | 45 734    | 45 734    | 49 390    | 49 390    | 49 390    | 49 390    | 49 390    | 49 390    | 45 734    | 45 734    | 49 390    |

Note: Explanatory variables are normalized to have a mean of zero and standard deviation of one. Coefficients can be interpreted as a percentage point change in slaughter under 36 months in response to a one standard deviation change in the explanatory variable. Observations are at the property level. Standard errors are clustered at the municipal level. ∗ p < 0.10, ∗∗ p < 0.05, ∗∗∗ p < 0.01.
Stocking density has a skewness of 18.5 and kurtosis of 358. In contrast, slaughter age has a skewness of $-0.33$ and a kurtosis of 2.61. To account for this, we assign municipalities to percentiles in terms of slaughter age and stocking density. In figure 8, we plot the municipal-level correlations of the percentile of head slaughtered under 36 months against percentile of stocking density. We still find only a small, positive relationship with slaughtered head per ha ($\rho = 0.03$).

Our results demonstrate that slaughter age is a distinct facet of productivity. Given its importance for lifetime emissions, slaughter age should be measured directly given that stocking density is a poor proxy for slaughter age. Stocking density based on herd size may not capture the type of investment and intensification that leads to decreases in slaughter age. There may be municipalities with large (and relatively densely stocked) herds, but where producers have not invested in the methods needed to finish an animal faster.

Slaughter age may also serve well in cases where data on stocking density perform poorly. First, measures of stocking density display extreme values, particularly in regions where high cloud cover and low overall production preclude reliable measures of pasture area. In Brazil, data on slaughter age are available at high-frequency (i.e. transaction-level) and fine-grain (i.e. property-level) scales. In contrast, data on herd size is only available at the municipal level, although property-level measures of herd size are available every ten years from the Agricultural Census. The GTA tracks flows of cattle, precluding its use as a reliable measure of stocking density.

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Figure 8. Correlations of the percentile of percent of head slaughtered under 36 months and percentile in municipal stocking density (head per hectare of pasture). Linear trend is in red.

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6 For robustness, we also graph the raw values of both variables in the appendix, excluding the 5% of observations with the lowest total production.
A.3. Regression tables

Table 3. Regressions of the relationship between municipal characteristics and percent of head slaughtered under 36 months.

|                  | Combined Individual models |      |      |      |      |
|------------------|-----------------------------|------|------|------|------|
|                  | (1)                         | (2)  | (3)  | (4)  | (5)  |
| Pct natural vegetation | 0.018                       | 0.003| -0.033**|      | (0.012) |
|                  | (0.014)                     | (0.012)|      |      |      |
| Pct soy          | 0.088***                    | 0.047***| 0.093***|      | (0.011) |
|                  | (0.011)                     | (0.011)|      |      |      |
| Municipal credit | 0.032***                    | 0.005| 0.070***|      | (0.012) |
|                  | (0.012)                     | (0.011)|      |      |      |
| Stocking density | 0.054***                    | 0.022*| 0.055***|      | (0.014) |
|                  | (0.014)                     | (0.013)|      |      |      |
| PA               | -0.242**                   |      |      |      | (0.025) |
|                  | (0.025)                     |      |      |      |      |
| RO               | -0.072**                   |      |      |      | (0.030) |
|                  | (0.030)                     |      |      |      |      |
| Observations     | 283                        | 283  | 283  | 283  | 283  |

Note: Explanatory variables are normalized to have a mean of zero and standard deviation of one. Coefficients can be interpreted as a percentage point change in slaughter under 36 months in response to a one standard deviation change in the explanatory variable. Observations are at the municipal level. Standard errors are robust. * p < 0.10, ** p < 0.05, *** p < 0.01.

Table 4. Enteric emissions by slaughter age and feed regime.

| Months            | Traditional | Modern (silage only) | Modern (silage/soy) |
|-------------------|-------------|----------------------|---------------------|
|                   | Slow        | Fast                 | Standard Fast       | Standard Fast       | Standard Fast       |
| Milk-fed          | 12          | 12                   | 8                   | 8                   | 8                   |
| Growing: pasture  | 6           | 6                    | 10                  | 10                  |                     |
| Grain             |             |                      |                     | 7                   | 7                   |
| Pasture           |             | 30                   | 18                  | 3                   | 3                   |
| Finish: grain     |             | 30                   | 18                  | 3                   | 3                   |
| Slaughter age     |             | 48                   | 36                  | 24                  | 24                  |
| Price premia eligible | Yes       | Yes                  | Yes                 | Yes                 |
| Lifetime emissions| 201.83 kg   | 151.23 kg            | 72.71 kg            | 54.15 kg            |
| CO₂ equivalent    | 5 Mg        | 3.8 Mg               | 1.8 Mg              | 1.4 Mg              |

| Months            | Heifers | Modern (silage) | Modern (silage/soy) | Bulls | Modern (silage) | Modern (silage/soy) |
|-------------------|---------|-----------------|----------------------|-------|-----------------|---------------------|
|                   | Trad.   | Modern (silage) | Modern (silage/soy) | Trad. | Modern (silage) | Modern (silage/soy) |
| Milk-fed          | 12      | 8               | 8                    | 12    | 8               | 8                   |
| Pasture           | 24      | 13              | 13                   | 21    | 13              | 13                  |
| Finish: feedlot   | 3       | 3               | 3                    | 3     | 3               | 3                   |
| Slaughter age     | 36      | 24              | 24                   | 36    | 24              | 24                  |
| Lifetime emissions| 168.12 kg | 97.37 kg       | 100.38 kg            | 145.29 kg  | 70.24 kg        | 73.71 kg            |
| CO₂ equivalent    | 4.2 Mg  | 2.4 Mg           | 2.5 Mg               | 3.6 Mg | 1.8 Mg           | 1.8 Mg              |

Cattle are assumed to have a constant growth rate from weaning until slaughter in traditional systems. Under modern systems, they are assumed to have constant growth rates between weaning and entering finishing, and between entering finishing and slaughter. Weights at each life stage come from Millen and Arrigoni (2013) and Boi Saude (2019). Necessary coefficients for estimating daily emissions come from Mangino et al (2003), IPCC (2019), and Paustian et al (2006). We do not assume that heifers are in-milk or pregnant at any point during their life cycle. We assume constant rates of growth in each life stage (milk-fed, pasture-fed, and grain-finished (if applicable)). Global warming potential values are derived from the Environmental Protection Agency (2020) Greenhouse Gas Equivalencies Calculator, which estimates one kilogram of methane as being equivalent to 0.025 metric tons of carbon dioxide equivalent (Cardoso et al 2016).
A.4. The role of cows and age at slaughter

We focus on male animals (steers and bulls) in our analysis due to the different production incentives ranchers may face when making decisions about their female animals (cows). There are different patterns of slaughter age for male versus female animals. Figure 9 shows that the proportion of female animals being sold for slaughter above 36 months has remained steady above 60% over our study period. Female cows serve a number of purposes in addition to beef production which affect the incentives for slaughter, including breeding and milking. In a traditional system, the age at first calving is between 33 and 45 months; in a modern system this falls to 27 to 33 months (Millen and Arrigoni 2013). In a modern system, a cow will calf every 14 to 16 months, with calves being weaned at 6 to 8 months. Thus, a beef cow may remain productive for breeding long after 36 months. Additionally, cows may be milk producers that also remain productive after 36 month.

However, we believe that most cows in our sample are involved in beef production rather than dairy. Our study region is not a high milk-producing region of Brazil. Mato Grosso, Pará, and Rondônia together account for only 6.7% (2260 million liters) of Brazil’s milk production, although they produce 30% of the country’s beef (Instituto Brasileiro de Geografia e Estatística 2017, Embrapa 2018). In our sample, Rondônia has the highest milk production relative to its beef production, producing 46% of the milk in the three states, but only 22% of the beef. In Rondônia, the dairy herd was estimated at 581,000 head in 2018. In 2017, our final year of complete GTA coverage in Rondônia, 767,000 female head were slaughtered.

A.5. Alternative markets: veal and leather

Ranchers may have other market-based motivations for decreasing slaughter age beyond increased productivity, including access to markets for specialized products. Both veal and leather markets incentivize younger slaughter age, either structurally or in practice. The Brazilian veal market explicitly requires animals be less than 1 year (Ministério da Agricultura Pecuária e Abastecimento/Secretaria de Defesa Agropecuária 2020), while leather is more valuable when free of wrinkles and markings, which is more difficult to accomplish in an older hide (Mulvany and Tsekova 2019).

We show in figure 1 that the share of cattle slaughtered between 0 and 12 months of age—the age range for beef sold as veal—remained below 1% for the entire period of 2013 and 2018. In this period, 51,502 head were sold for slaughter at 12 months or less. We further account for possible changes in the demand for veal by dropping all sales of cattle between 0 and 12 months. While animals between 13 and 24 months are not eligible to be sold in the veal market, this category could capture animals that were...
discarded due to lack of on-farm resources prior to reaching an adult weight. Lower volume properties sell a higher proportion of male animals between 13 and 24 months than high-volume properties, which runs counter to the rest of our findings. Low-volume properties also sold higher numbers of animals less than 12 months; animals less than 12 months made up 1% of male slaughter of the bottom 25% of properties compared to 0.2% of male slaughter on the top 75% of properties. Thus, we cannot rule out that low-volume properties discard young animals that are not at an adult weight, both from 0–12 and 13–24 months. The bottom 25% of properties only sold 14,027 head for slaughter between 2013 and 2018, or 0.3% of production. We therefore do not believe this phenomenon drives our results. However, whether animals are being slaughtered prematurely by small-volume properties, and why, is an important research question that should be addressed in future work.

We are unable to determine whether a hide from a slaughtered animal registered in the GTA was sold to a tannery. However, more hides of leather are produced in Brazil than are officially slaughtered, so it is likely that all carcasses are harvested as leather. In our region, the majority of leather is procured by tanneries from slaughterhouses (Instituto Brasileiro de Geografia e Estatística 2013, 2015, 2017). Indeed, between 2012 and 2017, nearly the entire leather market was supplied as a byproduct from meatpackers in Rondônia (98%) and Pará (99%). In Mato Grosso, there may be a small leather market, as 32% of leather is acquired by tanneries from third parties (Instituto Brasileiro de Geografia e Estatística 2013, 2015, 2017).

At slaughterhouses, the value of leather is built into the price per arroba. However, ranchers state that leather is undervalued in comparison to the value of the meat itself. In order to receive a system being specifically ordered. Moreover, the price of leather fell dramatically during the study period while beef prices remained relatively stable (U.S. Bureau of Labor Statistics 2020a), thereby further decreasing the relative importance of leather as a source of revenue for the producer.

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