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Increasing beef production could lower greenhouse gas emissions in Brazil if decoupled from deforestation

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Recent debate about agricultural greenhouse gases (GHG) emissions mitigation highlights trade-offs inherent in the way we produce and consume food, with increasing scrutiny on emissions-intensive livestock products[1–3]. While most research has focussed on mitigation through improved productivity[4,5], systemic interactions resulting from reduced beef production at regional level are still unexplored. A detailed optimisation model of beef production encompassing pasture degradation and recovery processes, animal and deforestation emissions, soil organic carbon (SOC) dynamics and upstream lifecycle inventory was developed and parameterized for the Brazilian *Cerrado*. Economic return was maximized considering two alternative scenarios: Decoupled Livestock Deforestation (DLD), assuming baseline deforestation rates controlled by effective policy; and Coupled Livestock Deforestation (CLD), where shifting beef demand alters deforestation rates. In DLD, reduced consumption actually leads to less productive beef systems, associated with higher emissions intensities and total emissions, while increased production leads to more efficient systems with boosted SOC stocks, reducing both per kg and total emissions. Under CLD, increased production leads to 60% higher emissions than in DLD. The results indicate the extent to which deforestation control contributes to sustainable intensification in *Cerrado* beef systems, and how alternative life-cycle analytical approaches[6] result in significantly different emission estimates.

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Rising global population combined with shifting dietary preferences in emerging economies are leading to a significant increase in demand for livestock products, which is expected to double by 2050[2]. This shift is happening in the context of global climate change and associated resource scarcities, leading to calls for sustainable agricultural intensification (SI)[3,5,7]. Although a contested concept, the SI debate highlights elements of resource use efficiency in production, combined with the management of demand or consumption[3,8,9]. While persuasive, the SI literature is limited in its illustration of the environmental and economic trade-offs that can emerge when implementing SI measures in globally significant production systems.

Ruminant livestock is specifically implicated as a major cause of agricultural externalities in terms of GHG emissions (CH_4 and N_2O) and appropriation of land that otherwise provisions valuable ecosystem services[5]. A counter-argument suggests grass-fed beef systems have significantly lower emissions when accounting for atmospheric carbon dioxide (CO_2) uptake by deep-root grasses promoting greater soil carbon (C) storage. Such systems could play a significant role in stabilising GHGs[10]. Moreover this sequestration in specific systems may off-set direct livestock emissions[10].

Brazilian livestock production accounts for 8.3% of global consumption[11] and the sector aims to capitalise on growing demand. But related emissions are significant in the national GHG total including those related to deforestation. If both beef demand and target deforestation rates are to be met, while also reaching ambitious GHG mitigation targets, further productivity growth will be required. Alternatively product demand or consumption may need to be managed[3,8].

This study focuses on the central savannah (*Cerrado*) core (Fig. 1), an area accounting for approximately 34% of Brazilian beef production[12]. Considered part of the Brazilian agricultural frontier, the *Cerrado* is credited as the driver of the country's ascendance in global agricultural commodity markets[13,14]. Around 90% of Brazilian livestock are solely grass-fed (mainly tropical grasses of genus *Brachiaria*). Several studies show that improving tropical grasses productivity results in increased soil carbon stocks[15,16], with net atmospheric CO_2 removals of almost 1 Mg C $ha^{-1}yr^{-1}$ (ref. 15) when comparing degraded and improved pastures under a standard IPCC method[17].

Figure 1: Brazilian Central *Cerrado* (shaded).

The analysis quantifies the relationship between beef demand, production intensification, deforestation and soil carbon dynamics, indicating how deforestation rates influence emission intensities. We employed a linear programming model (**Methods** and **Supplementary Methods**) representing *Cerrado* beef production subject to market demand and pasture area scenarios. The model combines economic and bio economic variables to optimise farm resource allocation, including the adjustment of intensification levels through the representation of pasture degradation and restoration processes. It estimates GHG emissions - including direct animal emissions (**Supplementary Table 1**), changes in SOC, plus loss of biomass through deforestation, and life-cycle assessment (LCA) data covering inputs and farm operations used to maintain and recover pasture, and crop production, the latter used to formulate animal feedlot rations (**Supplementary Table 2**).

As there is no published biome-specific beef demand projections in Brazil, baseline demand (D_{BAU}) is assumed to be proportional to the whole country projected demand, i.e. exports plus domestic consumption[18].

We compared the accumulated emissions 2006-2030 under two land use scenarios: the Decoupled Livestock-Deforestation (DLD) scenario, where the same baseline pasture area projection (A_{BAU}) associated with the baseline demand is used for all demand scenarios; i.e., the same deforestation projections irrespective of consumption levels; and the Coupled Livestock-Deforestation (CLD) scenario, in which deforestation projections are sensitive to variations in demand. In both scenarios, intensification occurs only by pasture restoration promoting improvements in forage productivity through mechanical and chemical treatment of the soil (**Supplementary methods**).

The varied demand scenarios are: $D_{BAU-10\%}$, $D_{BAU-20\%}$, $D_{BAU-30\%}$, representing decreasing demand/consumption scenarios relative to baseline demand by 2030, and conversely increasing demand scenarios $D_{BAU+10\%}$, $D_{BAU+20\%}$, $D_{BAU+30\%}$, (Fig. 2a).

Deforestation is assumed exogenous, avoiding the need to model competition between livestock and agricultural land use explicitly. To explore the link between beef demand and deforestation we use a parameter (k) to represent the percentage variation of pasture area in relation to changes in demand. Based on empirical evidence[11,12] estimated k values decreased from over 0.4 in the early 1970's to zero in the latest available data period (1995-2006), see **Supplementary file**. In the CLD scenario we assume the worst case $k = 0.4$, i.e., for every 1% variation in demand, pasture area changes by 0.4%, which would generate a deforested area of 10.9 Mha by 2030 relative to 1.5 Mha for the baseline projections (**Supplementary Table 3**).

In the scenario of controlled deforestation (DLD), the analysis shows that lower than projected beef demand may increase emissions in the *Cerrado* grazing system as a result of comparatively less efficient systems with higher emission intensities. Lower demand and smaller herds require less grass production, reducing the incentive to maintain or increase productivity; pastures then degrade, losing organic matter and soil carbon stocks. Higher demand combined with effective deforestation control policies leads to more efficient systems with lower emissions intensity due to significant increases in carbon uptake by deep rooted grasses in improved pastures.

Under DLD, emissions increase by 3%, 5% and 9%, respectively for the consumption reduction scenarios $D_{BAU-10\%}$, $D_{BAU-20\%}$ and $D_{BAU-30\%}$. But in $D_{BAU+10\%}$, $D_{BAU+20\%}$ and $D_{BAU+30\%}$, emissions decrease by 3%, 7% and 10%, respectively relative to D_{BAU} (Fig. 2b). Increased cattle emissions in these scenarios are offset by increased grassland carbon sequestration rates. Higher annual demand leads the model to increase productivity by restoring degraded pastures, and more productive pasture is associated with a higher carbon equilibrium value (**Supplementary Table 4**). Accumulated emissions (2006-2030) range from 1.9 Gt to 2.3 Gt of CO_2-e, respectively for $D_{BAU+30\%}$ and $D_{BAU-30\%}$.

But this result is undermined by altering the deforestation scenarios. Under CLD and assuming pasture expansion responds to changes in demand as in the 1970's, accumulated emissions (2006-2030) from beef production would range from 2.1 Gt to 3.0 Gt of CO_2-e, respectively for

$D_{BAU-30\%}$ and $D_{BAU+30\%}$, i.e., emissions would be 60% higher than in DLD for the same demand scenario $D_{BAU+30\%}$. The analysis shows that under both $D_{BAU-10\%}$ and $D_{BAU-20\%,}$ emissions decrease by 6%. Under $D_{BAU-30\%}$ scenario emissions are reduced by 2%, relative to D_{BAU}. Under $D_{BAU+10\%}$, $D_{BAU+20\%}$ and $D_{BAU+30\%}$, emissions increase 12%, 28% and 44%, relative to D_{BAU} (Fig. 2c). The changes are mainly due to direct animal emissions and deforestation. Note that the increasing demand scenarios drive proportional increases in deforestation, but under decreasing demand scenarios deforestation cannot be less than zero. In fact for $D_{BAU-30\%,}$ $D_{BAU-20\%}$ and $D_{BAU-10\%}$, deforestation rates are insignificant in relation to baseline figures, making GHG reductions more modest for these scenarios relative to the increases driven by deforestation under increasing demand scenarios.

Sensitivity analysis helps to identity the value of k representing the mid-way between CLD and DLD scenarios; i.e., the value where increases in deforestation and cattle emissions would be offset by gains from increased SOC uptake (Fig. 2d). The analysis suggests that this offsetting occurs approximately when $k = 0.1$, i.e., only 10% of production increases are due to pasture expansion and therefore 90% due to productivity gains.

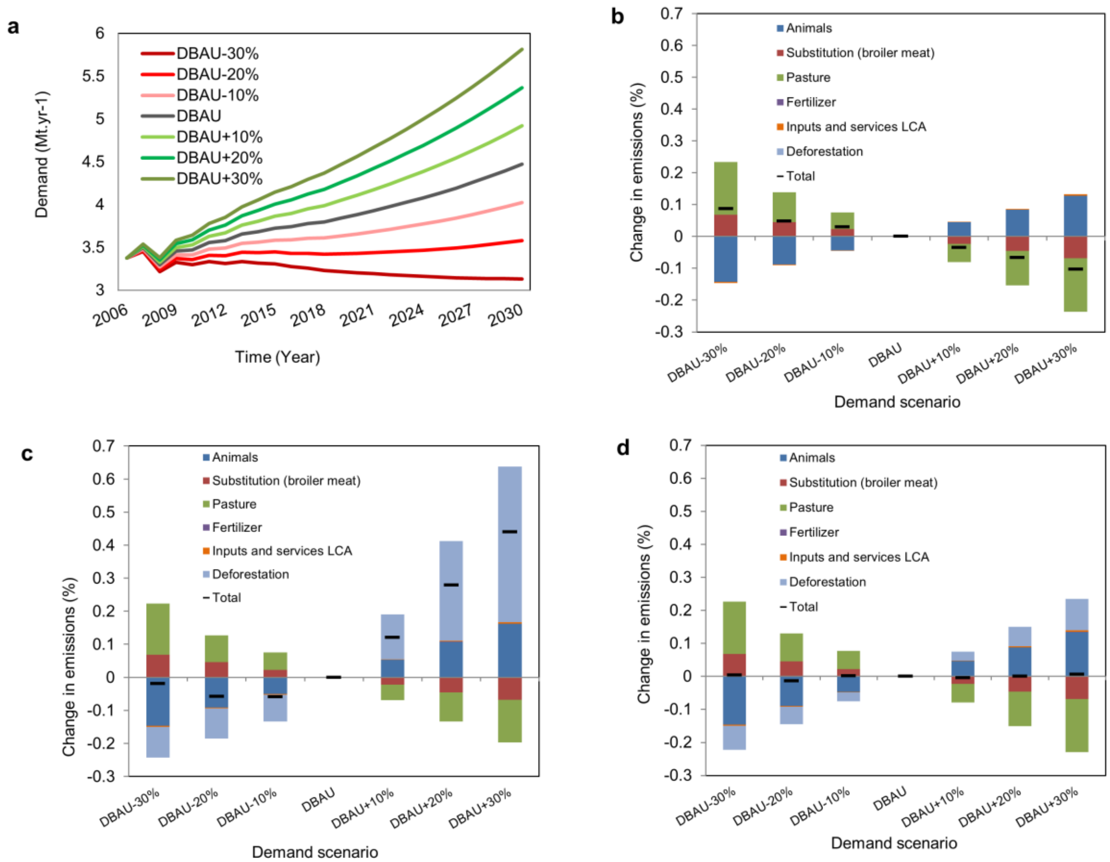

Figure 2: Demand scenarios and sensitivity analysis. **a**, *Cerrado* baseline demand (D_{BAU}) and varied demand projections that correspond to percentage variation by 2030 in relation to D_{BAU}, **b**, percentage changes in accumulated emissions (2006-2030) as a function of demand scenarios under the DLD scenario, **c**, changes under the CLD scenario, **d**, changes for k=0.1. The analysis assumes that beef consumption is substituted by broiler meat (**Supplementary Table 5**) and accounts for the net change in production emissions arising from this substitution.

Emissions mitigation by demand-driven intensification in the DLD scenario is space and time dependent. The results depend on specific geographical data and system characteristics of *Cerrado* production, and SOC is unlikely to be accumulated indefinitely[19]. To estimate the longevity of the inverse demand – emissions relationship (when SOC stocks approaches equilibrium content and no longer offset increased animal emissions), we conducted long-term analysis for 125 years. Assuming fixed demand from 2030 to 2130 and observing: a) the annual net emissions and b) the changes in accumulated emissions in 10 year periods from 2010 for each demand scenario under DLD. As demand projections increase up to 2030, the assumption of constant demand and area from 2030 leads to stabilized land productivity from 2030 to 2130.

Under the DLD scenario, increases in demand would lead to decreases in annual emissions up to 2057, when the situation inverts (Fig. 3a). But Fig. 3b shows that in terms of accumulated emissions, reducing beef consumption would lead to decreased emissions around 2120.

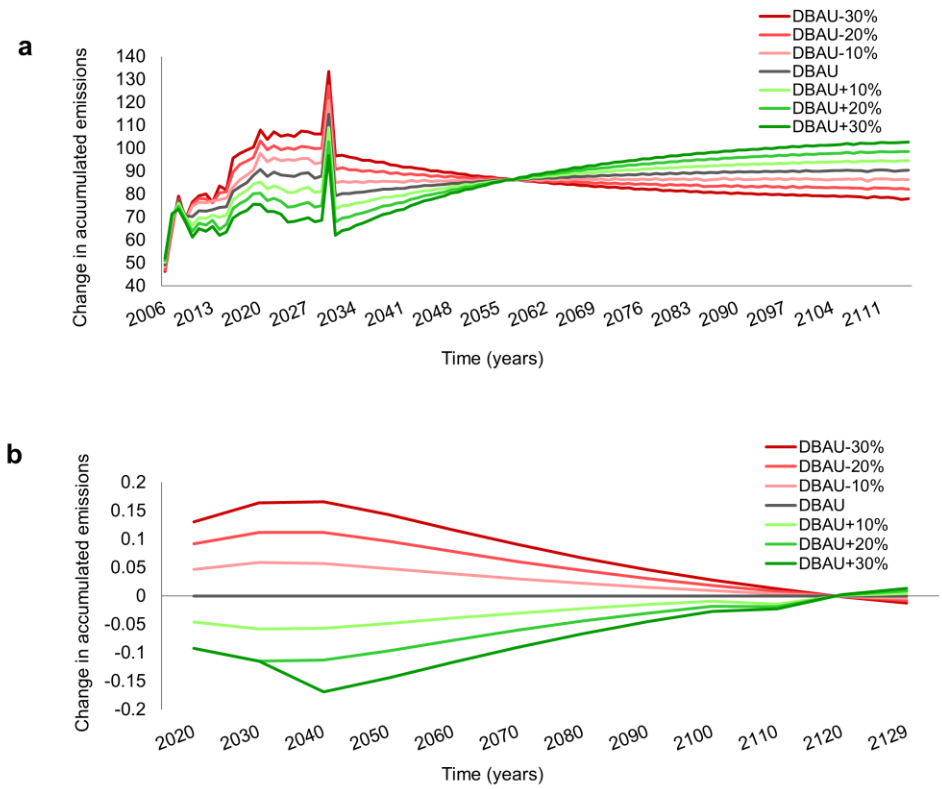

Figure 3: Long term GHG emissions analysis for the demand scenarios. **a**, annual net GHG emissions. **b**, percentage changes in accumulated GHGs. Note that the emissions peak in 2030 (Fig. 3a) is due to high deforestation rates in that year in the baseline projections employed[18]

Although SOC equilibrium has not been reached by 2057, the average sequestration rate of 0.08t of $C.ha^{-1}.yr^{-1}$ (under $D_{BAU+30\%}$) no longer offsets emissions from increased animal numbers. By 2057 SOC stocks reaches 60% of the difference between initial stocks and equilibrium values (**Supplementary Table 6**), i.e., 27 years after land productivity is stabilized, which is consistent with experimental evidence[20–22].

Our results implicitly show significant changes in emissions intensity depending on demand scenarios and deforestation. The lowest value (18.1 kg of CO_2-e/ kg of carcass equivalent (carcass-e) is observed under DLD and $D_{BAU+30,}$ which uses the least area to produce most beef (Fig. 4a). Under the CLD scenario, the lowest value is found in the baseline demand (22.2 kg of CO_2-e/ kg of carcass-e), while emissions intensity could reach 31.0 kg of CO_2-e/ kg of carcass-e under $D_{BAU+30\%}$, around 40% of this being due to deforestation (Fig. 4b).

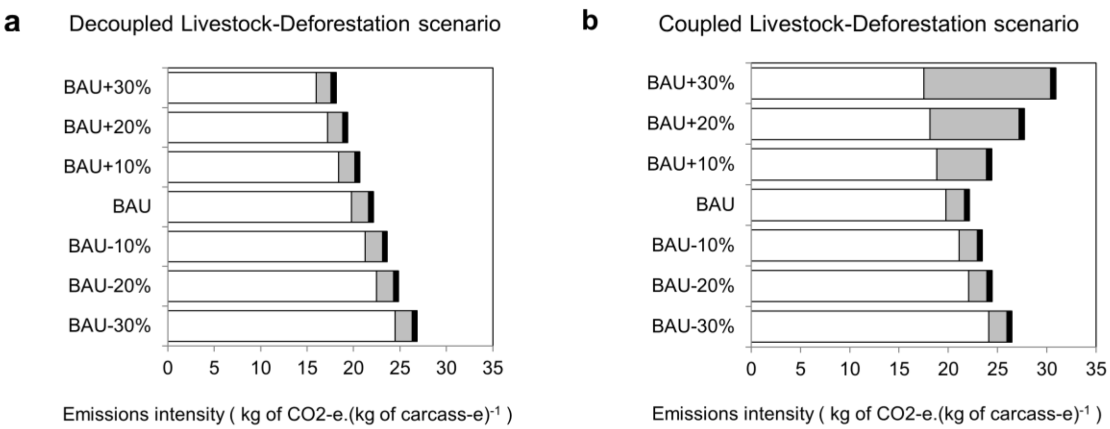

Figure 4: Emissions intensity as a function of demand scenario for **a**, Decoupled Livestock-Deforestation and **b**, Coupled Livestock-Deforestation land use scenarios. Carbon footprint calculated as the average value from 2010 to 2025, showing the sum of farm-emissions: animals and pasture (emissions by degradation or carbon sequestration and nitrogen fertilizers nitrification) (white), deforestation emissions (grey) and LCA emissions from inputs and farm operations used to restore pastures and changed land use (e.g., fertilisers, seeds, and machinery operations) (black).

The analysis contributes to the SI debate by highlighting the potentially inverse relationship between consumption and emissions that may be found in a globally significant beef production system.

A key factor in the results is how deforestation responds to changes in beef demand (parameter *k*). In the increasingly likely scenarios of controlled deforestation, the analysis shows that lower than projected beef demand may increase emissions in the *Cerrado* grazing system due to comparatively higher emission intensities.

Empirical evidence supports the DLD scenario by showing a calibrated value of k=0 (see **Supplementary file**). Since 2005, data show an apparent decoupling of cattle herd sizes and deforestation in Amazonia and *Cerrado*, replacing an historic correlation over the period 1975-2005; a trend attributed to a combination of supply and demand side factors including intensification in large-scale commodity-oriented farming, market regulation (e.g. moratoria on beef and soy grown in recently opened areas), product certification, and more effective law enforcement[23–25].

Recent studies indicate that current global trends in livestock productivity will not accommodate future projected global demand[1]. But this result adds to evidence that Brazil in particular has enough land to meet demand for food and energy at least until 2040 without further natural habitat conversion[18,26]. In fact under DLD the highest average stocking rate in the model, 1.33 head.ha^{-1} (under $D_{BAU+30\%}$), is below the 2 head.ha^{-1} carrying capacity associated with negative climate impacts[26].

The analysis also indicates that restoration of degraded pastures is the biggest opportunity for national mitigation plans; indeed, after avoided deforestation, the restoration of 15 Mha nationwide from 2010 to 2020 is the main measure contributing to the 40% reduction target by 2020 (ref. 27).

Because the analysis employs consequential LCA approach[6], it contrasts to other results[1,2,28] using attributional analysis based on constant emission intensity irrespective of consumption level.

More generally our results reflect *Cerrado* system-specific data, and the picture might differ if we analyse other regions of Brazil or worldwide. The *Cerrado* is nevertheless seen as model for transforming other global savannahs[29].

Methods

EAGGLE model.

The analysis employed the EAGGLE (Economic Analysis of Greenhouse Gases for Livestock Emissions) model (**Supplementary Methods**), a bottom-up multi-period linear programming model that simulates beef production systems in Brazil subject to demand and pasture area. The model maximizes farm profit by optimally allocating resources, including the adjustment of pasture intensification levels according to bioeconomic parameters and estimates the GHGs - including changes in soil carbon stocks - for a production period.

GHG emissions sources

EAGGLE estimates GHG's using emissions factors for direct emissions and Life-Cycle Assessment (LCA). GHG emissions associated with farm activities are: (a) CH_4 from cattle enteric fermentation (CH_4 from excreta is not accounted); (b) N_2O from cattle excreta; (c) N_2O from N fertilisation conversion; (d) CO_2 from *Cerrado* deforestation (due to loss of natural vegetation); (e) CO_2 from pasture degradation and land use change from pasture to crops; and (f) LCA factors for inputs and farm operations applied in land use change and restoration practises (**Supplementary Table 2**). Items (a) and (b) depend on herd composition: each age cohort of males and females (heifer or cow) has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology[17], see values in **Supplementary Table 1**. Due to the lack of studies for Brazilian conditions, for (c) we used the Tier 1 IPCC default factor of 1%[17]. The emissions from (d) are calculated using a coefficient of loss of natural vegetation per hectare of deforested area, estimated as 34.6 tons of C per hectare[30]. For (e), the emissions are calculated according to equations (1) and (2) in section **Soil carbon stocks**.

Soil carbon stocks

Depending on the dry matter productivity (DMP) level, the C flux may change significantly. The EAGGLE model works with equilibrium values of the C stock for each type of pasture and crops. The higher the pasture productivity, the higher the C equilibrium value (See **Supplementary Table 4**). Equilibrium values and the time to reach equilibrium were calculated exogenously, using simulations from the CENTURY model[31] applied to *Cerrado* biophysical characteristics and using the annual DMP calculated for each pasture category.

Demand and pasture area data

Projections from The World Bank[18] were used for both pasture area and beef demand. The projections correspond to the period 2006-2030. Historical data 2006-2013 were used to validate the employed demand projections (**Supplementary file**). For pasture area projections, the last observational data was in 2006 (last agricultural census).

We assume *Cerrado* pasture area and beef demand share are a fixed proportion of the national projections - since there is no biome- specific predictions in the literature. The *Cerrado* pasture area represented around 34% of the national total in 2006 (when the last agricultural census[12] was undertaken). We therefore assume *Cerrado* pasture area corresponds to 34% of Brazil's pasture area projections, and that this proportion is constant during the study period (2006-2030). Similarly, we assume beef demand to be proportional to area, thus demand for *Cerrado* output is also equivalent to 34% of national demand. The model is partial with comparative static equilibrium adjustment between demand and supply; i.e., each year, production equals demand and prices remain constant for the whole period

Scenario construction and deforestation

In both Coupled Livestock-Deforestation and Decoupled Livestock-Deforestation scenarios, pasture area and therefore deforestation is exogenous to the optimisation model.

The analysis employs baseline pasture area projections from a World Bank study[18]. For the CLD scenario, we estimate changes in deforestation as a function of changes in beef demand by assuming that for every change in annual demand in relation to baseline projections would cause a proportional change in annual pasture area:

$$\frac{A_{BAU+X\%,t} - A_{BAU,t}}{A_{BAU,t}} = k\,\frac{D_{BAU+X\%,t} - D_{BAU}}{D_{BAU}} \Rightarrow A_{BAU+X\%,t} = \left[1 + k\left(\frac{D_{BAU+X\%,t}}{D_{BAU,t}} - 1\right)\right] A_{BAU,t}$$

Where $A_{BAU+X\%,t}$ represents the altered pasture area projections in relation to baseline projections $A_{BAU,t}$; $D_{BAU+X\%}$ represents the altered demand projection where X is in [-30,-20,-

10,10,20,30] and represents the change by 2030; D_{BAU} the baseline demand; *k* is the proportional change in pasture area due to changes in demand projections.

For the DLD scenario, the same area projections is used regardless level of consumption (demand scenarios).

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Contributions

R.O.S, L.G.B. and D.M. designed the study and wrote the paper, R.O.S. and L.G.B. developed the mathematical model, R.O.S implemented the model and generated the results, J.A.J.H. contributed to the model development and mathematical solutions, M.F.M. provided the LCA data, T.Z.A. provided the bioeconomic data, F.A.F. performed the simulations with the CENTURY model.