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POLICY BRIDGE

Asymmetries of cattle and crop productivity and efficiency during Brazil's agricultural expansion from 1975 to 2006

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Brazil has global importance for food production and conservation of natural resources. The country has plans to increase yields and commitments to decrease deforestation that require higher productivity. Plans and policies for the growth of Brazilian agriculture, however, have been made without an integrated analysis of the harvest and not supported by a universal metric regarding its efficiency. Applying methods to model flows of energy and matter along food supply chains for agricultural production from 1975 to 2006, we found that crop and cattle harvests and their productivity have increased during the last four decades in consolidated and deforestation frontier regions. Yet in 2006, crop protein production was 20 times larger than cattle protein, using an area 2.6 times smaller than pastures. Crop protein productivity was 0.25 ton.ha⁻¹ with emissions of 2 ton GHG per ton of protein, while cattle productivity was 0.01 ton.ha⁻¹ with emissions of 283 ton GHG per ton of protein. From 1975 to 2006, the portion of crop protein and energy going to feed increased while the portion going to direct human consumption decreased. Our findings suggest that more efficient food systems would be achieved by a combination of intensification of cattle systems, optimization of feed-meat systems and an increase in the share of the consumption of crops as a source of protein. We suggest an initial road map to the expansion of the cultivated area and intensification of agriculture for zero deforestation, efficient and sustainable land use and food systems where cattle pasture intensification is a transition that will last until the expansion of crops replace all pasture present on suitable arable land. During this transition, pasture area will decrease until it is limited only to marginal non-arable lands. Such change could be achieved by a robust strategy that combines penalties and incentives and prevents the risks of a rebound effect for the intensification of agriculture.

Keywords: crop; expansion; harvest; intensification; pasture; productivity

Introduction

The provision of food, feed, livestock and bioenergy for a growing global population is linked to deforestation, habitat loss and biodiversity impacts, greenhouse gases (GHG) emissions and depletion of water resources (Foley et al., 2011). Achieving the profound challenge of reconciling production and environmental conservation requires a paradigm shift in the way we use land and other agricultural resources to meet burgeoning demand. Public and private sector actors alike have

recently made an unprecedented set of commitments to reduce environmental impacts and deforestation from the production of commodities, manifested most prominently in the UN Sustainable Development Goals, the Paris Agreement of the UNFCCC and the New York Declaration on Forests.

Brazil is one of the world's major agricultural producers and exporters while also being among the biologically wealthiest nations (Ferreira et al., 2014). Agribusiness represents around 25% of the country's economy, but an increase in production has been associated with severe social and environmental impacts such as deforestation of tropical forests (Nepstad et al., 2014), emissions of greenhouse gases (Brown and Zarin, 2013) and precarious labor conditions (Phillips and Sakamoto, 2012). Substantial growth of overall Brazilian production of crops and cattle is planned by the Federal government (MAPA, 2016) and the private sector for the next decade (FIESP, 2015), positioning Brazil as a key country to provide food and bioenergy globally.

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Deforestation has decreased in the last decade, but continues at high levels in the Amazon (Moutinho et al., 2016) and, in Cerrado, has increased from 2014 to 2016 (Strassburg et al., 2017). Studies have shown that productivity and intensification of crop and cattle production are key for a sustainable growth of the national harvest and to contribute to stopping deforestation (Dias et al., 2016, Strassburg et al., 2014). Despite this complexity, forecasts, plans and policies for the growth of Brazilian agriculture have been made without an integrated analysis of the national harvest and were not supported by a universal metric regarding efficiency of the harvest.

We define national harvest (*safra* in Portuguese) as the aggregated production of the crop and cattle sectors in the country in one year. And we define productivity as the amount of crop or cattle produced per unit of land and intensification as a mean to increase productivity. Means of intensification can include more use of resources per unit of land (such as fertilizers per hectare) or changes in production systems or practices that do not necessarily require more resources, but can result in more efficient resource use. Finally, efficiency refers to the ratio of an amount of a resource (land, labor, energy, fertilizers or other inputs) or of an emission in relation to an amount of a product (tons of crop or cattle, for example). In this study, we measure efficiency as production in relation to units of emission of greenhouse gases.

The objective of this study is to provide a rational basis for planning for the growth of Brazilian agriculture by making, for the first time, an integrated and time series analyses of the productivity and efficiency of the national harvest. The analyses that we present below allow us to identify potential inefficiencies of the production of crops and cattle to provide food and energy to society. We assume that understanding inefficiency will provide insights for the development of policies to support the sustainable growth of the harvest and contribute to the end of deforestation.

Methods

We applied methods to model flows of energy and matter along food supply chains (Wirsenius et al., 2010) based on physically consistent and summable units that are common to all agricultural and livestock products and residues: Protein (Prt), Gross Energy (Gr_ε), Metabolizable Energy (Mt_ε) and Non-Metabolizable Energy (noMt_ε). These units represent the core functional elements for nutrition of humans and livestock and for conversion of bio-products to energy. It offers a consistent basis for comparisons along supply chains, from production (within farm boundaries), via transformation, to final consumption (Figure 1). We refer to Production Functionality (PF) of the harvest (PF-harvest) as representing the total national agricultural production appropriated

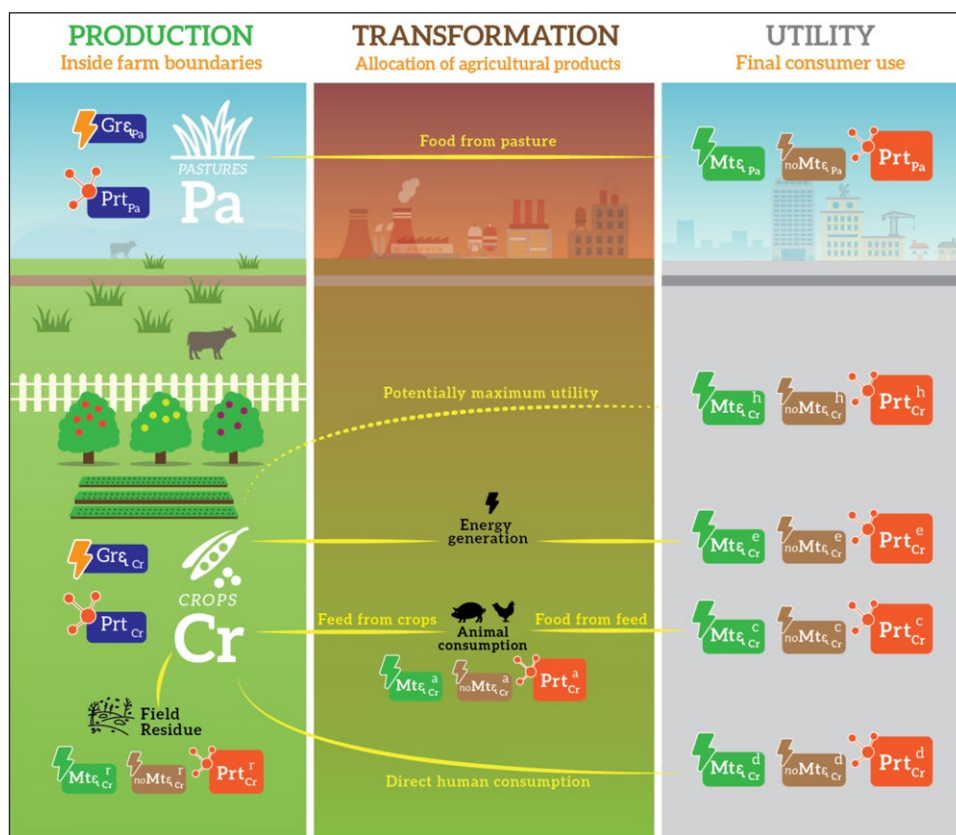


Figure 1: Production Functionality Model System.

Legend: Stage flows of functional elements along supply chains, from production to final consumption, where Cr = crops, Pa = pasture, Gr_ε = gross energy, Mt_ε = metabolizable energy, noMt_ε = non-metabolizable energy, Prt = protein, r = field residue, a = animal consumption, h = potentially maximum utility, e = energy generation, c = carcass (conversion from feed to food), d = direct human consumption. DOI: <https://doi.org/10.1525/elementa.187.f1>

by humans as food or energy. We can consistently obtain the value of PF-harvest by estimating the suggested fundamental utility units along the food, feed and energy systems.

We completed this assessment using data from the Brazil's 12 main crops in the country (cotton, rice, banana, coffee, orange, sugarcane, bean, cassava, corn, soybean, wheat and cocoa) and figures on the production of beef, pig and poultry meat, milk and eggs obtained from the Brazilian National Agricultural Census database (1975, 1985, 1996 and 2006) (IBGE, 2016). We converted these products and their estimated residues into basic functional elements (Protein, Gross energy, Metabolizable energy and Non-Metabolizable energy). We linked our findings with estimates of direct GHG agriculture emissions made by SEEG (2017) and the monetary value of Brazilian agriculture calculated by the Ministry of Agriculture (MAPA, 2015).

Database sources

The Brazilian agricultural database was obtained from the Brazilian Institute of Geography and Statistics – IBGE. We selected information from the Brazilian Agricultural Census for the years 1975, 1985, 1996 and 2006. The studied time period ends in 2006 because it was the last performed Brazilian Agricultural Census.¹

The database is composed of information with the greatest possible level of detail, which means state level (or federation units) for the years 1975 and 1985 and municipality level for the years 1996 and 2006. To ensure the consistency of the database, the data for the years 1996 and 2006 were grouped by federation units (States), which thus is the smallest unit of analysis.

Information regarding crop production was tabulated for the 12 main Brazilian agricultural crops, which accounts for 96% of the national agricultural crop area (**Table 1**). For these crops, the following information was tabulated: harvested area, planted area (temporary crops), area destined to harvesting (permanent crops) and production.² Based on these primary data, we calculated the total land use occupied by agricultural crops in each federation unit (State) – i.e., the sum of the areas occupied by temporary and permanent crops.

Livestock information was tabulated regarding the occupied area by pastures, effective number of animals on pastures (including cattle, buffaloes, goats, sheep, horses, donkeys and mules), number of pigs and chickens, and the production of other animal foodstuffs such as goat milk, cattle milk and chicken eggs (see data example in **Table 2**).

Additionally, we used information regarding the economic value of agricultural and livestock production and greenhouse gas emissions (GHG). For GHG we used data from 1975 to 2006 from the System of Greenhouse Gas Emissions Estimates – SEEG Brazil (SEEG, 2017). For the economic value of the crop and cattle harvests, we used data of 2006 from the website of the Ministry of Agriculture, Livestock and Supply – MAPA (MAPA, 2017).

Table 1: Area occupied by the main Brazilian agricultural crops in 2016^a. DOI: <https://doi.org/10.1525/elementa.187.t1>

Main agricultural crops	Area (hectares)	% of total area
Soybean	33,310,365	42%
Corn	16,039,474	20%
Sugarcane	11,369,507	14%
Bean	2,945,367	4%
Coffee	2,307,102	3%
Cassava	2,173,318	3%
Wheat	2,167,539	3%
Rice	2,004,644	3%
Cotton (herbaceous)	1,001,952	1%
Cocoa	812,123	1%
Orange	741,062	1%
Banana	521,465	1%
Analyzed crops coverage area	75,393,918	96%
Total Brazilian agricultural crops area	78,681,081	100%

^a Source: Systematic Statistic of Agricultural Production (IBGE, 2016).

Table 2: Example of livestock information tabulated for the year 2006^a. DOI: <https://doi.org/10.1525/elementa.187.t2>

Livestock variables	Unit	Value
Pasture	hectares	160,001,453
Cattle	heads	176,146,884
Buffaloes	heads	806,580
Goats	heads	7,083,570
Sheeps	heads	14,139,742
Horses	heads	4,541,321
Dunkeys	heads	651,106
Mules	heads	748,719
Pigs	heads	31,189,351
Chickens	heads	1,143,458,000
Cattle milk	liters	20,567,868,000
Goat milk	liters	35,742,000
Chicken eggs	units	33,379,404,000

^a Source: Brazilian Agricultural Census (IBGE, 2016).

Modelling the production, transformation, and utility of agricultural crops and livestock

We created a model system that considers crops and pastures as the unique and primary sources of macronutrients for human nutrition, what we call as functional

elements (Protein – Prt, Gross Energy – Gr ϵ , Metabolizable Energy – Mt ϵ and Non-Metabolizable Energy – noMt ϵ). The model is capable to account for the production of functional elements from primary sources, the allocation (or transformation) of this production into fertilizer, energy, animal feed or human food and hence to determine the utility of functional elements to humans.

In the model, everything that is produced within farm boundaries is allocated for some intermediary (animal feed) or final use (field residue, energy generation or human food). The allocation of production to utility considers six main stage flows (**Figure 1**):

- i) Food from pasture (Mt ϵ_{pa} , noMt ϵ_{pa} and Prt $_{pa}$) – all the production from pastures (animal carcasses and milk share)³ is destined directly for human consumption;
- ii) Feed from crops (Mt ϵ_{Cr}^a , noMt ϵ_{Cr}^a and Prt $_{Cr}^a$) and food from feed (Mt ϵ_{Cr}^c , noMt ϵ_{Cr}^c and Prt $_{Cr}^c$) – allocation of crop production to feed is based on standard coefficients obtained in databases from institutions, cooperatives and associations related to each crop. To account for animal carcass produced with feed, the model considers that all feed was destined equally to poultry and pork consumption;
- iii) Potentially maximum utility of crops (Mt ϵ_{Cr}^h , noMt ϵ_{Cr}^h and Prt $_{Cr}^h$) – this stage flow is hypothetical because not all edible crop protein and energy are directly appropriated by humans, but it demonstrates the potentially maximum utility of crops production, i.e., if the present allocations to food, animal feed, and other products were entirely diverted to food production and none to animal feed and other products;
- iv) Field residues (Mt ϵ_{Cr}^r , noMt ϵ_{Cr}^r and Prt $_{Cr}^r$) – the model considers that all production of crop residues from harvesting is used as mulch and fertilizer, being left inside farm boundaries;⁴
- v) Energy generation (Mt ϵ_{Cr}^e , noMt ϵ_{Cr}^e and Prt $_{Cr}^e$) – the production of energy from crops is restricted to three by-products from industrial process, namely sugarcane bagasse, ethanol from sugarcane and rice hulls.⁵
- vi) Direct human consumption (Mt ϵ_{Cr}^d , noMt ϵ_{Cr}^d and Prt $_{Cr}^d$) – this flow calculates human appropriation of protein and energy as food, which is smaller than the total production from crops since it considers the current choices on the allocation of crops to other uses such as feed, energy and field residues.

Partitioning of agricultural crops and livestock production into functional elements

The Production Functionality approach requires the partitioning of agricultural crops and livestock production into products, by-products, and harvest residues and later into their contents of dry matter and functional elements.

By-products represent parts of the production that are used for different purposes (e.g. cassava tubers and cassava

leaves) or that are derived from some industrial processing (e.g. sugarcane bagasse obtained in the production of ethanol or sugar). Harvest residues are the parts of crops usually left in the field as mulch or fertilizing (e.g. maize stover and wheat straw) contributing to soil protection and fertility.

The 12 initial agricultural crops were partitioned into 25 and later into 42 products, by-products, and harvest residues to allow the estimates of *Functional Elements Production and Utility*, respectively (**Figure 2**).

For livestock, the stage flows are simpler and the same products and by-products measured in the Brazilian Agricultural Census are converted to functional elements. The unique difference remains on the units of measurement because the model converts the effective numbers of animals on pastures to carcass weight (tonnes) based on a standard offtake rate (number of slaughtered animals per number of animals in stock) and the respective carcass weight of each type of herd (**Figure 3**). In addition, the model considers that all meat and other animal foodstuff are essentially allocated to food for humans and, hence, the estimations of Functional Elements Production and Utility are exactly the same for livestock products.

For both agricultural crops and livestock production, the contents of Prt and Gr ϵ are derived directly from the dry matter content of each product, by-product and harvest residues (latter used only for crops). The model calculates the contents of Mt ϵ and noMt ϵ only for the products (or by-products) allocated to food or animal feed and other products (or by-products) that have an alimentary potential for humans or animals but are currently allocated to other transformation process. For this group, the calculation of noMt ϵ content is based on the subtraction of Gr ϵ by Mt ϵ .

We highlight that PF-harvest analysis is restricted to the macronutrients present in the agricultural products and does not differentiate the quality of protein in terms of amino acids composition neither among the different agricultural products nor between animal and vegetable products. Therefore, our estimates neglect the fact that animal sources of protein tend to deliver all the amino acids humans need while vegetable sources generally lack one or more essential amino acids. Although this simplification may result in overestimation of the nutritional value of vegetable protein we claim that this fact does not alter the big picture of the asymmetries between cattle and crops production presented in this paper.

In addition, we highlight that our analyses were done based on official data of IBGE with unknown and likely variable levels of uncertainty in these quantitative estimates. However similar studies assessing the expansion and intensification of Brazilian Agriculture have used the same database (Barreto et al., 2013, Dias et al., 2016). Thus, despite the uncertainty, such data present trends and provide knowledge for a critical analysis and planning of the sector on a national scale and in a long-term perspective.

The Supplemental Materials presents a set of figures that illustrate the partitioning of each agricultural crop and livestock products to functional elements (Figure S1

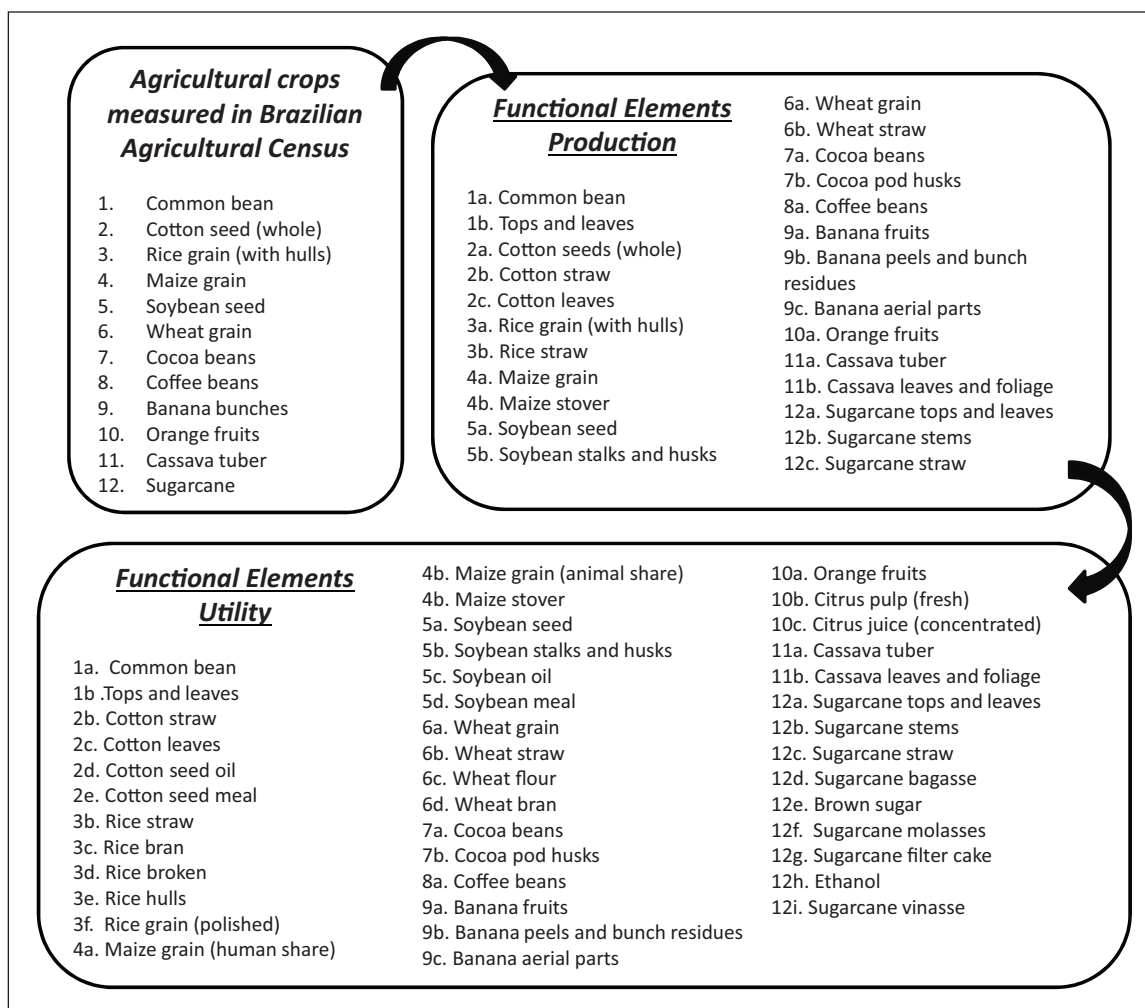


Figure 2: Partitioning of agricultural crops into products, by-products, and harvest residues.

Legend: This figure illustrates the partitioning of the 12 initial agricultural crops into 25 and later into 42 products, by-products, and harvest residues to allow the estimates of Functional Elements Production and Utility, respectively. The number of the agricultural crop is accompanied with a prefix-number to allow the identification of the by-products and the harvest residues originated from it. For example, the agricultural product named “Cotton seed (whole)” is accompanied by the prefix-number 2 in the upper left panel. In the upper right panel, it is possible to see two harvest residues originated from it (“2a. Cotton Straw” and “2b. Cotton leaves”). In the lower panel, which accounts for the final utility of the original agricultural product, two by-products are included (“2d. Cotton seed oil” and “2e. Cotton seed meal”). DOI: <https://doi.org/10.1525/elementa.187.f2>

to Figure S16). We also present the coefficients adopted for the estimations of *Functional Elements Production* and *Utility*, in Tables S1, S2 and S3 (Supplemental Materials).

Results

Asymmetries between crops and livestock, their productivity, and emissions of GHG

Crop and cattle production of protein (Mton) and energy (Exa joules) and productivity (tons and joules per hectare) progressively increased from 1975 to 2006 in all regions of Brazil (Figures 4 and 5). Area of crops was stable and decreased for pastures in the consolidated regions (South and Southeast) and increased in the expansion and frontier regions (North – mostly pastures and Center-West – mostly crops) (Figure 5). However, growth rates of production and productivity were constantly higher for crops than pastures-cattle

at both the national and sub-national scales (Tables S4 to S14).

Crops were much more effective in producing protein, metabolizable energy, and non-metabolizable energy than pasture-cattle. From 1975 to 2006 protein and gross energy from crops increased 3.5 times and 3.3 times, summing up to 38 Mton of protein and 6.1 EJ of gross energy (Figure 4; Table S4). In 2006 crop protein production was 20 times larger than cattle protein production, using an area 2.6 times smaller than the pasture area; 23.4 Mton of protein was contained in crops cultivated on 61 Mha, while cattle produced 1.2 Mton of protein on 160 Mha of pasture (Tables S5, S6 and S7). Crop cultivation generated 0.25 ton Prt.ha⁻¹ while cattle generated 0.008 ton Prt.ha⁻¹ in 2006 (32 times difference in land use efficiency) (Figure 6 and Tables S8 and S9). Finally, crops produced 2.1 EJ of total human metabolizable energy, 45 times more than cattle produced at 0.05 EJ (Figure 7; Tables S6 and S7).

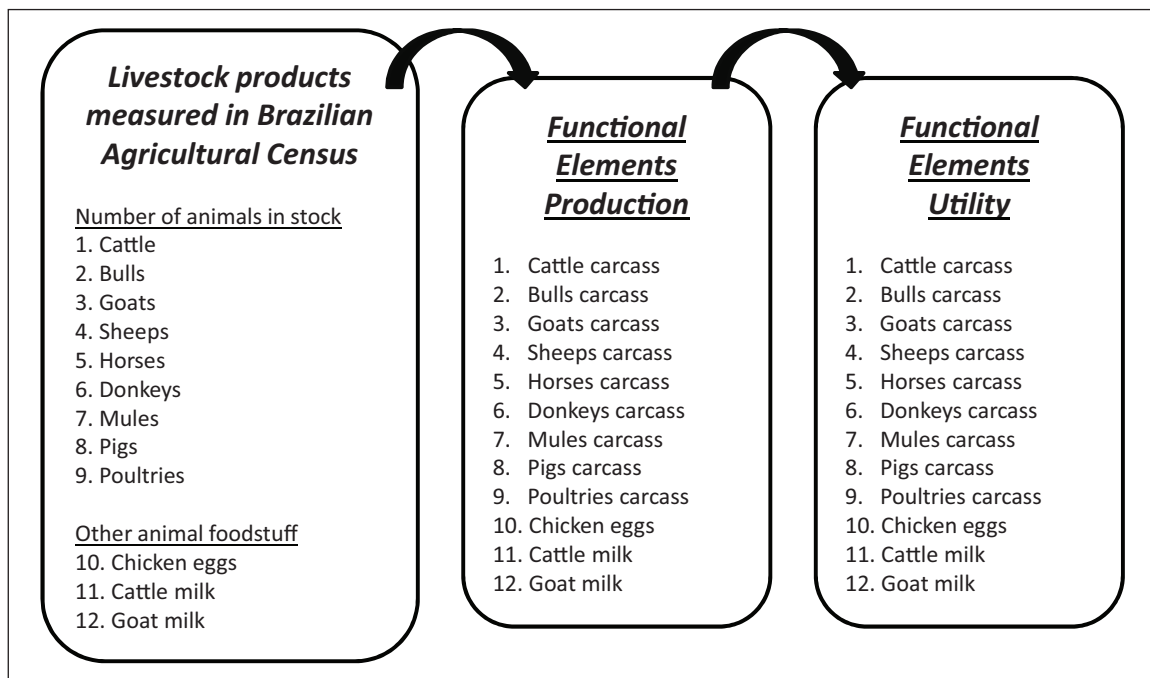


Figure 3: Partitioning of animals in stock and other animal foodstuff into products and by-products.

Legend: This figure illustrates the partitioning of the 12 initial livestock products into products and by-products to allow the estimates of Functional Elements Production and Utility. The number of the livestock product is accompanied with a prefix-number to allow the identification of the by-products originated from it. Once the model considers that all livestock products are essentially allocated to food for humans, the estimates of Functional Elements Production and Utility are based on the same livestock products or by-products. For example, the livestock product named “Cattle” is accompanied by the prefix-number 1 in the left panel. In the middle panel, it is possible to see the by-product originated from it (“1. Cattle carcass”), which is used for the estimates of Functional Elements Production. In the right panel, the same by-product is considered for the estimates of Functional Elements Utility (“1. Cattle carcass”). DOI: <https://doi.org/10.1525/elementa.187.f3>

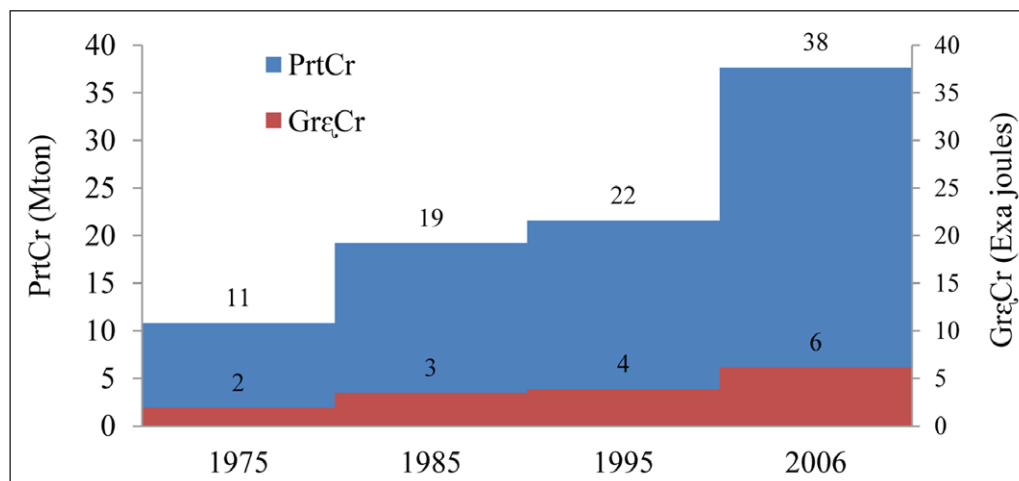


Figure 4: Change of protein and gross energy derived from crops between 1975 and 2006.

Legend: Change of total protein (in million tons – Mton) and gross energy (in Exa joules) from crops in the four analyzed years. From 1975 to 2006, crops protein content increased from 11 Mton to 38 Mton whereas crops gross energy content increased from 2 Exa joules to 6 Exa joules. DOI: <https://doi.org/10.1525/elementa.187.f4>

Considering a per capita consumption requirement of 3.8 GJ.yr⁻¹ of food energy (2,500 kcal per day) and 17.5 Kg.yr⁻¹ of protein (50 g per day), the Brazilian crop harvest of 2006 would have been sufficient to meet the food energy needs of 540 million people and the protein needs of 1.3 billion people. In contrast, cattle production

in the same year could have potentially provided energy needs for only 12 million and protein for 66 million people, respectively 98% and 95% less than the value of crops. In addition, crop production also generated 3.8 EJ of non-metabolizable energy in the form of non-edible by-products or harvest residues (1.6 times more than

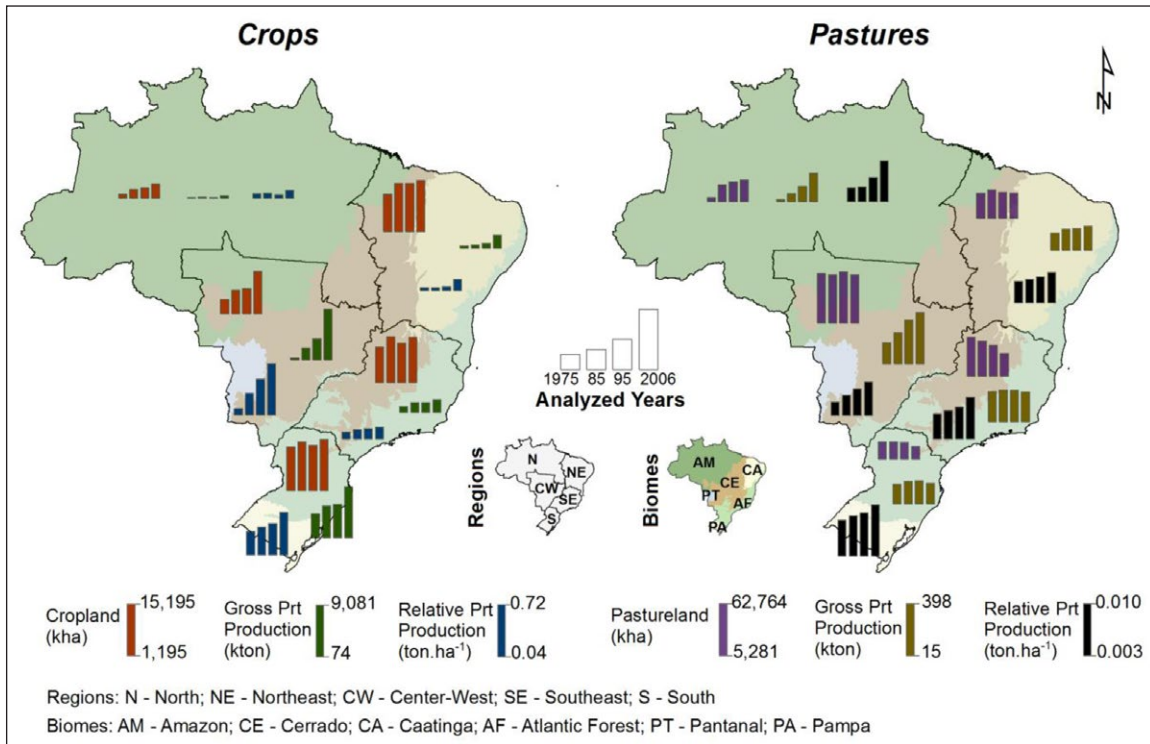


Figure 5: Change of area, production, and productivity of proteins of crops and pasture-cattle in Brazil between 1975 and 2006.

Legend: The bars in the map present three distinct information: i) the colors represent different variables (red – cropland area (in thousand hectares – kha), green – crops gross protein production (in thousand tons – kton), blue – crops relative protein production (tons per hectare), purple – pastureland area (in thousand hectares – kha), brown – pastures gross protein production (in thousand tons – kton), black – pastures relative protein production (in tons per hectare); ii) the size is related to variable's maximum and minimum values considering the entire study period and all Brazilian regions. For example, the value of 1,195 kha of cropland is related to the smallest red bar in the map (which is in the northern region of Brazil) and the value of 15,195 kha is related to the largest red bar in the map (which is in the southern region of Brazil); and iii) the four possible positions of the bars indicates the year being represented (ex. The first position refers to 1975 and the fourth position refers to 2006). DOI: <https://doi.org/10.1525/elementa.187.f5>

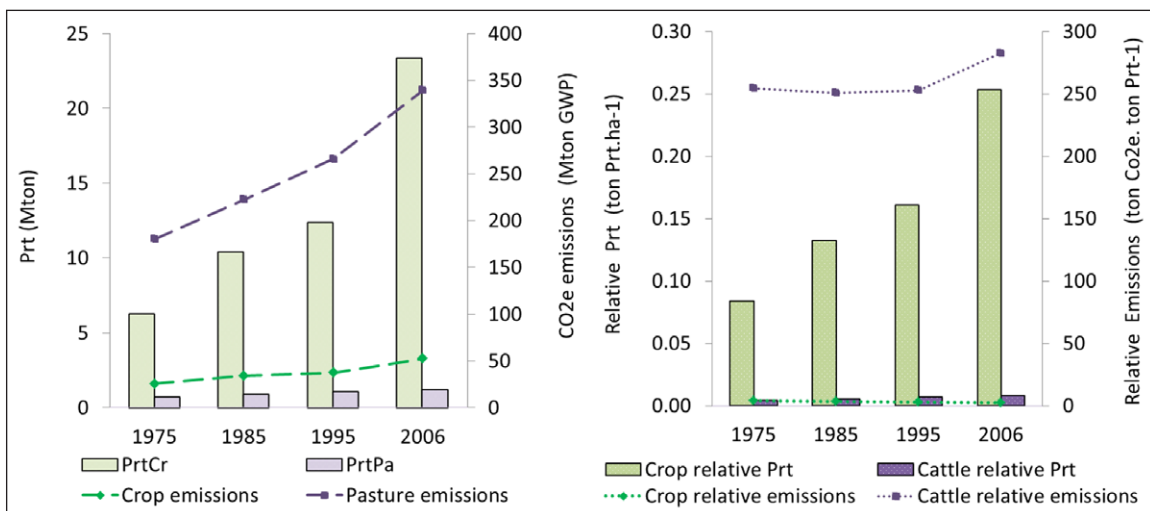


Figure 6: Changes from 1975 to 2006 in crop and cattle protein production and associated CO₂e emissions (left), and in relative production (efficiency) and emissions (right).

Legend: In the left graph: the bars represent the total amount of protein produced (in millions of tons – Mton) by crops (PrtCr) and pastures (PrtPa) for each analyzed year, and the lines represent the total emissions of CO₂e (in millions of tons of CO₂e) by croplands and pastures. In the right graph: the bars represent the relative production of protein (in tons per hectare based on total hectares reported in table S5) by crops and cattle, and the lines represent the relative emissions of CO₂e (in tons of CO₂e per tons of protein produced). DOI: <https://doi.org/10.1525/elementa.187.f6>

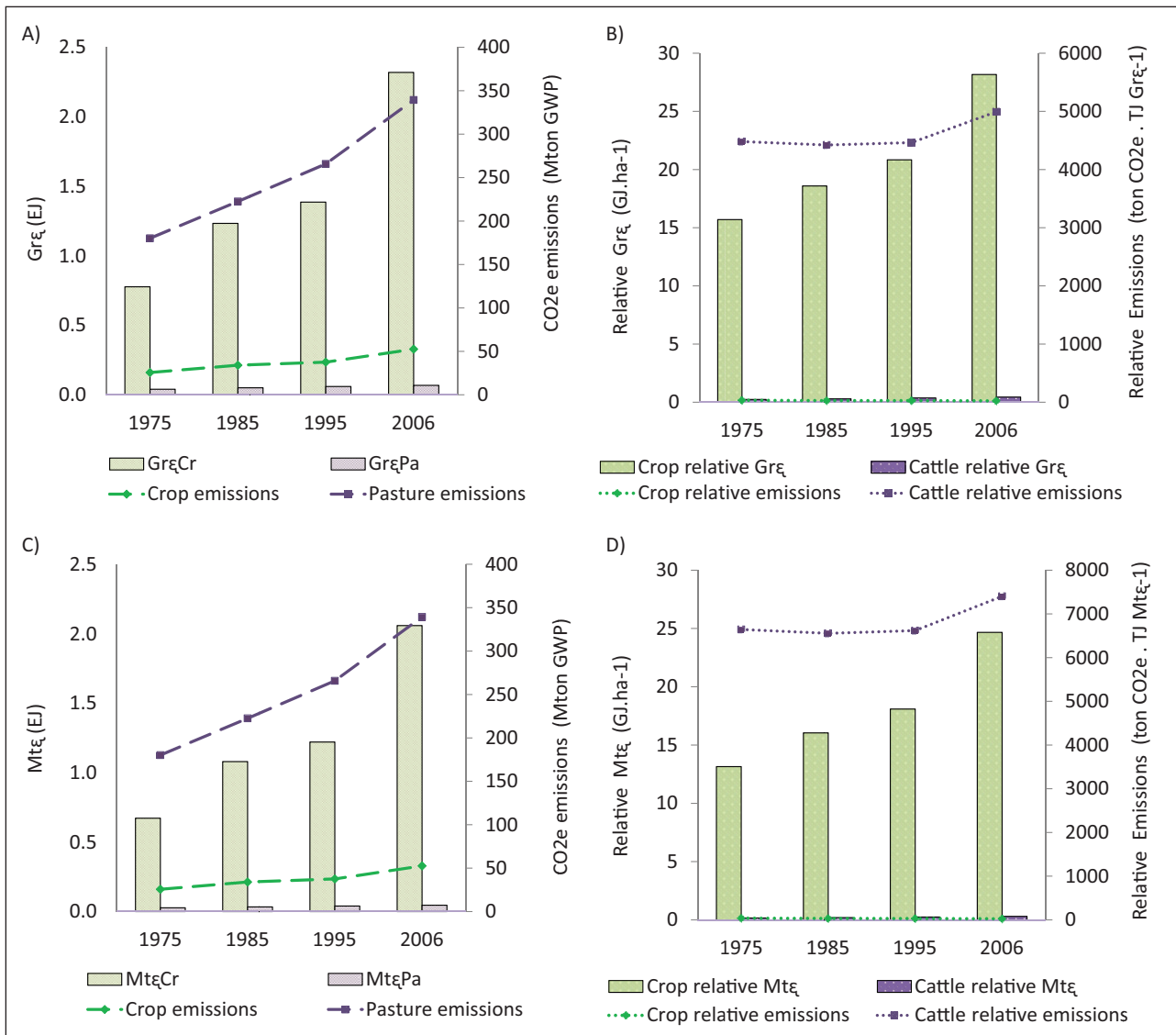


Figure 7: Change of crop and cattle (A) gross energy, (B) relative energy, (C) metabolizable energy production and (D) relative metabolizable energy production in function of their GHG emissions from 1975 to 2006.

Legend: In graph (A) the bars represent the total amount of gross energy produced (in Exa joules or 10^{15} joules) by crops (GrE_{Cr}) and pastures (GrE_{Pa}) for each analyzed year, and the lines represent the total emissions of CO_2e (in millions of tons of CO_2e or Mton) by croplands and pastures. In graph (B) the bars represent the relative production of gross energy (in Giga joules – 10^9 joules – per hectare) by crops and cattle (total occupied area by crops and pastures, for each analyzed year, can be obtained in Table S5), and the lines represent the relative emissions of CO_2e (in tons of CO_2e per Tera joule – 10^{12} – joules of gross energy). In graph (C) the bars represent the total amount of metabolizable energy produced (in Exa joules or 10^{15} joules) by crops (MtE_{Cr}) and pastures (MtE_{Pa}) for each analyzed year, and the lines represent the total emissions of CO_2e (in millions of tons of CO_2e or Mton) by croplands and pastures. In graph (D) the bars represent the relative production of metabolizable energy (in Giga joules – 10^9 joules – per hectare) by crops and cattle, and the lines represent the relative emissions of CO_2e (in tons of CO_2e per Tera joule – 10^{12} joules – of metabolizable energy). DOI: <https://doi.org/10.1525/elementa.187.f7>

metabolizable), representing a very significant source of any biomass use purpose (e.g. feedstock, fuels, electricity generation, soil conservation or fertilization) (Tables S11 and S12).

The contrast between cattle and crops is equally stark when assessing emissions of GHG and economic value as opposed to functional benefits. In 2006, total GHG emissions associated with crop production amounted to 53 Mton GHG, corresponding to 2 ton GHG per ton of protein produced, while cattle production generated 339

Mton GHG or 283 ton GHG per ton of protein produced (Figure 6).

Moreover, the monetary production value of crops was only twice as high as for cattle, despite the fact that crops provided 20 times more maximum gross protein in production (Tables S6 and S7) and 5 times more in utility (Tables S7 and S10) for direct human consumption. Regarding relative profitability ($US\cdot ha^{-1}$), crop production is on average 6.4 times higher than cattle production (Figure 8).

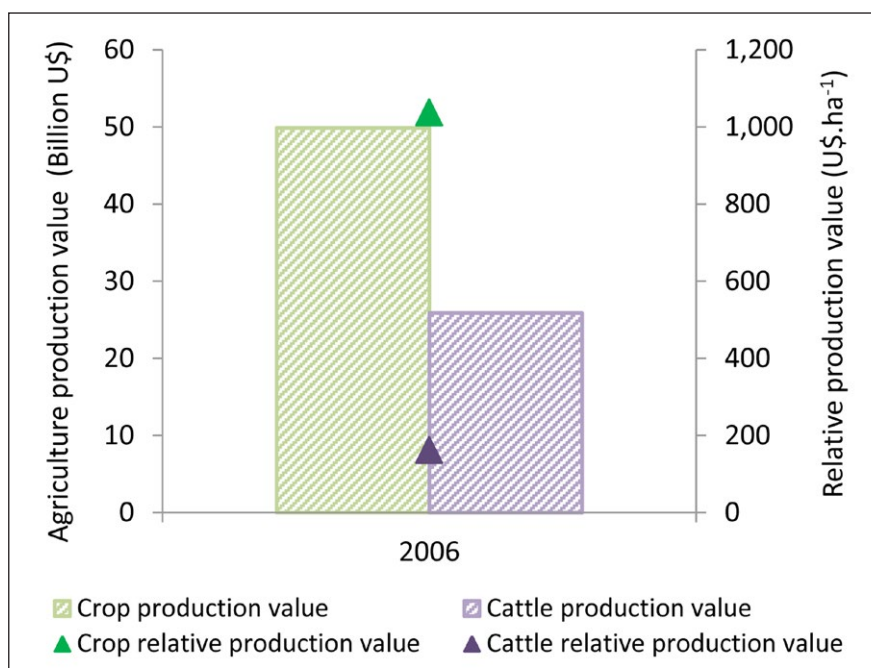


Figure 8: Gross and relative agriculture crop and cattle production values.

Legend: The graph illustrates in bars the value of agricultural production for crops and cattle (in billions of dollars) and also illustrates in points (triangles) the relative value of agricultural production (in dollars per hectare). The graph shows that the production value of crops is twice as high as the production value of cattle and that the relative profitability of crops (dollars per hectares) is about 6 times higher than cattle relative profitability. DOI: <https://doi.org/10.1525/elementa.187.f8>

The utility of crop functional elements

The share of crop functional elements going to feed increased in the period 1975–2006, rising from 37% to 46% for protein and from 16% to 17% for gross energy, while the share going to direct human consumption decreased from 23% to 17% for protein and from 26% to 21% for gross energy (Tables S13 and S14).

Of the total 38 Mton of protein produced in 2006, 17 Mton were used as feed while only 7 Mton were used as food (Tables S10, S11 and S12). The 17 Mton used as feed provided a utility equivalent to 3Mton of protein if destined for the most efficient conversion meat system (feed-meat) that is given by pig and poultry, almost a six-fold reduction of the nutritional potential (Figure 9).

Discussion

Our data confirm that expansion and growth in production and productivity occurred simultaneously in the consolidated and frontier regions from 1975 to 2006. This is in accordance with Buainain et al. (2015) who concluded that, over the last four decades, Brazilian agriculture has grown substantially due to an increase in total cultivated area and also as a result of significant gains in productivity. Our data also agree with Dias et al. (2016) who investigated historical patterns of agricultural land use (1940–2012) and productivity (1990–2012) in Brazil and concluded that, although Brazilian agriculture has been historically known for its expansion taking over areas of natural vegetation, data from recent years indicate that expansion has slowed down and was replaced by a strong trend of intensification. Although expansion of the cultivated area

has not been the main driver of growth of the harvest, it occurred on the scale of 15 million ha from 1975 to 2006 (summing crop and pasture lands – Table S5) and mostly in frontier regions. It occurred with the conversion of natural vegetation (mainly in the Amazon and Cerrado biomes) to pasture and the establishment of extensive and low productivity beef production followed by cropland establishment in the most suitable lands (Nobre et al., 2016, Barretto et al., 2013, Dias et al., 2016).

This is confirmed by pastures occupying 65% of the deforested land of the Amazon (TerraClass, 2016) and around 30% of all pastures in Brazil having low productivity (Ferreira et al., 2014). Our reported trend of decrease of the pasture area from 1985 to 2006 contrasts with the findings of Parente et al. (2017) who mapped the pasture area and observed a systematic increase from 2002 to 2015, which they considered consistent with the land conversion and livestock dynamics observed in the country in recent years, when the cattle herd increased from around 185 million of heads in 2002 to 215 million of heads in 2015. As a consequence, the cattle herd remains the most important source of GHG emissions of the agriculture sector in Brazil (SEEG, 2017). Our findings highlight that, in addition to the large herd and the high amount of GHG released by animals, protein production of cattle had low efficiency when compared to crops regarding GHG emissions, as was also found by previous studies (Carlsson-Kanyama and González, 2009).

The destination of crops for feed for pig and poultry increases the efficiency of animal protein but still results in a lower efficiency rate than offering crops directly as a

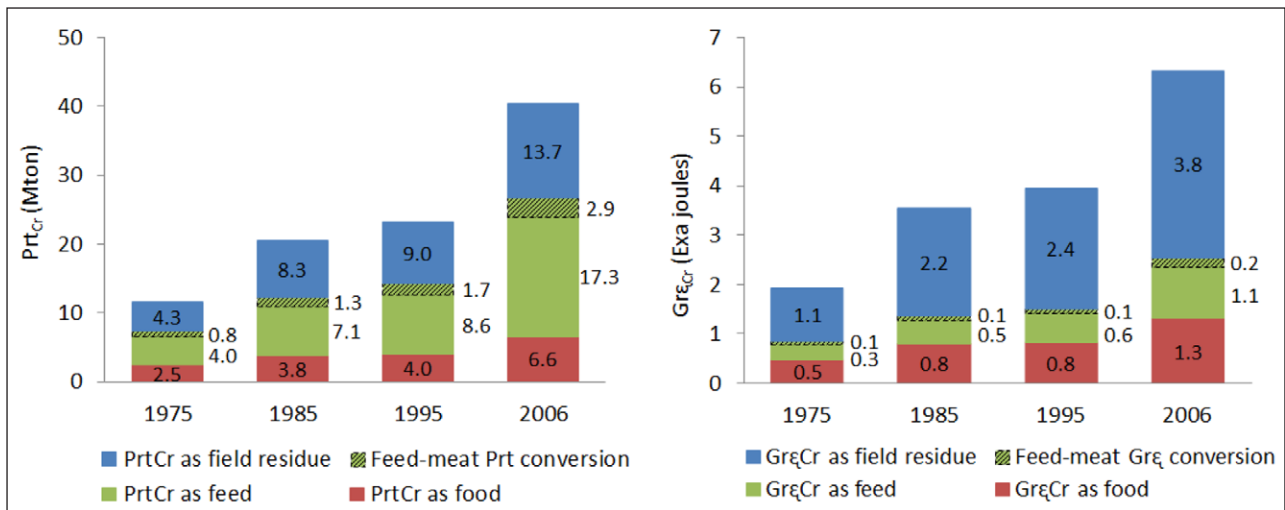


Figure 9: Crops protein and gross energy partitioning into food, feed and field residues.

Legend: The graphs illustrate the allocation of functional elements to food, feed or field residues, and also the amount of functional elements produced after feed to meat conversion. For example, in 2006, from the total crop protein production (37.7 Mton), 6.6 Mton were allocated by the model as food (“PrtCr as food”), 13.7 Mton as field residues (“PrtCr as field residue”), and 17.3 Mton as feed (“PrtCr as feed”). Considering that all feed was consumed equally by pigs and poultry, it would have generated 2.9 Mton of protein from meat (“Feed-meat Prt conversion”). DOI: <https://doi.org/10.1525/elementa.187.f9>

source of protein for humans. Our finding of a six times reduction of the nutritional potential of the crop-feed-meat route against the direct crop-food one confirms the results of Smil (2002) and Reijnders and Soret (2003) about the loss of efficiency when moving from the bottom to the top of the food chain (e.g. from vegetal to meat diets). Although livestock consumes annually one third of global cereal production, 86% of these cereal materials are currently not eaten by humans and soybean cakes represents only 4% of the global livestock feed intake (Mottet et al., 2017). These authors concluded that modest improvements in animal feed use efficiency could reduce further expansion of land for animal feeds. Another comprehensive study made a meta-analysis of life cycle assessments that included 742 agricultural systems and over 90 foods and concluded that grass-fed beef requires more land and emits similar GHG emissions as grain-feed beef (Clark and Tilman, 2017). This meta-analysis also showed that increasing agricultural input efficiency (the amount of food produced per input of fertilizer or feed) would have environmental benefits for both crop and livestock systems; and, that for all environmental indicators and nutritional units examined, plant-based foods have the lowest environmental impacts while ruminant meat had impacts 100 times those of plant-based food (Clark and Tilman, 2017).

Clark and Tilman (2017) added that dietary shifts towards low-impact foods and increases in agricultural input use efficiency would offer larger environmental benefits. Intensification for sustainability outcomes requires increases in production and higher yields but it also demands radical rethinking of food production to achieve major reductions in environmental impact. For example, increases in yield will be compatible with some environmental improvements whereas yield reductions or land reallocation will be needed to deliver other

environmental benefits such as wildlife conservation, carbon storage, flood protection, and recreation (Garnett et al., 2013). Additionally, Loos et al. (2014) highlighted that intensification is likely to fail in improving social dimensions of sustainability, such as food security, if it continues to focus narrowly on food production. It should also address issues such as food accessibility, equitable distribution of food and individual empowerment in the intensification decision process.

Achieving a more efficient and sustainable land use and food system, however, is not a simple task for Brazilian agriculture. First, our findings show a continuous increase in productivity of cattle production, but still with low rates of efficiency while other studies have emphasized the need for shorter-term and sharper increases in the efficiency of the cattle pasture sector overall (Strassburg et al., 2014, Silva et al., 2016). Merry and Soares-Filho (2017) went further by suggesting that intensification of the cattle-beef system in Brazil may not deliver sustainability goals. They argued that cattle ranching will intensify as a result of conservation investments rather than intensifying in order to produce conservation results and that the new intensive system will continue to require large natural resource inputs, government subsidies, and be plagued by social and conservation problems. Moreover, a policy change towards a more intensified production and a consequent gain in productivity and efficiency may result in more profits and more agricultural expansion. And such a rebound effect (also known as Jevon's paradox) is more likely where price elasticity is high, which is exactly the case of agricultural commodities dominant in Brazil such as soy and beef (Waroux et al., 2017).

Waroux et al., 2017 mentioned that the risks of a rebound effect of policies aiming to increase intensification and decrease deforestation depend on a balance of penalties and rewards for intensification. In this regard,

Brazil faces a number of contradictory public and private policy interventions that may act in opposing directions. Thus, Brazil needs an aligned and integrated approach for agricultural intensification to achieve sustainability outcomes. Policies favoring intensification for sustainability outcomes would have actions for the end of deforestation (e.g. designation of public lands for protected areas, implementation of the Forest Code) and more responsible land use and adoption of sustainable practices, such as review of land tax, new indicators of performance of agriculture for credit, payment for environmental services, certification and others (**Table 3**).

Thus, our findings and recent literature suggest that achieving both zero deforestation and more sustainable land use and food systems in Brazil would require a combination of intensification of pasture-cattle systems, optimization of feed-meat systems, an increase in the share of the consumption of crops as a source of protein, and alignment of policies that affect the forestry and agriculture sectors. Achieving these goals will be challenging and we offer an initial road map that should be deeply assessed in future studies:

1. Prioritize crops as the main source of protein for human food. Expansion of crops for food and feed should occur only in the most suitable arable lands occupied by pastures. It should be based on low impact and low carbon agriculture production systems. The stock of land occupied by pastures and suitable for arable crops is uncertain and needs to be further quantified and located in the Brazilian territory.
2. Prioritize meat from pig and poultry feed systems with a low carbon footprint.
3. Cattle should occupy marginal non arable lands al-

ready cleaned and not suitable for crop production. Pasture-cattle systems have a role in land use and food system, but their scale and locations should consider land suitability and other environmental variables (Smil, 2013).

4. Cattle intensification should occur in pasture systems in both non arable marginal lands and those arable lands suitable for crops while they are not needed for crop production. This approach should take in account that intensification in marginal land is limited as some intensification changes require land suitable for mechanization to implement practices such as soil fertilization and certain pasture management improvements described by Strassburg et al. (2014). And intensification of pastures in lands suitable for crops could occur only while the stock of land is sufficient for both crop expansion and pasture. Once crops and pastures compete for land, our findings clearly suggest that land should be prioritized for crop expansion. From this point forward, pasture area in suitable lands for crops should decrease until it disappears. That is, limited pasture-cattle intensification may continue in the long term in lands unsuitable for crops whereas cattle intensification in arable lands would be a transition strategy for food production. Future studies should quantify land stocks and model crop and cattle expansion to predict and provide data for such a transition strategy.

Final remarks

This paper presents evidence of a large difference in the productivity and efficiency of the Brazilian harvest when comparing the crop and cattle sector. This difference indicates a large potential for improvements in land use and

Table 3: Example of policy interventions that could affect outcomes of intensification of agriculture in Brazil. DOI: <https://doi.org/10.1525/elementa.187.t3>

Policies discouraging intensification for sustainability	Policies favoring intensification for sustainability
The reduction of protected areas in the Amazon	Designation of public lands for protected areas
Impunity of land grabbing	Private sector commitments to reduce deforestation (Soy moratorium and cattle agreement)
Reduction of environmental enforcement capacity	Economic incentives of the Forest Code
Low value of land tax (Portuguese acronym ITR)	Review of land tax system – ITR
Rural credit without environmental or social safeguards	Demand from financial sector for commitments against deforestation
Lack of ecological-economic zoning	Payment for environmental services
Indicators of performance of agriculture based in production and productivity (tons and tons/ha)	New indicators of performance of agriculture incorporating environmental and resource efficiency (ex.: tons/emission)
Externalities not incorporated in production costs and price of final products in the value chain	Externalities incorporated in production costs and price of final products in the value chain
Research prioritizing monocropping and simplified production systems heavily dependent on energy	Research on diversified and energy and resource efficient production systems
Commoditization of food systems	ABC (Low carbon agriculture) Plan
WTO (World Trade Organization) policies which do not recognize quality of products and production systems	Certification of sustainable land use and production

other resources already used for production. Our findings provide insights that intensification of crops and pasture-cattle is essential, but is not the only condition required to stop deforestation, as we found that intensification has occurred both in consolidated and frontier regions where high deforestation rates persist, especially in Amazon and Cerrado Biomes. Thus, our results reinforce the evidence of a connection between agricultural expansion and deforestation, although other studies demonstrated that, for specific regions or crops, such a connection is not always the rule (Macedo et al., 2012).

Our analysis did not consider important recent public and private initiatives that have influenced the dynamics of expansion and intensification of Brazilian agriculture since the publication of the last agricultural census in 2006. Examples are the soy and beef moratoriums, the new Forest Code, the ABC Plan (Low Carbon Agriculture Plan of the Ministry of Agriculture), the Brazilian 2015 NDC (Nationally Determined Contribution) of the Paris Agreement, the commitments of the Tropical Forest Alliance for the end of deforestation in commodities value chains, among others. These initiatives aim to encourage the expansion of crops over pastures, restrict the expansion of cattle and accelerate its intensification. Their ultimate goals have been to decrease deforestation and emissions of greenhouse gases. Nevertheless, the intensity of the on-the-ground effects of these initiatives is uncertain due to updated data gaps and more accurate estimates will require future, more specific studies based on an updated set of data of Brazilian agriculture. In this regard, conducting a new Agricultural Census is urgent because updated data about the sector is fundamental to support more accurate modeling, planning and forecasts for Brazilian agriculture, all of which would inform public and private policy on the national scale.

In conclusion, complementary intensification of crops and pastures that supports an efficient production can contribute to the end of deforestation and the provision of environmental services (Godfray et al. 2010) with equity. Such a sustainability transition is a need and an opportunity for the development of Brazilian agriculture. Policy makers, however, should consider a robust strategy that combines penalties and incentives and prevents the risks of a rebound effect.

Supplemental Files

The supplemental files for this article can be found as follows:

- **Figure S1.** Common bean partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S2.** Cottonseed partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S3.** Rice grain partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S4.** Maize grain partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S5.** Soybean seed partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S6.** Wheat grain partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S7.** Cocoa beans partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S8.** Coffee beans partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S9.** Banana bunches partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S10.** Orange fruits partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S11.** Cassava tuber partitioning into products, by-products and harvest residues and their conversions to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S12.** Sugarcane partitioning into products, by-products and harvest residues and their conversions to functional elements. Sugar production stage flows. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S13.** Sugarcane partitioning into products, by-products and harvest residues and their conversions to functional elements. Ethanol production stage flows. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S14.** Animal carcass conversion to functional elements. Offtake rate is defined as the proportion of animals sold or consumed in a year in comparison to animals in stock. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S15.** Eggs and milk conversion to functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Figure S16.** Feed to carcass conversion coefficients. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Text S1.** Assumed values on the partitioning of agricultural crops and livestock production into functional elements. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S1.** Assumed values on partition and allocation of agricultural crops stage flows. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S2.** Assumed values on partition and allocation of livestock stage flows. DOI: <https://doi.org/10.1525/elementa.187.s1>

- **Table S3.** Assumed values on feed to meat conversion. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S4.** Functional elements production from crops. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S5.** Occupied area by agricultural crops and pastures. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S6.** Crops potentially maximum utility for food. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S7.** Pasture production and utility for food. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S8.** Crops production and utility efficiency. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S9.** Pasture production and utility efficiency. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S10.** Protein utility from crops for food, feed and field residues. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S11.** Gross energy utility from crops for food, feed and field residues. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S12.** Metabolizable and non-metabolizable energy utility from crops for food and feed. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S13.** Protein production from crops considering its allocation to food or feed and its content in harvest residues. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Table S14.** Gross energy production from crops considering its allocation to food or feed and its content in harvest residues. DOI: <https://doi.org/10.1525/elementa.187.s1>
- **Excel.** Asymmetries of cattle and crop productivity and efficiency during Brazil's agricultural expansion from 1975 to 2006. DOI: <https://doi.org/10.1525/elementa.187.s2>

Notes

- ¹ A new Agricultural Census was foreseen in 2016 however it was postponed to 2018 due to economic and political constraints.
- ² Temporary crops are both sown and harvested during the same agricultural year, sometimes more than once; whereas permanent crops are sown or planted once and not replanted after each annual harvest (FAO 2011).
- ³ The model splits total milk production into two components, namely the amount of milk produced from pasture grazing and the amount of milk produced from feed. This step attributes all milk production that surpasses $6.L^{-1}.cow^{-1}.day^{-1}$ to feed. The production of milk per cattle head is obtained considering a lactation period of 255 days (NRC, 2001).
- ⁴ This assumption was necessary since there is a range of different uses of crop residues (e.g. fertilizer, animal feed, energy, bedding for poultry etc.) and these flows are not well documented in Brazilian literature.
- ⁵ These by-products are widely used in Brazil to generate heat or energy and their allocation for other uses are minimal.

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: GS, LFGP, VG
- Contributed to acquisition of data: VG, FC
- Contributed to analysis and interpretation of data: VG, GS, LFGP, AB
- Drafted and/or revised the article: GS, LFGP, VG, GB
- Approved the submitted version for publication: GS, VG, GB, LFGP, AB, FC

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