# Analysing intensification, autonomy and efficiencies of livestock production through nitrogen flows: A case study of an emblematic Amazonian territory

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## 1. Introduction

Through its land use, its consumption and its emissions, livestock farming is a major factor in the balance or disruption of bio-geochemical cycles, climate and biodiversity. Livestock occupy more than 70% of agricultural land worldwide (Herrero et al., 2015), consume more than 70% of agricultural production (Billen et al., 2014) and emit 14.5% of all anthropogenic greenhouse gases (Gerber et al., 2013). Our study area, the Brazilian Amazon, is emblematic of these tensions between livestock production and the environment. Extensive cattle production has spearheaded the territorial conquest of this region for more than 50 years, and is the main cause of deforestation (Kaimowitz and Angelsen, 1998). Margulis (2003) reported that prior to 2004, livestock occupied 70% to 88% of deforested areas. Then, between 2004 and 2012, thanks to increased satellite monitoring, strict land tenure policies and strict environmental policies, the rate of deforestation decreased by 80% (4,571 km$^2$ deforested in 2012, versus 27,772 km$^2$ in 2004). Interestingly, from 2012 to 2019, there was a new increase in annual deforestation, which reached 9,762 km$^2$ in 2019 (INPE-Prodes, 2020). The intensification of animal production is presented as a success factor for long-term maintenance of low deforestation and a good level of production (Bowman et al., 2012; De Oliveira Silva et al., 2017; Mandarino et al., 2019). The argument put forward is simple: within the framework of an effective policy to combat deforestation, the increase in production per hectare could constitute a growth driver without territorial expansion. Yet, in reality, there is no guarantee of this outcome, and very few studies focus on quantifying the intensification of the Amazonian livestock sector. Existing publications on intensification concern the scale of livestock farming systems, with analyses of optimized methods based on pasture restoration, rotational grazing, introduction of legumes and so on (De Oliveira Silva et al., 2017; Latawiec et al., 2014; Barreto et al., 2013). On the national or regional scales, most of the studies present statistical models and scenarios based on extrapolations of intensified livestock systems (Abmael et al., 2016; Bowman et al., 2012). Moreover, the notion of intensification, which is polysemic, is neither defined nor precisely monitored. Raising yields on existing farmland is essential for ‘saving land for nature’ (Tilman et al., 2002), but the prospects for yield increases are difficult to predict due to uncertain socio-economic factors. In this context, we aim to add a new case study based on empirical data.

The objective of our article is to characterize and discuss the evolution of livestock farming in Paragominas (Brazil). This municipality, where livestock farming and cultivation of soybeans are prevalent, is presented as an example of stopping deforestation. After several decades with one of the highest rates of Amazon deforestation, Paragominas reduced its annual deforestation rate tenfold between 2005 and 2012 (Piketty et al., 2015). We analyse the livestock sector, using the method of territorial metabolism. This method quantifies the flow of material mobilized, stored and transformed by livestock. We calculate the trends in intensity, production, efficiency and self-sufficiency from 1990 to 2012.

## 2. Material and methods

### 2.1 The municipality of Paragominas

Paragominas is situated in the north-eastern region of the state of Pará, 320 km to the south of Belém (Figure 1). The development of this 1.94 million hectare municipal area is based on agriculture, which accounts for 10% of GDP (IBGE-Sidra, 2016).

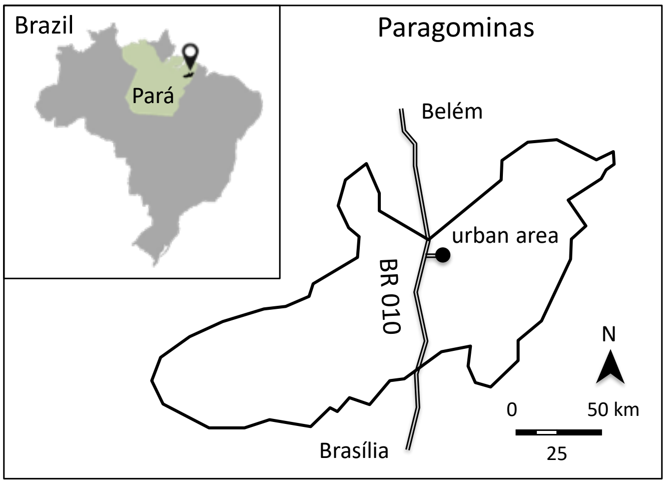


**Figure 1.** Map of Paragominas (Pará, Brazil)

Two phases of development can be distinguished (supplementary material section 1- Land use and annual deforestation): the first, from 1950 to 2005, was characterized by a continuous expansion of the agricultural area leading to significant deforestation. Between 2001 and 2005, the average deforestation rate was estimated at more than 18,000 ha/year (Piketty et al., 2015). Livestock farming is the main activity; pastures occupy more than 80% of deforested areas (Pinto et al., 2009). The second phase, from 2006 to date, was marked by a sharp decline in deforestation, a decrease in grazing areas and a significant increase in annual crops. Laurent (2014) calculated a 13% decrease in grazing areas between 2006 and 2012. To analyse the evolution of livestock farming, we chose to study two years representative of the first phase of development (1990 and 1995) and two years in the second phase of development (2006 and 2012). These years were chosen based on data availability.

## 2.2 A biochemical representation of livestock farming

We analysed the functioning of livestock systems from the perspective of nutrient cycles, by quantifying material flows between fodder resources (cropland and grassland), livestock, and the natural environment. This allowed us to discuss different productive and environmental indicators (Bonaudo et al., 2015; Gameiro et al., 2019). We used the GRAFS methodology (Generic Representation of Agro-Food Systems) to produce a biochemical representation of our system (Billen et al., 2014, 2015; Lassaletta et al., 2014). The first step consisted in making an inventory of all material flows and all areas used, either directly or indirectly, by livestock farming. We considered three categories: i) livestock (pigs, poultry, laying hens, dairy cows and beef cattle), of which we estimated the animal numbers, feed intake, production (milk, meat, eggs) and excretion; ii) croplands and iii) grasslands dedicated to feeding animals, of which we estimated the surface areas, fertilization and production. A review of the scientific and technical literature was carried out to identify and prioritize the use of existing local and regional references. We also used a group of experts (three technicians and agronomists, and three researchers) to confirm farming practices in the region.

In the second step, we converted all of these material flows into N flows by calculating the N contained in each material. N flows are expressed on an annual basis in weight units (kilograms or tons). We describe the data and assumptions used to establish livestock metabolism in the next paragraphs.

Livestock numbers, production and excretion

In the IBGE-PPM (Municipal Livestock Survey) database, livestock is expressed in heads. For comparison purposes, we converted heads into Livestock Units (LU). We use the same livestock unit (LU), characterized by Billen et al. (2014) (the number of animals of any species annually excreting 85 kg N).

The objective was to estimate the quantity of products marketed for human consumption. The quantities of milk and eggs are directly accessible in the IBGE-PPM (Municipal Livestock Survey) database, but there are no figures on meat production. To obtain the quantity of pork, poultry meat and beef, we multiplied the number of heads slaughtered by the average carcass weight. For pork, we applied the slaughter rate given by Miele and Soares Machado (2007) (Table 1). The slaughter rate corresponds to the number of animals slaughtered per year divided by the total number of animals present in herds. For poultry and cattle, we applied the slaughter rate and carcass weight calculated from the IBGE-PPM database, but these data were only available from 1997 and for the state of Pará. We therefore assumed that herds in Paragominas have the same slaughter rate and carcass weight as those in Pará State. We applied the 1997 slaughter rate and carcass weight for the years 1990 and 1995 (Table 1). For cattle production, we must also estimate the numbers of live animals exported. Live exports correspond to international trade. Exportation began in the 2000s and has experienced very strong inter-annual variability due to market uncertainty. The only data available were the average weight and the number of animals exported by Pará State. We therefore calculated live cattle export rates for 2006 and 2012, which we applied to the Paragominas cattle herd (Table 1). We considered only the edible output, and the inedible wastes or by-products were considered as losses leaving the food system (skin, blood, hides, heads, feet, tails, entrails and gut fill).

The production of animal protein was calculated from the production figures of carcasses, eggs and milk, using the N content of each commodity as provided in Lassaletta et al. (2014) and FAO (2001) (Table1).

**Table 1.** Coefficients used to calculate animal production

| Products | Average weight | Slaughter rate or live cattle export rate | %N in product |
|---|---|---|---|
| Eggs | | | |
| 1990-2012 | 60 g/egg | - | 1.712%**** |
| Milk | | | |
| 1990-2012 | 1 kg/liter | - | 0.528%**** |
| Cattle Slaughtered | | | |
| 1990-1995 | 210.8 kg carcass/head* | 7.4%* | |
| 2006 | 229.4 kg carcass/head* | 12.7%* | 3.08%**** |
| 2012 | 240.7 kg carcass/head* | 11.7%* | |
| Cattle Exported | | | |
| 1990-1995 | - | 0%** | |
| 2006 | 255.8 kg carcass/head** | 0.76%** | 3.08%**** |
| 2012 | 256.6 kg carcass/head** | 2.32%** | |
| Pigs | | | |
| 1990-1995 | 47.4 kg carcass/head* | 71%*** | |
| 2006 | 44.7 kg carcass/head* | 71%*** | 1.872%**** |
| 2012 | 40.5 kg carcass/head* | 71%*** | |
| Poultry | | | |
| 1990-1995 | 2.16 kg carcass/head* | 102%* | |
| 2006 | 2.35 kg carcass/head* | 257%* | 1.968%**** |
| 2012 | 2.53 kg carcass/head* | 418%* | |

Sources: *IBGE-PPM, 2016; **ABEG, 2015; ***Miele and Soares Machado, 2007; ****Lassaletta et al., 2014; FAO, 2001

Excretion was calculated from livestock numbers using N excretion factors specific to each animal category (see Table 2). We followed the Van der Hoek (1998) excretion factors for Latin America. We distinguished dairy from non-dairy cattle. To estimate the numbers of non-dairy cattle, we subtracted the milking cow stocks provided by the IBGE PPM from the total cattle stock.

**Table 2.** N excretion factors for different livestock classes and corresponding livestock units (defined as the number of animals excreting 85 kg N/yr)

| | Excretion kg N/head/year (Van der Hoek, 1998)* | Conversion rate from head to LU (Billen et al., 2014; Lassaletta et al., 2016)** |
|---|---|---|
| Dairy cattle | 60 | 0.705 |
| Non-dairy cattle | 40 | 0.47 |
| Pigs | 11 | 0.13 |
| Poultry | 0,5 | 0.006 |

Sources: *Van der Hoek (1998) for "Region II" Latin America. Oceania outside Australia and NZ, Africa and Asia except for the former USSR. **Billen et al. (2014), Lassaletta et al. (2016) consider annual excretion per LU, i.e. 85 kg N/LU/year.

Cropping and fodder systems

In line with many studies, animal consumption was estimated by adding together the excreted N and the N fixed in products (Billen et al., 2014, 2015). For cattle, we considered that grazing provides the whole diet (Oliveira Miranda, 2016). For monogastric animals, we considered that rations are composed of corn and soybeans (Gameiro et al., 2019). Crop production was converted from kilograms of fresh matter to kilograms of N, based on the coefficients of fixed N in products (Lassaletta et al., 2014 and FAO, 2001) (Table 3).

As figures for grazing areas were not available in the IBGE database for the entire study period, we estimated them from a compilation of satellite image studies of the municipal area. These studies consist of Landsat image analyses for 1991, 2008 and 2010 (Oliveira and De Ferreira, 2011; Piketty et al., 2015; Coutinho et al., 2013). We estimated the grazing area in 1990, 1995 and 2006 through linear regression applied to existing data. For the 2009-2012 period, Laurent (2014) showed a 13% decrease in grazing area. Therefore, we applied this decrease to obtain the grazing area in 2012.

To calculate the areas of maize and soybeans, the total production was divided by the average production per hectare. We applied the average yield for each year, provided by the IBGE-PAM (Municipal Agricultural Production). For maize, we considered the yields of the municipal area. For soybeans, we took the national average yield for 1990 and 1995 and the municipal yields for 2006 and 2012.

Crop and grassland fertilization

Fertilization refers to all inputs of N to cropland and grassland, including synthetic fertilizers, atmospheric deposition, manure application and symbiotic $N_2$ fixation. Symbiotic $N_2$ fixation varies, depending on pedoclimatic conditions, the varieties farmed and cultural practices. Filoso et al. (2006) report that the symbiotic fixation of grazing areas, predominantly under Brachiaria, is between 15 and 30 kg N/ha/year in Brazil. Due to a large proportion of degraded pastures (Pinto et al., 2009) that fixate little or no N, we retain the lower estimate of 15 kg N/ha/year. Soy symbiotic $N_2$ fixation is estimated according to the relationships developed by Herridge et al. (2008) and Lassaletta et al. (2014), linking N fixation to yields. Soy symbiotically fixates the equivalent of 1.53% of the yield.

Dentener et al. (2006) estimate the atmospheric deposit for the region at 8 kg N/ha/year.

As statistical data do not exist for fertilizers, we estimate fertilizer use by reconstructing the technical practices in the region according to the group of experts. We assume that chemical fertilizers are not applied to grazing areas (Corrêa et al., 2005) and that cattle excreta are deposited on pasture. We apply loss rates based on volatilization of ammonia ($NH_3$) during grazing. Volatilization of $NH_3$ emission varies widely, depending on agricultural practices, soil type, climate and measurement methods. For cattle grazing systems, N losses by $NH_3$ generally range from 10% to 30% of excreted N (Béline et al., 2012; Lessa et al., 2014). For the Cerrado region (Goiás state), Lessa et al. (2014) estimate nitrogen volatilization at 15% of excreted nitrogen. Our study is based on the study of Lessa et al. (2014), which was carried out in a pedoclimatic context similar to that of our study area (Table 2). We assume that $N_2O$ emissions are very low for grazing cattle (Lessa et al., 2014), so we do not consider them.

Only synthetic fertilizers were applied to the feed crops, maize and soybeans (Table 3). According to the experts, a very small proportion of animal excreta was recovered and was used mainly for perennial crops. We estimated that banana, pepper and cocoa were fertilized with organic nitrogen at 700 kg N/ha/yr, 120 kg N/ha/yr and 20 kg N/ha/yr, respectively. The amount of excretion recovered was estimated by multiplying the amount of organic nitrogen applied per hectare by the total surface area under crops (banana, pepper and cocoa areas were provided by the IBGE-PAM database).

**Table 3.** Yield, synthetic fertilization and symbiotic $N_2$ fixation of soybean, maize and rice

| | Soybean | Maize | Rice |
|---|---|---|---|
| %N in product* | | | |
| 1990-1995-2006-2012 | 6.08% | 1.52% | 1.6% |
| Yield (kg/ha)** | | | |
| 1990 | 1,732 | 500 | 700 |
| 1995 | 2,199 | 840 | 1,050 |
| 2006 | 3,000 | 4,650 | 2,672 |
| 2012 | 3,500 | 5,500 | 3,316 |
| Synthetic fertilization (kg N/ha/year)*** | | | |
| 1990-1995 | 20 | 55 | - |
| 2006 | 20 | 175 | - |
| 2012 | 20 | 110 | - |
| Symbiotic $N_2$ fixation (% of the yield)**** | | | |
| 1990-1995-2006-2012 | 1.53% | - | - |

Sources: *Lassaletta et al., 2014; FAO, 2001; ** IBGE-PAM database, yield in FM; ***Experts group, **** Herridge et al. (2008) and Lassaletta et al. (2014)

## 2.3 Methods for calculating indicators

In order to characterize animal production and its changes, we define the following indicators:

- Animal production per ha used for livestock farming (kg N/ha/year) and animal production per livestock unit (kg N/LU/year);
- Livestock N Conversion Efficiency (NCE), defined as the percentage of ingested N that is exported in products. Animal products are calculated from the production figures of meat, eggs and milk (Billen et al., 2014; Lassaletta et al., 2014);
- Total N input per hectare (kg N/ha/year), consisting of synthetic and organic fertilizers, symbiotic fixation and atmospheric deposition;
- N Self-Sufficiency (NSS) or Autonomy in terms of inputs, defined as a %: $\frac{(\sum \text{inputs} - (\text{synthetic inputs} + \text{feed import})) * 100}{\sum \text{inputs}}$;

- N Surplus (NS) is defined as the difference between N inputs (fertilizers, symbiotic fixation, atmospheric deposition) and N outputs (crop harvesting and pasture consumed, volatilization) (kg N/ha/year). The N surplus is a proxy for losses from the soil to the environment, as N leaching. A part of the N surplus can also be stored in the SOM pool (Billen et al., 2014).

### 2.4 Sensitivity analysis of livestock N conversion efficiency

In modeling real systems, there is always uncertainty regarding the parameter values used. It is important to analyse how the solution derived from the model would change if the values assigned to the parameters were changed to other plausible values (Hillier and Lieberman, 2005).

Sensitivity analysis attempts to identify which parameters are the most critical in determining the results of the problem. In the context of this paper, we propose that the key parameters are those related to beef cattle production (carcass weight, slaughter rate and herd), because it is the most important in terms of livestock, land use and animal production. Thus, we elaborated an analysis of the sensitivity of animal production and of the NCE to variations on these three parameters. We varied these parameters, independently and jointly, then we compared the results to the reference simulation for the year 2012 (Table 5). For the first simulation (S1), we increased the carcass weight of beef cattle slaughtered and exported by 10%. For the second simulation (S2), we increased the slaughter rate of the beef cattle and the export rate of live animals by 10%. Simulation three (S3) estimated the impact of a 10% increase in the beef cattle herd. Increasing the beef cattle herd on the same pasture area is equivalent to increasing the stocking rate. For the fourth simulation (S4), we combined the S1 and S2 (10% increase in carcass weight, slaughter rate and export rate). Simulation five (S5) combined the S1, S2 and S3 (10% increase in the three parameters). Finally, for simulation six (S6), our objective was to simulate an increase in the beef cattle herd to reach the maximum bovine density already reached in the municipality. This rate was 0.88 LU of cattle/ha in 1990 (305,265 cattle LU for 345,000 ha of pasture). Following the same logic as the previous simulations, we simulated changes only for the beef cattle herd. The dairy herd therefore remained the same as in 2012 (17,209 LU) and we increased the herd of beef cattle up to 275,668 LU to reach a total bovine herd of 292,877 LU for 331,000 ha of pasture in

2012 (corresponding to an average bovine density of 0.88 LU/ha). This corresponds to an increase in the beef cattle herd of 98%.

## 3. Results and discussion

### 3.1 Evolution of livestock farming

The calculation of LU shows that livestock in Paragominas is composed on average of more than 98% ruminants. Monogastric animals, bred mainly by small-scale farmers for their own consumption or local markets, account for only 1.7% to 0.6% of total LU (Figures 2 and 3). Suckler herds, bred mainly by large landowners for regional and international markets, accounted for 84% of ruminant LU in 1990 and 89% in 2012, which shows a specialization in beef production. Cattle, due to their large numbers and land use, are one of the main drivers of agricultural changes in the municipal area. All arable crops represent between 5% and 20% of the pasture area and rice, corn and soybean crops are dominant (supplementary material Figure 1 Evolution of pasture, crop and deforestation areas from 1990 to 2012).

From 1990 to 2012, monogastric livestock experienced a 48% decrease in terms of LU (Figure 2). This significant decline is due to a rural exodus, from 1995 onwards, of small-scale farmers looking for a stable job in town (Piketty et al., 2015). The area dedicated to feeding monogastric animals has decreased significantly (from 28,500 ha in 1990 to 850 ha in 2012), due to the sharp decline in livestock and the steep increase in crop yields (supplementary material section 2 - Evolution of production and crop yields from 1990 to 2012).

Regarding cattle herds, we distinguish three phases. From 1990 to 1995, there was a sharp decrease in livestock units (LU) and an increase in pastures. The decline in LU corresponds to a decapitalization of livestock to invest in the forestry industry. After logging, the forest areas are quickly cleared, and pastures are planted. Without land regulation, farmers take ownership of land, at low cost, by planting pastures. During this phase, there was a significant decline in cultivated areas (from 4,000 to 2,700 ha for rice and from 4,000 to 3,200 ha for corn). However, higher yields have allowed the maintenance of rice production (45 t N) and an increase in corn production (30.4 to 40.8 t N). The second phase between 1995 and 2006 was marked by stabilization of the livestock population and an increase in pasture areas to occupy deforested lands.

The forestry industry reached its peak at the end of the 1990s, before experiencing a sharp decline in the early 2000s. Livestock farming was once again seen as a safe investment, with a profitable market. This phase was also marked by the introduction of soybeans in 1997 and the rapid expansion of areas and crop yields. Rice areas reached 11,000 ha, those of corn 16,000 ha and those of soybeans increased from a few hundred ha to more than 10,000 ha in 2006. Production increased even more with 470 t N of rice, 1,130 t N of corn and 1,824 t N of soybeans (supplementary material Figure 2 - Evolution of production and crop yields from 1990 to 2012). The last phase, from 2006 to 2012, was characterized by a renewed decrease in the livestock population, this time accompanied by a decrease in grazing areas and rice areas (5,500 ha). Rice production decreased to 291 t N. In fact, rice is a so-called "opening" crop, planted just after the land is cleared (Piketty et al., 2015). After 2-3 years of rice cultivation, corn and soybeans are planted. In contrast, there is a tripling of soybean cultivation area (35,000 ha) and a quadrupling of production (7,523 t N). Maize, in rotation with soybeans one year in three, saw its areas and production increase in a more limited way (22,000 ha and 1,845 t N). This phase was marked by strict public policies restricting deforestation. Without the possibility of extension, for the first time there was land competition, between pasture and other crops like soybeans and maize. The corn/soybean rotation is established on the best former rice or pasture plots, that is to say on large fertile, mechanizable plots close to roads (Piketty et al., 2015).

We noticed an uncoupling of the dynamics of livestock and pasture areas (Figure 2). The growth of grazing areas is not parallel to the size of the herd; these dynamics can be explained in terms of land expansion and land grabbing. Indeed, a plot of pastureland allows the development of land capital and generates income. Finally, after a few years, this plot can be planted with crops.

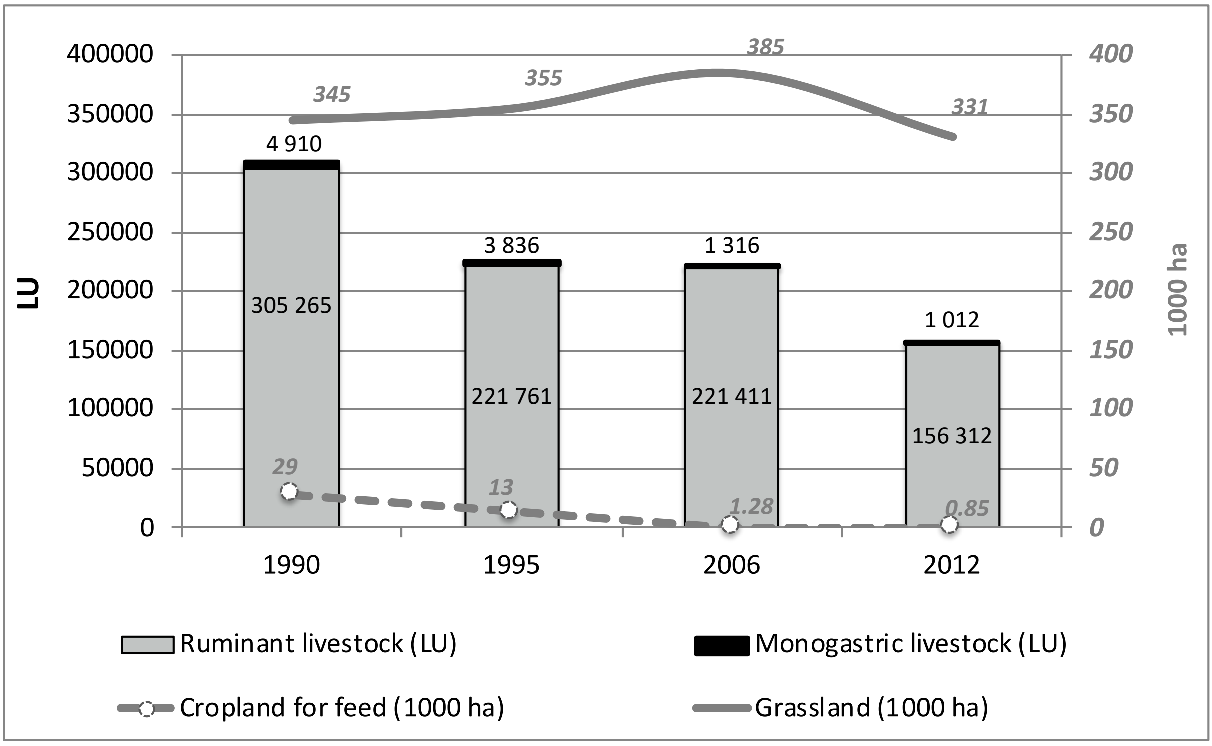


**Figure 2.** Evolution of livestock and fodder area from 1990 to 2012

The grey vertical bars represent the number of ruminants and the black bars the monogastrics. The diagram shows a sharp decrease in the herd. The solid line represents the area under pasture, which increased from 1990 to 2006 and then decreased. Finally, the dotted line represents the area under cropland for feed, which decreased over the entire study period.

The average livestock density decreased by 43% during the study period, from 0.83 LU/ha in 1990 to 0.61 LU/ha in 1995, 0.58 LU/ha in 2006 and 0.47 LU/ha in 2012. This is an apparent density based on the entire forage area. In fact, densities are heterogeneous because many grazing areas are degraded or under-used. This average density does, nevertheless, reflect the extensive use of land, due either to pasture mismanagement or to the main purpose of grazing, namely land occupation at a reduced cost.

The analysis of animal production confirms the importance of cattle, which account for over 95% of production (Figure 3). Animal production data confirm the decrease in livestock farming, with a 12% reduction in production over the period between 1990 and 2012 (Figures 3 and 4). There are, however, significant intra-period variations. Production decreased from 1990 to 1995 due to the decline in herd sizes. From 1995 to 2006, despite a stable herd, we note a significant increase in production from 356 to 572 t N, due to beef cattle production (increasing from 215 t N to 435 t N). This indicates a change in cattle ranching systems, with animals being slaughtered heavier and at a younger age. The average carcass weight increased from 210 kg to 229 kg, and the slaughter rate increased from 7.4% to 12.7%. We must add to this the live animals exported, estimated at 2,400 LU (equivalent to 27 t N or 4.7% of production). The period between 2006 and 2012 once again experienced a decrease in production (21%) due to a sharp decline in the livestock population (30%), a 1% decline in the slaughter rate (11.7%), and a slight increase in carcass weight (5%). The only production that increased was the live animals exported, with 5,200 LU (equivalent to 59 t N or 13% of production).

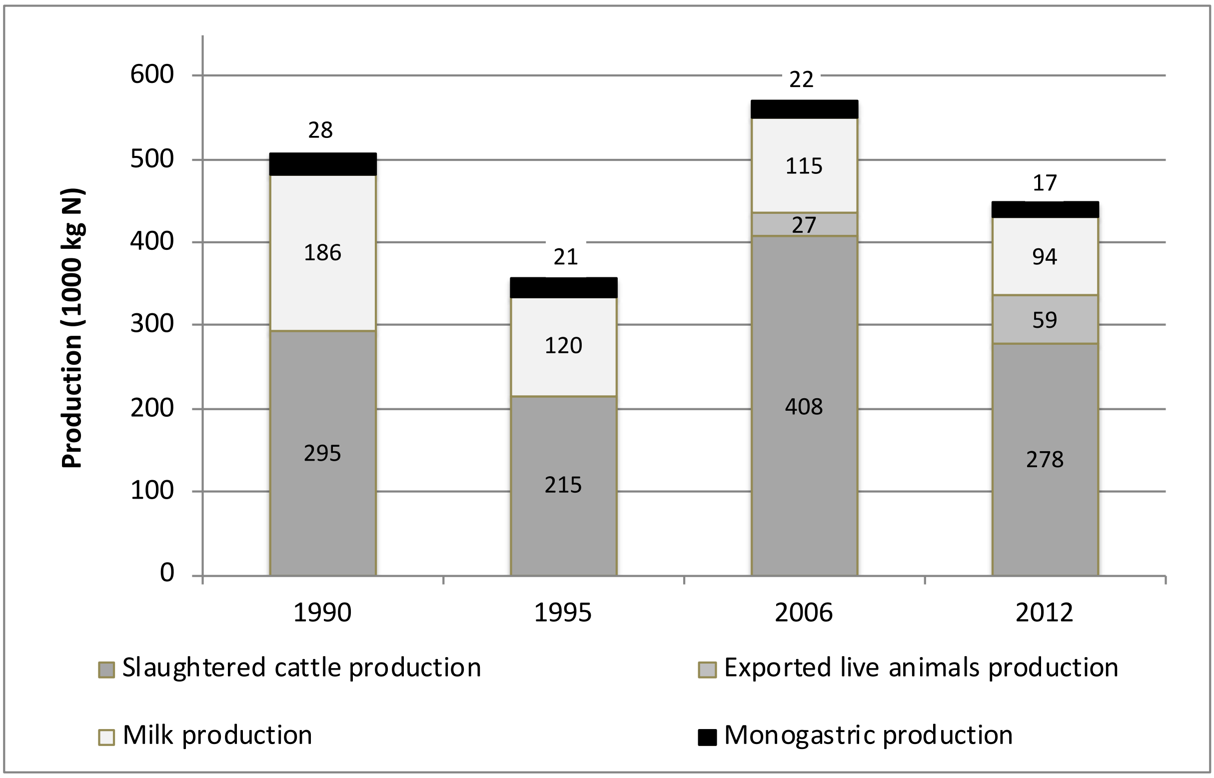


**Figure 3.** Evolution of animal production from 1990 to 2012

Cattle production is shown in grey (meat and milk production) and monogastric production in black (chicken and pork meat and eggs). Monogastric production is very low. Beef production is dominant and variable.

Our N flow diagram (Figure 4) shows a high degree of circularity in N flows. In fact, the livestock diet is based on grazing (98% of total N consumed in 1990 and 99% in 2012), and excretion is the main source of N in grazing areas. Excretion accounted for over 76% of the total N input in these areas in 1990 and 63% in 2012. This decrease is explained by the reduction of LU and, therefore, in excretion. Because of this, other sources of N, such as atmospheric deposits and symbiotic fixation, increase proportionally. Flows are marked by low N inputs. A very small proportion of excretion is recovered to fertilize other crops, and a very small proportion of crops are used to feed the animals. Livestock systems and arable cropping systems are thus largely disconnected.

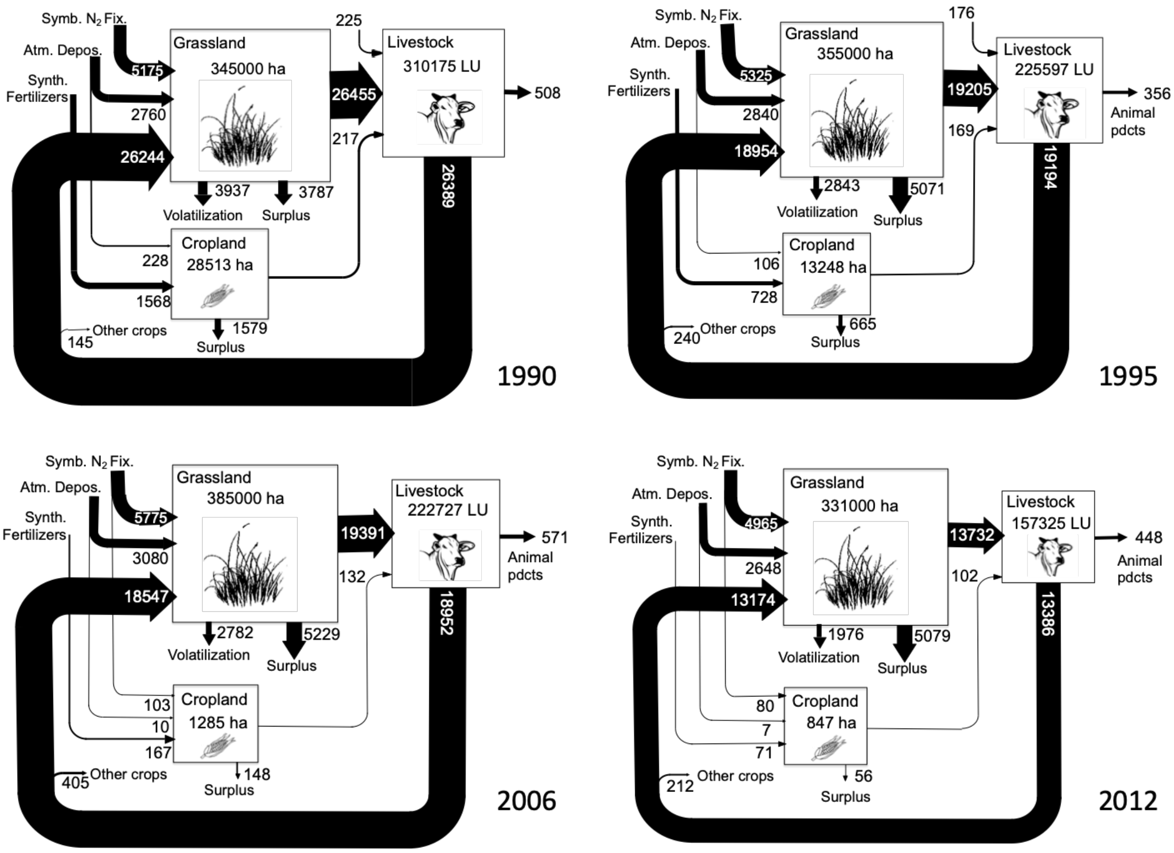


**Figure 4.** Diagram of N flows for livestock farming in Paragominas for the years 1990, 1995, 2006 and 2012 (1,000 kg N/year)

3.2 Livestock farming indicators: production, efficiency and self-sufficiency

Compared with national and regional production (Gameiro et al., 2019; Billen et al., 2014), animal production per hectare in Paragominas is low (between 0.97 kg N/ha/year in 1995 and 1.48 kg N/ha/year in 2006) (Table 4). This is explained by a low level of production per LU and livestock density. There was a sharp decrease in production per hectare in 1995, due to decapitalization of livestock, low production per LU and a considerable expansion of grazing areas. If we look at production per LU over the study period, it is low but increased sharply from 1.64 to 2.85 kg N/LU/year. The forage system remained very extensive. Only a few producers have intensified it by establishing dynamic rotating pasture or plots of elephant grass, fodder sugar cane or corn to make silage for distribution to animals for 1 to 3 months during the dry season. At the same time, cropping systems have intensified considerably with the development of the corn-soybean rotation. Average crop yields increased markedly from 1990 to 2012 (9 kg N/ha, 15 kg N/ha, 93 kg N/ha and 154 kg N/ha). The efficiency of animal production (NCE) is low; nevertheless, it increased over the study period (+71%, Table 4). Improvement in NCE and production per LU is due to increased carcass weights, the livestock exploitation rates (number of animals slaughtered and exported) and, for the last phase, a higher proportion of dairy cows in livestock (9.6% to 11%). Since dairy cows have a higher NCE than beef cattle, this results in an increase in the average NCE of cattle. The beef cattle herd is decreasing, but the animals are more productive.

The total N input per hectare decreased regularly over the study period (34%, Table 4), in particular due to the decrease in the livestock density and therefore in the amount of excrement (Figure 4). Feed imports are low and concern only soybeans for monogastrics for 1990 and 1995. Synthetic N input levels are low, as these inputs are used only for crops other than grass, and in small quantities. This has enabled the livestock farming system to achieve a large degree of self-sufficiency, exceeding 95% and increasing by +5% (Table 4).

The surplus per hectare of grassland is very low and relatively stable (Table 4). Permanent grasslands are generally associated with low nitrate leaching, especially if they are farmed extensively (Béline et al., 2012; Lessa et al., 2014). Below a threshold of about 100 kg N/ha/year, N surplus in grasslands does not result in high leaching (Watson and Foy, 2001). The fertilization rate is between 40 and 76 kg N/ha. This average surplus does not result in structural pollution problems; it may, nevertheless, hide one-time and/or localized surpluses that may be significant.

The indicators generally used to characterize the intensity of farming systems are divergent: indicators expressed per unit area do not show intensification but rather extensification, with a decrease in animal density, inputs per ha and a stabilization of production per ha. However, production per animal unit and livestock efficiency (NCE) increase across the study period (Table 4).

**Table 4.** Evolution of production, N inputs, efficiency of N use and surpluses of livestock farming

| | Year | | | | Evolution |
|---|---|---|---|---|---|
| | 1990 | 1995 | 2006 | 2012 | 1990-2012 |
| Animal production per ha (kg N/ha/year) | 1.36 | 0.97 | 1.48 | 1.35 | -1% |
| Animal production per LU (kg N/LU/year) | 1.64 | 1.58 | 2.57 | 2.85 | +74% |
| Total N input (kg N/ha/year) | 96 | 76 | 72 | 63 | -34% |
| N Self-Sufficiency (NSS) (%) | 95% | 96.8% | 99.4% | 99.7% | +5% |
| Livestock N Conversion Efficiency (NCE) (%) | 1.89 % | 1.82% | 2.93% | 3.24% | +71% |
| N surplus (NS) (kg N/ha/year) | 14 | 16 | 14 | 15 | +8% |

### 3.3 Sensitivity to selected beef cattle production parameters

The S1 and S2 simulations led to a 7% increase in animal production and a 6.8% improvement of the NCE compared with the 2012 reference simulation. The increase in animal production is lower than 10%, because milk production is not affected by these parameters. Simulation three (S3) resulted in a 6.9% increase in production and a -1.7% decrease in the NCE. The decline in NCE is explained by the relative increase in beef cattle in the total herd. Since beef cattle have a lower efficiency than dairy cows and monogastrics, the efficiency of the total herd is slightly lower. The fourth simulation (S4) resulted in a 14.8% increase in production and a 14.3% increase in NCE. Simulation five resulted in a 23.2% increase in production and a 12.7% increase in the NCE. The simulation six (S6) increased production by 68% and decreased the NCE (-9.7%). This situation corresponds to the cattle stocking rate of 1990, with an average feed intake of 73 kg N/ha/year. This is an achievable yield for a well-managed pasture, without a major change in the production system. This increase, although significant, seems achievable in the short to medium term.

These simulations show a significant weight of these parameters in the calculation of production and NCE. Simulations S1, S2 and S3 show that the parameters have a comparable effect on production. Simulations S4 and S5 show that they have an additive effect on production. However, these parameters do not have the same effect on the NCE. While increased carcass weight and slaughter rate improve NCE, the increased beef cattle herd reduce NCE.

**Table 5.** Analysis of the sensitivity of animal production and of NCE to variations in three key parameters (% changes over 2012-year values)

| | PARAMETERS | | | RESULTS | |
|---|---|---|---|---|---|
| | Carcass weight of beef cattle slaughtered and exported | Slaughter rate of beef cattle and the export rate of live animals | Beef cattle herd | Animal Production | Livestock N Conversion Efficiency (NCE) |
| **S1** | +10 | - | - | +7 | +6.8 |
| **S2** | - | +10 | - | +7 | +6.8 |
| **S3** | - | - | +10 | +6.9 | -1.7 |
| **S4** | +10 | +10 | - | +14.8 | +14.3 |
| **S5** | +10 | +10 | +10 | +23.2 | +12.7 |
| **S6** | - | - | +98 | +68 | -9.7 |

3.4 General discussion

The estimates of N flows allow us to carry out a multi-indicator study of livestock farming. This method, however, requires the availability of statistical data and expertise in livestock farming systems. Biases may apply to the estimate of N flows. It is therefore important to specify and discuss calculation assumptions and the results obtained. In this regard, we note that our livestock farming production and efficiency estimates are probably slightly underestimated. We use carcass weights, the slaughter rate and the proportion of live animal sales from the state of Pará, whereas Paragominas is probably a little more productive than the average for Pará. Due to the lack of accessible data, trading of live animals between municipal areas was not considered. For our study, calculation assumptions and results have been discussed and confirmed by a group of experts. Moreover, our results are consistent with existing publications.

For South America, Billen et al. (2014) calculate an animal production of 2.7 kg N/ha/year and a livestock efficiency of 6.3%. For Brazil over the period 1994-2013, Gameiro et al. (2019) estimate an efficiency of beef cattle production of 5.2%. These results, which are significantly higher than ours, can be explained by a larger proportion of intensive animal production at the regional and national levels. The agribusiness sector, mainly the monogastric and dairy industries, is highly concentrated in the south and southeast of Brazil. Gameiro et al. (2019) estimate livestock efficiency at between 25.7% for pigs and 52.6% for poultry. Even the beef sector, with the best pasture management and the use of concentrates, is more productive in these areas (Cederberg et al., 2011; De Zen et al., 2018; Gameiro et al., 2019). Our study area is known for its specialization in extensive cattle production, with low technology and low performance. Bovine production per hectare is very low in Amazonia and, despite significant variability of the results, there is an improvement in production at the animal level. Cederberg et al. (2011) estimate Amazonian production at 0.74 kg N/ha/year for 1996-97 and 1.29 kg N/ha/year for 2006 (respectively 24 and 42 kg carcass/ha/year). These estimates are equivalent to those estimated for Paragominas with 0.61 kg N/ha/year in 1995 and 1.13 kg N/ha/year in 2006.
We distinguish three periods of change in livestock farming in this municipal area. The first period, from 1990 to 1995, combined low-cost territorial expansion through the establishment of grazing areas, with the decapitalization of livestock to the benefit of the forestry industry. The second period, from 1995 to 2006, combined territorial expansion with investments to improve the production of livestock and to benefit from a buoyant cattle market. Lastly, the third period, from 2006 to 2012, corresponded to a cessation of territorial expansion and a marked increase in grain crops. This resulted in a decline in livestock numbers and grazing areas, as the best plots of land were devoted to crops. This evolution reaffirms the multiple functions of livestock farming and its flexibility when faced with shifting economic and political contexts. We also note that the establishment of grazing areas is not correlated with the size of herds or animal production. This increases the benefit of using multiple types of indicators, expressed in terms of area as well as livestock units.

Due to the decrease in the number of head of cattle, we do not observe an intensification on the scale of the municipality (there is a decrease in animal density, animal production and N inputs per unit of area indicated). However, on the animal or herd scale, we highlight an intensification (animal production per LU, the slaughter rate and the efficiency of N use increase). The crop system has, at the same time, greatly intensified and extended. This has led to a decline in pasture area (Piketty et al., 2015). We found no evidence of a link between the increase in animal production and efficiency and the decrease in deforestation or greater competition for land use. The increased oversight of land use, along with repressive policies, enabled the cessation of deforestation, but this did not result in a massive intensification of livestock farming for the moment. It would be useful to work in detail on the determinants of the crop intensification and its links with deforestation.

Locally, we find the emergence of intensified practices, with feedlot projects, combined agriculture-livestock farming systems, a pig farm with more than 1,500 sows and three dairy plant projects (3,000 L/day) combining specialized producers. These projects are, however, still too small to result in changes to livestock farming and the flows associated with it at the municipal level. There are, nevertheless, wide margins of progress when increasing the use of pastures, the number of animals and their production (S6).

In conditions similar to those of Paragominas, studies have estimated that a well-managed pasture can allow feed intake between 70 and 120 kg N/ha/year. This calculation is obtained using a fodder production of 15 t DM/ha/year (Embrapa, 2002), a mean protein level of 0.016 kg N/kg DM (Corrêa et al., 2005) and a feed intake of 30-50% of the dry material produced. For the most productive areas of the Amazon, Arima et al. (2005) estimate animal production between 1.73 and 2.45 kg N/ha/year (56-80 kg carcasses/ha/year). For the states of Para, Acre, Bahia, Maranhão and Tocantins, De Zen et al. (2018) calculate an average animal production of 2.19 kg N/ha/year for the period from 2007 to 2012. Mandarino et al. (2019) estimate the production of low-tech farms in northern Mato Grosso at 3.1 kg N/ha/year for the year 2014. These differences show that there are still growth margins. Mandarino et al. (2019) show that production systems can double or triple their production by adopting good practices.

One of the difficulties in Paragominas is the lack of fodder at the end of the dry season. To bridge this critical gap, multiple solutions may exist, such as the establishment of combined grazing reserves with cutting (ensilage, haymaking) or the development of small, irrigated areas of highly productive fodder crops, such as sugar cane or elephant grass. This also includes territorial specialization with cow-calf production areas using extensive grazing and fattening zones based on distributed fodder. Fattening based on grazing between two crops is also being tested in the field. An area under maize is grazed after the harvest, during the dry season. Last of all, the area produces a significant quantity of grain, which may enable the development of monogastric livestock farming. A pig farm project with the objective of 3,000 sows is currently under development. This offering will develop if the market grows and if producers meet consumers' demands in terms of quality, price, and societal expectations regarding the environment and animal wellbeing. Investments will therefore need to be more productive and efficient. The environmental functions of livestock farming must be increased through the re-diversification of land plots, production systems and landscapes, by establishing a diversity of grazing species, the planting of trees in grazing areas, and the reforestation of wetlands and river banks. As monogastric livestock farming increases, it would be essential to better integrate livestock and arable cropping systems, which are currently disjointed. This would maintain closed N cycles, high self-sufficiency and very low N losses.

## 4. Conclusion

By describing in detail 20 years of evolution of material flows, this study allows us to characterize the dynamics of livestock farming in Paragominas. Livestock farming essentially remains extensive, with low levels of production and efficiency. Despite a huge decrease in the livestock population and in grazing areas, animal production per hectare stabilized in 2012 at the same level as in 1990, and the production per LU is increasing. We did not find any relation between this process and the decrease in deforestation from 2006 to 2012. In fact, this is explained by a zootechnical progression (at the animal level). There is a significant potential to increase animal production. The land occupation and capital mobilization functions of livestock farming remain very important. We highlighted a phenomenon of competition for land use after 2006 and an intensification of cropping systems with the significant development of corn and soybeans. A further increase in the production of the livestock systems depends not only on control of the land but also on a favorable economic context.

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