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1 **Analysing intensification, autonomy and efficiencies of livestock production** 2 **through nitrogen flows: a case study of an emblematic Amazonian territory**

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13

14 **1. Introduction**

15 Through its land use, its consumption and its emissions, livestock farming is a major
16 factor in the balance or disruption of bio-geochemical cycles, climate and biodiversity.
17 Livestock occupy more than 70% of agricultural land worldwide (Herrero et al., 2015),
18 consume more than 70% of agricultural production (Billen et al., 2014) and emit 14.5%
19 of all anthropogenic greenhouse gases (Gerber et al., 2013). Our study area, the
20 Brazilian Amazon, is emblematic of these tensions between livestock production and
21 the environment. Extensive cattle production has spearheaded the territorial conquest
22 of this region for more than 50 years, and is the main cause of deforestation (Kaimowitz
23 and Angelsen, 1998). Margulis (2003) reported that prior to 2004, livestock occupied
24 70% to 88% of deforested areas. Then, between 2004 and 2012, thanks to increased
25 satellite monitoring, strict land tenure policies and strict environmental policies, the rate
26 of deforestation decreased by 80% (4,571 km² deforested in 2012, versus 27,772 km²
27 in 2004). Interestingly, from 2012 to 2019, there was a new increase in annual
28 deforestation, which reached 9,762 km² in 2019 (INPE-Prodes, 2020). The
29 intensification of animal production is presented as a success factor for long-term
30 maintenance of low deforestation and a good level of production (Bowman et al., 2012;
31 De Oliveira Silva et al., 2017; Mandarino et al., 2019). The argument put forward is
32 simple: within the framework of an effective policy to combat deforestation, the

33 increase in production per hectare could constitute a growth driver without territorial
34 expansion. Yet, in reality, there is no guarantee of this outcome, and very few studies
35 focus on quantifying the intensification of the Amazonian livestock sector. Existing
36 publications on intensification concern the scale of livestock farming systems, with
37 analyses of optimized methods based on pasture restoration, rotational grazing,
38 introduction of legumes and so on (De Oliveira Silva et al., 2017; Latawiec et al., 2014;
39 Barreto et al., 2013). On the national or regional scales, most of the studies present
40 statistical models and scenarios based on extrapolations of intensified livestock
41 systems (Abmael et al., 2016; Bowman et al., 2012). Moreover, the notion of
42 intensification, which is polysemic, is neither defined nor precisely monitored. Raising
43 yields on existing farmland is essential for 'saving land for nature' (Tilman et al., 2002),
44 but the prospects for yield increases are difficult to predict due to uncertain socio-
45 economic factors. In this context, we aim to add a new case study based on empirical
46 data.

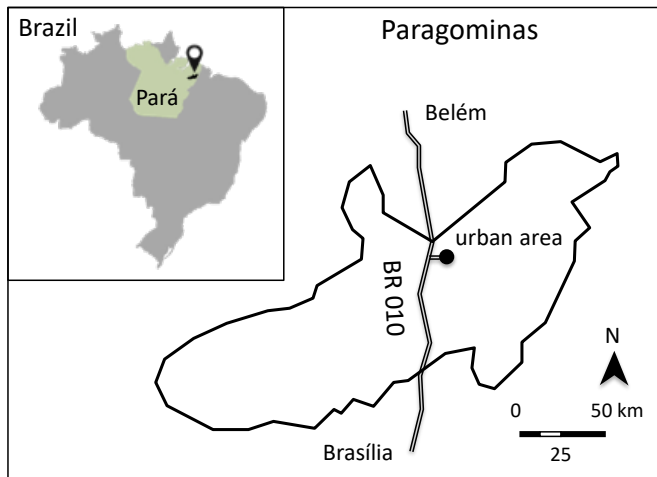
47 The objective of our article is to characterize and discuss the evolution of livestock
48 farming in Paragominas (Brazil). This municipality, where livestock farming and
49 cultivation of soybeans are prevalent, is presented as an example of stopping
50 deforestation. After several decades with one of the highest rates of Amazon
51 deforestation, Paragominas reduced its annual deforestation rate tenfold between
52 2005 and 2012 (Piketty et al., 2015). We analyse the livestock sector, using the method
53 of territorial metabolism. This method quantifies the flow of material mobilized, stored
54 and transformed by livestock. We calculate the trends in intensity, production,
55 efficiency and self-sufficiency from 1990 to 2012.

56

57 **2. Material and methods**

58 2.1 The municipality of Paragominas

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



62
63 **Figure 1.** Map of Paragominas (Pará, Brazil)

64

65 Two phases of development can be distinguished (supplementary material section
66 1- Land use and annual deforestation): the first, from 1950 to 2005, was characterized
67 by a continuous expansion of the agricultural area leading to significant deforestation.
68 Between 2001 and 2005, the average deforestation rate was estimated at more than
69 18,000 ha/year (Piketty et al., 2015). Livestock farming is the main activity; pastures
70 occupy more than 80% of deforested areas (Pinto et al., 2009). The second phase,
71 from 2006 to date, was marked by a sharp decline in deforestation, a decrease in
72 grazing areas and a significant increase in annual crops. Laurent (2014) calculated a
73 13% decrease in grazing areas between 2006 and 2012.-To analyse the evolution of
74 livestock farming, we chose to study two years representative of the first phase of
75 development (1990 and 1995) and two years in the second phase of development
76 (2006 and 2012). These years were chosen based on data availability.

77

78 2.2 A biochemical representation of livestock farming

79 We analysed the functioning of livestock systems from the perspective of nutrient
80 cycles, by quantifying material flows between fodder resources (cropland and
81 grassland), livestock, and the natural environment. This allowed us to discuss different
82 productive and environmental indicators (Bonaudo et al., 2015; Gameiro et al., 2019).
83 We used the GRAFS methodology (Generic Representation of Agro-Food Systems)
84 to produce a biochemical representation of our system (Billen et al., 2014, 2015;
85 Lassaletta et al., 2014). The first step consisted in making an inventory of all material
86 flows and all areas used, either directly or indirectly, by livestock farming. We

87 considered three categories: i) livestock (pigs, poultry, laying hens, dairy cows and
88 beef cattle), of which we estimated the animal numbers, feed intake, production (milk,
89 meat, eggs) and excretion; ii) croplands and iii) grasslands dedicated to feeding
90 animals, of which we estimated the surface areas, fertilization and production. A review
91 of the scientific and technical literature was carried out to identify and prioritize the use
92 of existing local and regional references. We also used a group of experts (three
93 technicians and agronomists, and three researchers) to confirm farming practices in
94 the region.

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

99

100 Livestock numbers, production and excretion

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

105 The objective was to estimate the quantity of products marketed for human
106 consumption. The quantities of milk and eggs are directly accessible in the IBGE-PPM
107 (Municipal Livestock Survey) database, but there are no figures on meat production.
108 To obtain the quantity of pork, poultry meat and beef, we multiplied the number of
109 heads slaughtered by the average carcass weight. For pork, we applied the slaughter
110 rate given by Miele and Soares Machado (2007) (Table 1). The slaughter rate
111 corresponds to the number of animals slaughtered per year divided by the total number
112 of animals present in herds. For poultry and cattle, we applied the slaughter rate and
113 carcass weight calculated from the IBGE-PPM database, but these data were only
114 available from 1997 and for the state of Pará. We therefore assumed that herds in
115 Paragominas have the same slaughter rate and carcass weight as those in Pará State.
116 We applied the 1997 slaughter rate and carcass weight for the years 1990 and 1995
117 (Table 1). For cattle production, we must also estimate the numbers of live animals
118 exported. Live exports correspond to international trade. Exportation began in the
119 2000s and has experienced very strong inter-annual variability due to market
120 uncertainty. The only data available were the average weight and the number of

121 animals exported by Pará State. We therefore calculated live cattle export rates for
 122 2006 and 2012, which we applied to the Paragominas cattle herd (Table 1). We
 123 considered only the edible output, and the inedible wastes or by-products were
 124 considered as losses leaving the food system (skin, blood, hides, heads, feet, tails,
 125 entrails and gut fill).

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

129

130 **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%*	

131 Sources: *IBGE-PPM, 2016; **ABEG, 2015; ***Miele and Soares Machado, 2007; ****Lassaletta et al.,
 132 2014; FAO, 2001

133

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

139

140 **Table 2.** N excretion factors for different livestock classes and corresponding livestock
 141 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

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

145

146 Cropping and fodder systems

147 In line with many studies, animal consumption was estimated by adding together the
 148 excreted N and the N fixed in products (Billen et al., 2014, 2015). For cattle, we
 149 considered that grazing provides the whole diet (Oliveira Miranda, 2016). For
 150 monogastric animals, we considered that rations are composed of corn and soybeans
 151 (Gameiro et al., 2019). Crop production was converted from kilograms of fresh matter
 152 to kilograms of N, based on the coefficients of fixed N in products (Lassaletta et al.,
 153 2014 and FAO, 2001) (Table 3).

154 As figures for grazing areas were not available in the IBGE database for the entire
 155 study period, we estimated them from a compilation of satellite image studies of the
 156 municipal area. These studies consist of Landsat image analyses for 1991, 2008 and
 157 2010 (Oliveira and De Ferreira, 2011; Piketty et al., 2015; Coutinho et al., 2013). We
 158 estimated the grazing area in 1990, 1995 and 2006 through linear regression applied
 159 to existing data. For the 2009-2012 period, Laurent (2014) showed a 13% decrease in
 160 grazing area. Therefore, we applied this decrease to obtain the grazing area in 2012.
 161 To calculate the areas of maize and soybeans, the total production was divided by the
 162 average production per hectare. We applied the average yield for each year, provided

163 by the IBGE-PAM (Municipal Agricultural Production). For maize, we considered the
164 yields of the municipal area. For soybeans, we took the national average yield for 1990
165 and 1995 and the municipal yields for 2006 and 2012.

166

167 Crop and grassland fertilization

168 Fertilization refers to all inputs of N to cropland and grassland, including synthetic
169 fertilizers, atmospheric deposition, manure application and symbiotic N₂ fixation.
170 Symbiotic N₂ fixation varies, depending on pedoclimatic conditions, the varieties
171 farmed and cultural practices. Filoso et al. (2006) report that the symbiotic fixation of
172 grazing areas, predominantly under Brachiaria, is between 15 and 30 kg N/ha/year in
173 Brazil. Due to a large proportion of degraded pastures (Pinto et al., 2009) that fixate
174 little or no N, we retain the lower estimate of 15 kg N/ha/year. Soy symbiotic N₂ fixation
175 is estimated according to the relationships developed by Herridge et al. (2008) and
176 Lassaletta et al. (2014), linking N fixation to yields. Soy symbiotically fixates the
177 equivalent of 1.53% of the yield.

178 Dentener et al. (2006) estimate the atmospheric deposit for the region at
179 8 kg N/ha/year.

180 As statistical data do not exist for fertilizers, we estimate fertilizer use by reconstructing
181 the technical practices in the region according to the group of experts. We assume that
182 chemical fertilizers are not applied to grazing areas (Corrêa et al., 2005) and that cattle
183 excreta are deposited on pasture. We apply loss rates based on volatilization of
184 ammonia (NH₃) during grazing. Volatilization of NH₃ emission varies widely, depending
185 on agricultural practices, soil type, climate and measurement methods. For cattle
186 grazing systems, N losses by NH₃ generally range from 10% to 30% of excreted N
187 (Béline et al., 2012; Lessa et al., 2014). For the Cerrado region (Goiás state), Lessa et
188 al. (2014) estimate nitrogen volatilization at 15% of excreted nitrogen. Our study is
189 based on the study of Lessa et al. (2014), which was carried out in a pedoclimatic
190 context similar to that of our study area (Table 2). We assume that N₂O emissions are
191 very low for grazing cattle (Lessa et al., 2014), so we do not consider them.

192 Only synthetic fertilizers were applied to the feed crops, maize and soybeans (Table 3).
193 According to the experts, a very small proportion of animal excreta was recovered and
194 was used mainly for perennial crops. We estimated that banana, pepper and cocoa
195 were fertilized with organic nitrogen at 700 kg N/ha/yr, 120 kg N/ha/yr and
196 20 kg N/ha/yr, respectively. The amount of excretion recovered was estimated by

197 multiplying the amount of organic nitrogen applied per hectare by the total surface area
 198 under crops (banana, pepper and cocoa areas were provided by the IBGE-PAM
 199 database).

200

201 **Table 3.** Yield, synthetic fertilization and symbiotic N₂ fixation of soybean, maize and
 202 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 N₂ fixation (% of the yield)****			
1990-1995-2006-2012	1.53%	-	-

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

205

206 2.3 Methods for calculating indicators

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

- 209 - Animal production per ha used for livestock farming (kg N/ha/year) and animal
 210 production per livestock unit (kg N/LU/year);
- 211 - Livestock N Conversion Efficiency (NCE), defined as the percentage of ingested
 212 N that is exported in products. Animal products are calculated from the
 213 production figures of meat, eggs and milk (Billen et al., 2014; Lassaletta et al.,
 214 2014);
- 215 - Total N input per hectare (kg N/ha/year), consisting of synthetic and organic
 216 fertilizers, symbiotic fixation and atmospheric deposition;
- 217 - N Self-Sufficiency (NSS) or Autonomy in terms of inputs, defined as a %:
 218
$$\frac{(\sum \text{inputs} - (\text{synthetic inputs} + \text{feed import})) * 100}{\sum \text{inputs}}$$

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

224

225 2.4 Sensitivity analysis of livestock N conversion efficiency

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

230 Sensitivity analysis attempts to identify which parameters are the most critical in
231 determining the results of the problem. In the context of this paper, we propose that
232 the key parameters are those related to beef cattle production (carcass weight,
233 slaughter rate and herd), because it is the most important in terms of livestock, land
234 use and animal production. Thus, we elaborated an analysis of the sensitivity of animal
235 production and of the NCE to variations on these three parameters. We varied these
236 parameters, independently and jointly, then we compared the results to the reference
237 simulation for the year 2012 (Table 5). For the first simulation (S1), we increased the
238 carcass weight of beef cattle slaughtered and exported by 10%. For the second
239 simulation (S2), we increased the slaughter rate of the beef cattle and the export rate
240 of live animals by 10%. Simulation three (S3) estimated the impact of a 10% increase
241 in the beef cattle herd. Increasing the beef cattle herd on the same pasture area is
242 equivalent to increasing the stocking rate. For the fourth simulation (S4), we combined
243 the S1 and S2 (10% increase in carcass weight, slaughter rate and export rate).
244 Simulation five (S5) combined the S1, S2 and S3 (10% increase in the three
245 parameters). Finally, for simulation six (S6), our objective was to simulate an increase
246 in the beef cattle herd to reach the maximum bovine density already reached in the
247 municipality. This rate was 0.88 LU of cattle/ha in 1990 (305,265 cattle LU for
248 345,000 ha of pasture). Following the same logic as the previous simulations, we
249 simulated changes only for the beef cattle herd. The dairy herd therefore remained the
250 same as in 2012 (17,209 LU) and we increased the herd of beef cattle up to
251 275,668 LU to reach a total bovine herd of 292,877 LU for 331,000 ha of pasture in

252 2012 (corresponding to an average bovine density of 0.88 LU/ha). This corresponds
253 to an increase in the beef cattle herd of 98%.

254

255 **3. Results and discussion**

256 3.1 Evolution of livestock farming

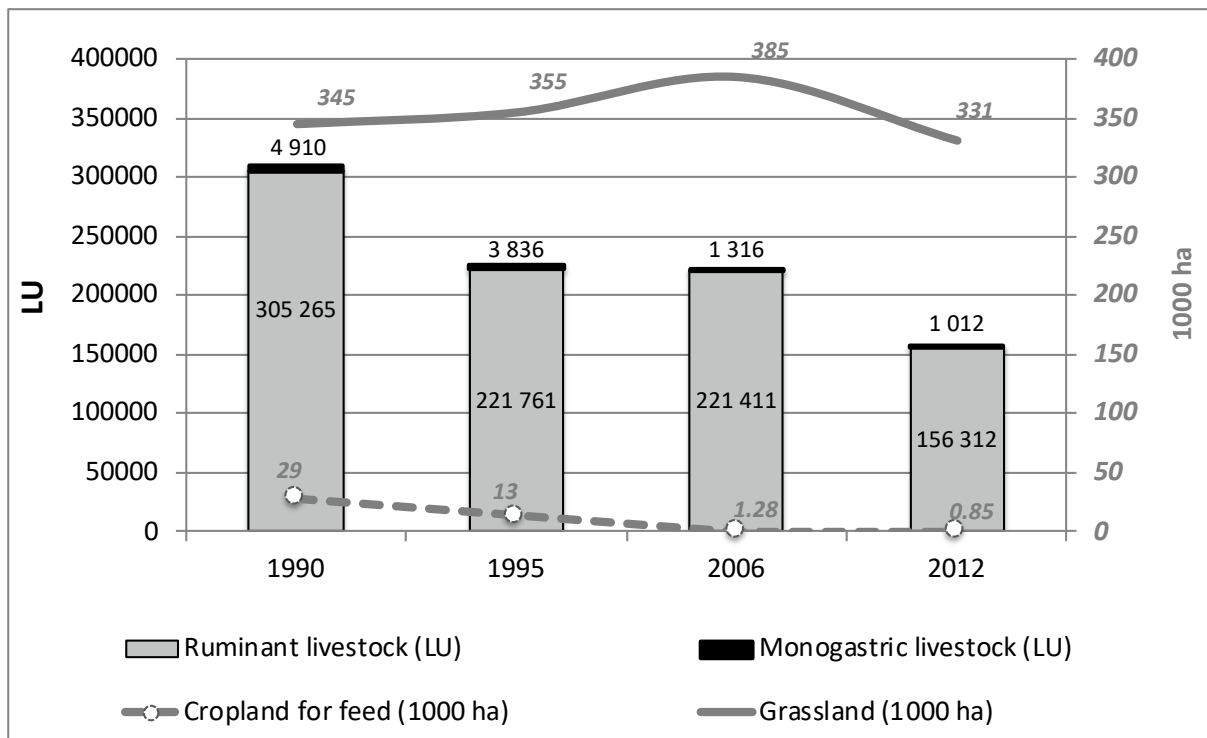
257 The calculation of LU shows that livestock in Paragominas is composed on average of
258 more than 98% ruminants. Monogastric animals, bred mainly by small-scale farmers
259 for their own consumption or local markets, account for only 1.7% to 0.6% of total LU
260 (Figures 2 and 3). Suckler herds,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

267

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

275 Regarding cattle herds, we distinguish three phases. From 1990 to 1995, there was a
276 sharp decrease in livestock units (LU) and an increase in pastures. The decline in LU
277 corresponds to a decapitalization of livestock to invest in the forestry industry. After
278 logging, the forest areas are quickly cleared, and pastures are planted. Without land
279 regulation, farmers take ownership of land, at low cost, by planting pastures. During
280 this phase, there was a significant decline in cultivated areas (from 4,000 to 2,700 ha
281 for rice and from 4,000 to 3,200 ha for corn). However, higher yields have allowed the
282 maintenance of rice production (45 t N) and an increase in corn production (30.4 to
283 40.8 t N). The second phase between 1995 and 2006 was marked by stabilization of
284 the livestock population and an increase in pasture areas to occupy deforested lands.

285 The forestry industry reached its peak at the end of the 1990s, before experiencing a
286 sharp decline in the early 2000s. Livestock farming was once again seen as a safe
287 investment, with a profitable market. This phase was also marked by the introduction
288 of soybeans in 1997 and the rapid expansion of areas and crop yields. Rice areas
289 reached 11,000 ha, those of corn 16,000 ha and those of soybeans increased from a
290 few hundred ha to more than 10,000 ha in 2006. Production increased even more with
291 470 t N of rice, 1,130 t N of corn and 1,824 t N of soybeans (supplementary material
292 Figure 2 - Evolution of production and crop yields from 1990 to 2012). The last phase,
293 from 2006 to 2012, was characterized by a renewed decrease in the livestock
294 population, this time accompanied by a decrease in grazing areas and rice areas
295 (5,500 ha). Rice production decreased to 291 t N. In fact, rice is a so-called "opening"
296 crop, planted just after the land is cleared (Piketty et al., 2015). After 2-3 years of rice
297 cultivation, corn and soybeans are planted. In contrast, there is a tripling of soybean
298 cultivation area (35,000 ha) and a quadrupling of production (7,523 t N). Maize, in
299 rotation with soybeans one year in three, saw its areas and production increase in a
300 more limited way (22,000 ha and 1,845 t N). This phase was marked by strict public
301 policies restricting deforestation. Without the possibility of extension, for the first time
302 there was land competition, between pasture and other crops like soybeans and maize.
303 The corn/soybean rotation is established on the best former rice or pasture plots, that
304 is to say on large fertile, mechanizable plots close to roads (Piketty et al., 2015).
305 We noticed an uncoupling of the dynamics of livestock and pasture areas (Figure 2).
306 The growth of grazing areas is not parallel to the size of the herd; these dynamics can
307 be explained in terms of land expansion and land grabbing. Indeed, a plot of
308 pastureland allows the development of land capital and generates income. Finally,
309 after a few years, this plot can be planted with crops.



310

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

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

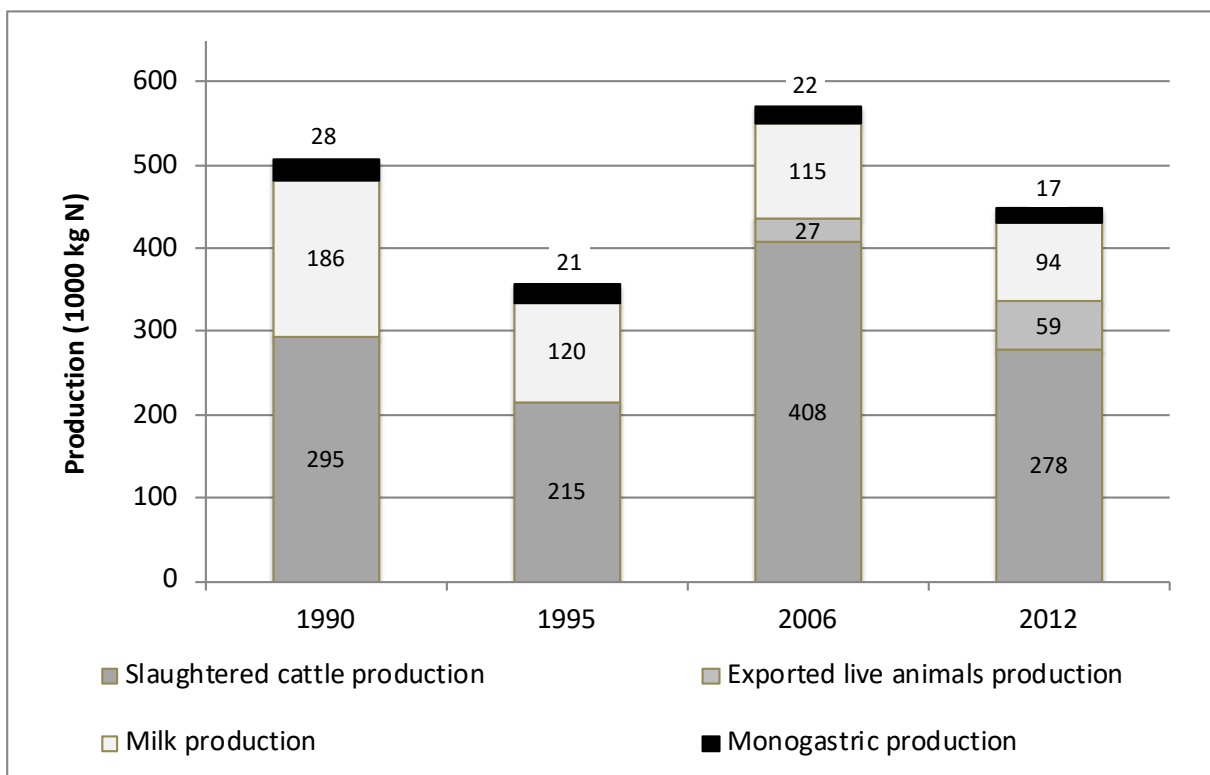
316

317 The average livestock density decreased by 43% during the study period, from
 318 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.
 319 This is an apparent density based on the entire forage area. In fact, densities are
 320 heterogeneous because many grazing areas are degraded or under-used. This
 321 average density does, nevertheless, reflect the extensive use of land, due either to
 322 pasture mismanagement or to the main purpose of grazing, namely land occupation at
 323 a reduced cost.

324

325 The analysis of animal production confirms the importance of cattle, which account for
 326 over 95% of production (Figure 3). Animal production data confirm the decrease in
 327 livestock farming, with a 12% reduction in production over the period between 1990
 328 and 2012 (Figures 3 and 4). There are, however, significant intra-period variations.
 329 Production decreased from 1990 to 1995 due to the decline in herd sizes. From 1995
 330 to 2006, despite a stable herd, we note a significant increase in production from 356

331 to 572 t N, due to beef cattle production (increasing from 215 t N to 435 t N). This
 332 indicates a change in cattle ranching systems, with animals being slaughtered heavier
 333 and at a younger age. The average carcass weight increased from 210 kg to 229 kg,
 334 and the slaughter rate increased from 7.4% to 12.7%. We must add to this the live
 335 animals exported, estimated at 2,400 LU (equivalent to 27 t N or 4.7% of production).
 336 The period between 2006 and 2012 once again experienced a decrease in
 337 production (21%) due to a sharp decline in the livestock population (30%), a 1%
 338 decline in the slaughter rate (11.7%), and a slight increase in carcass weight (5%). The
 339 only production that increased was the live animals exported, with 5,200 LU (equivalent
 340 to 59 t N or 13% of production).

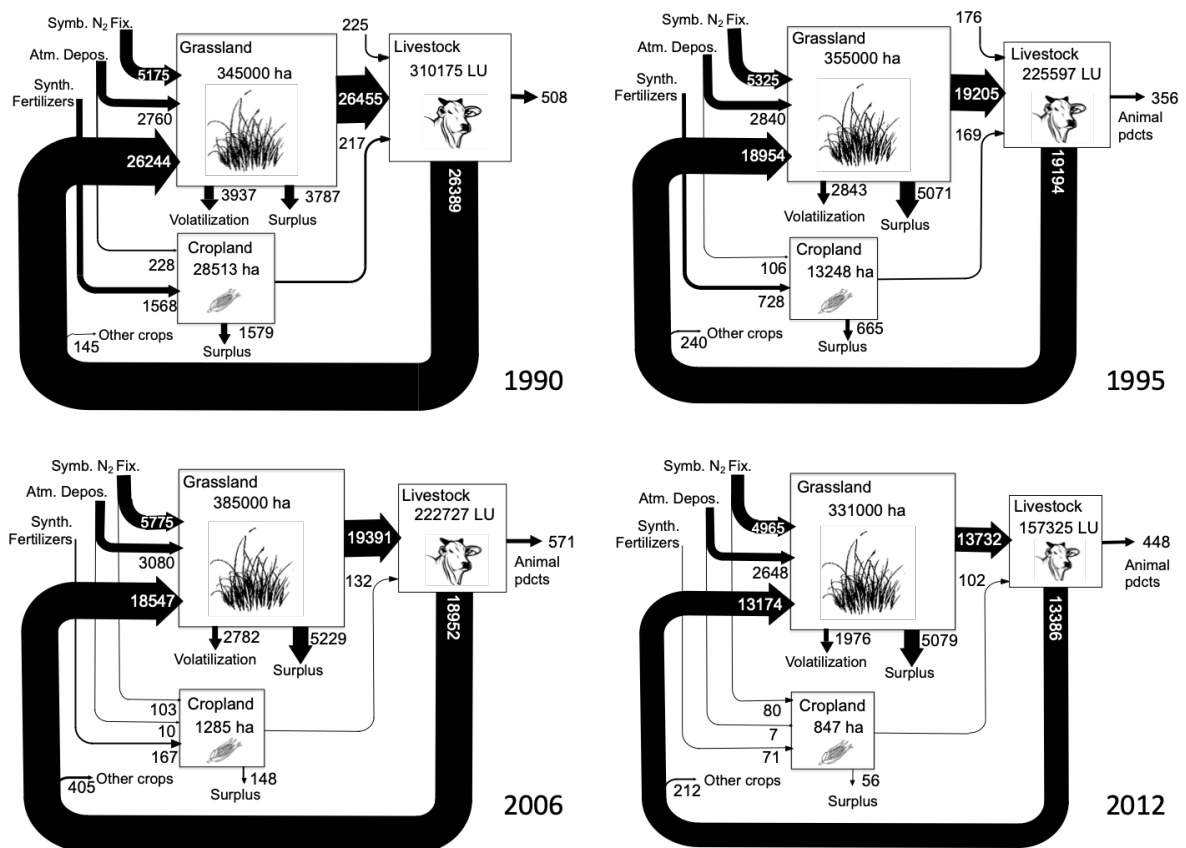


341
 342 **Figure 3.** Evolution of animal production from 1990 to 2012

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

346
 347 Our N flow diagram (Figure 4) shows a high degree of circularity in N flows. In fact, the
 348 livestock diet is based on grazing (98% of total N consumed in 1990 and 99% in 2012),
 349 and excretion is the main source of N in grazing areas. Excretion accounted for over
 350 76% of the total N input in these areas in 1990 and 63% in 2012. This decrease is
 351 explained by the reduction of LU and, therefore, in excretion. Because of this, other

352 sources of N, such as atmospheric deposits and symbiotic fixation, increase
 353 proportionally. Flows are marked by low N inputs. A very small proportion of excretion
 354 is recovered to fertilize other crops, and a very small proportion of crops are used to
 355 feed the animals. Livestock systems and arable cropping systems are thus largely
 356 disconnected.
 357



358
 359 **Figure 4.** Diagram of N flows for livestock farming in Paragominas for the years 1990,
 360 1995, 2006 and 2012 (1,000 kg N/year)
 361

362 3.2 Livestock farming indicators: production, efficiency and self-sufficiency

363 Compared with national and regional production (Gameiro et al., 2019; Billen et al.,
 364 2014), animal production per hectare in Paragominas is low (between
 365 0.97 kg N/ha/year in 1995 and 1.48 kg N/ha/year in 2006) (Table 4). This is explained
 366 by a low level of production per LU and livestock density. There was a sharp decrease
 367 in production per hectare in 1995, due to decapitalization of livestock, low production
 368 per LU and a considerable expansion of grazing areas. If we look at production per LU
 369 over the study period, it is low but increased sharply from 1.64 to 2.85 kg N/LU/year.
 370 The forage system remained very extensive. Only a few producers have intensified it

371 by establishing dynamic rotating pasture or plots of elephant grass, fodder sugar cane
372 or corn to make silage for distribution to animals for 1 to 3 months during the dry
373 season. At the same time, cropping systems have intensified considerably with the
374 development of the corn-soybean rotation. Average crop yields increased markedly
375 from 1990 to 2012 (9 kg N/ha, 15 kg N/ha, 93 kg N/ha and 154 kg N/ha). The efficiency
376 of animal production (NCE) is low; nevertheless, it increased over the study period
377 (+71%, Table 4). Improvement in NCE and production per LU is due to increased
378 carcass weights, the livestock exploitation rates (number of animals slaughtered and
379 exported) and, for the last phase, a higher proportion of dairy cows in livestock (9.6%
380 to 11%). Since dairy cows have a higher NCE than beef cattle, this results in an
381 increase in the average NCE of cattle. The beef cattle herd is decreasing, but the
382 animals are more productive.

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

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

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

402

403 **Table 4.** Evolution of production, N inputs, efficiency of N use and surpluses of
404 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%

405

406 3.3 Sensitivity to selected beef cattle production parameters

407 The S1 and S2 simulations led to a 7% increase in animal production and a 6.8%
408 improvement of the NCE compared with the 2012 reference simulation. The increase
409 in animal production is lower than 10%, because milk production is not affected by
410 these parameters. Simulation three (S3) resulted in a 6.9% increase in production and
411 a -1.7% decrease in the NCE. The decline in NCE is explained by the relative increase
412 in beef cattle in the total herd. Since beef cattle have a lower efficiency than dairy cows
413 and monogastrics, the efficiency of the total herd is slightly lower. The fourth simulation
414 (S4) resulted in a 14.8% increase in production and a 14.3% increase in NCE.
415 Simulation five resulted in a 23.2% increase in production and a 12.7% increase in the
416 NCE. The simulation six (S6) increased production by 68% and decreased the NCE
417 (-9.7%). This situation corresponds to the cattle stocking rate of 1990, with an average
418 feed intake of 73 kg N/ha/year. This is an achievable yield for a well-managed pasture,
419 without a major change in the production system. This increase, although significant,
420 seems achievable in the short to medium term.

421 These simulations show a significant weight of these parameters in the calculation of
422 production and NCE. Simulations S1, S2 and S3 show that the parameters have a
423 comparable effect on production. Simulations S4 and S5 show that they have an

424 additive effect on production. However, these parameters do not have the same effect
 425 on the NCE. While increased carcass weight and slaughter rate improve NCE, the
 426 increased beef cattle herd reduce NCE.

427

428 **Table 5.** Analysis of the sensitivity of animal production and of NCE to variations in
 429 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

430

431 3.4 General discussion

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

443 For South America, Billen et al. (2014) calculate an animal production of
444 2.7 kg N/ha/year and a livestock efficiency of 6.3%. For Brazil over the period 1994-
445 2013, Gameiro et al. (2019) estimate an efficiency of beef cattle production of 5.2%.
446 These results, which are significantly higher than ours, can be explained by a larger
447 proportion of intensive animal production at the regional and national levels. The
448 agribusiness sector, mainly the monogastric and dairy industries, is highly
449 concentrated in the south and southeast of Brazil. Gameiro et al. (2019) estimate
450 livestock efficiency at between 25.7% for pigs and 52.6% for poultry. Even the beef
451 sector, with the best pasture management and the use of concentrates, is more
452 productive in these areas (Cederberg et al., 2011; De Zen et al., 2018; Gameiro et al.,
453 2019). Our study area is known for its specialization in extensive cattle production, with
454 low technology and low performance. Bovine production per hectare is very low in
455 Amazonia and, despite significant variability of the results, there is an improvement in
456 production at the animal level. Cederberg et al. (2011) estimate Amazonian production
457 at 0.74 kg N/ha/year for 1996-97 and 1.29 kg N/ha/year for 2006 (respectively 24 and
458 42 kg carcass/ha/year). These estimates are equivalent to those estimated for
459 Paragominas with 0.61 kg N/ha/year in 1995 and 1.13 kg N/ha/year in 2006.

460 We distinguish three periods of change in livestock farming in this municipal area. The
461 first period, from 1990 to 1995, combined low-cost territorial expansion through the
462 establishment of grazing areas, with the decapitalization of livestock to the benefit of
463 the forestry industry. The second period, from 1995 to 2006, combined territorial
464 expansion with investments to improve the production of livestock and to benefit from
465 a buoyant cattle market. Lastly, the third period, from 2006 to 2012, corresponded to
466 a cessation of territorial expansion and a marked increase in grain crops. This resulted
467 in a decline in livestock numbers and grazing areas, as the best plots of land were
468 devoted to crops. This evolution reaffirms the multiple functions of livestock farming
469 and its flexibility when faced with shifting economic and political contexts. We also note
470 that the establishment of grazing areas is not correlated with the size of herds or animal
471 production. This increases the benefit of using multiple types of indicators, expressed
472 in terms of area as well as livestock units.

473 Due to the decrease in the number of head of cattle, we do not observe an
474 intensification on the scale of the municipality (there is a decrease in animal density,
475 animal production and N inputs per unit of area indicated). However, on the animal or

476 herd scale, we highlight an intensification (animal production per LU, the slaughter rate
477 and the efficiency of N use increase). The crop system has, at the same time, greatly
478 intensified and extended. This has led to a decline in pasture area (Piketty et al., 2015).
479 We found no evidence of a link between the increase in animal production and
480 efficiency and the decrease in deforestation or greater competition for land use. The
481 increased oversight of land use, along with repressive policies, enabled the cessation
482 of deforestation, but this did not result in a massive intensification of livestock farming
483 for the moment. It would be useful to work in detail on the determinants of the crop
484 intensification and its links with deforestation.

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

492 In conditions similar to those of Paragominas, studies have estimated that a well-
493 managed pasture can allow feed intake between 70 and 120 kg N/ha/year. This
494 calculation is obtained using a fodder production of 15 t DM/ha/year (Embrapa, 2002),
495 a mean protein level of 0.016 kg N/kg DM (Corrêa et al., 2005) and a feed intake of
496 30-50% of the dry material produced. For the most productive areas of the Amazon,
497 Arima et al. (2005) estimate animal production between 1.73 and 2.45 kg N/ha/year
498 (56-80 kg carcasses/ha/year). For the states of Para, Acre, Bahia, Maranhão and
499 Tocantins, De Zen et al. (2018) calculate an average animal production of
500 2.19 kg N/ha/year for the period from 2007 to 2012. Mandarino et al. (2019) estimate
501 the production of low-tech farms in northern Mato Grosso at 3.1 kg N/ha/year for the
502 year 2014. These differences show that there are still growth margins. Mandarino et
503 al. (2019) show that production systems can double or triple their production by
504 adopting good practices.

505

506 One of the difficulties in Paragominas is the lack of fodder at the end of the dry season.
507 To bridge this critical gap, multiple solutions may exist, such as the establishment of
508 combined grazing reserves with cutting (ensilage, haymaking) or the development of

509 small, irrigated areas of highly productive fodder crops, such as sugar cane or elephant
510 grass. This also includes territorial specialization with cow-calf production areas using
511 extensive grazing and fattening zones based on distributed fodder. Fattening based
512 on grazing between two crops is also being tested in the field. An area under maize is
513 grazed after the harvest, during the dry season. Last of all, the area produces a
514 significant quantity of grain, which may enable the development of monogastric
515 livestock farming. A pig farm project with the objective of 3,000 sows is currently under
516 development. This offering will develop if the market grows and if producers meet
517 consumers' demands in terms of quality, price, and societal expectations regarding the
518 environment and animal wellbeing. Investments will therefore need to be more
519 productive and efficient. The environmental functions of livestock farming must be
520 increased through the re-diversification of land plots, production systems and
521 landscapes, by establishing a diversity of grazing species, the planting of trees in
522 grazing areas, and the reforestation of wetlands and river banks. As monogastric
523 livestock farming increases, it would be essential to better integrate livestock and
524 arable cropping systems, which are currently disjointed. This would maintain closed N
525 cycles, high self-sufficiency and very low N losses.

526

527 **4. Conclusion**

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

541

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545

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