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Impacts of agricultural practices and individual life characteristics on ecosystem services: a case study on family farmers in the context of an Amazonian pioneer front

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1 **Impacts of agricultural practices and individual life characteristics on**
2 **ecosystem services: a case study on family farmers in the context of an**
3 **Amazonian pioneer front**

4
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42

43 **Abstract:** In tropical forests farmers are among the most important agents of deforestation. At the
44 interface between societies and their environment, ecosystem services (ES) is an integrated
45 working framework through which natural and anthropogenic dimensions can be addressed.
46 Here, we aimed to understand to what extent farmers impact ES availability. Based on case

47 studies in three locations in the Brazilian Amazon rainforest, we performed statistical analyses at
48 135 sampling points and 110 farms to link socioeconomic and ES data, both derived from field
49 work. The socioeconomic data characterized agricultural production, sociological characteristics
50 and quality of life. ES data were obtained from statistical analyses that yielded a multiple ES
51 indicator for each sampling point and farm. Our results produced three main findings: first, the
52 establishment of ES associations is due more to agricultural production characteristics than to
53 sociological and quality-of-life factors. Second, the impact of agricultural production on ES
54 availability depends on the level of total incomes. An increase in incomes causes a decrease in
55 the forest cover that provides many ES and an increase in other areas that provide fewer ES.
56 Finally, our analyses show a very strong site effect that probably expresses the heterogeneity of
57 the biophysical contexts, but also the importance for ES availability of the historical depth of
58 deforestation and/or the role of specific public policies. Finding ways of producing an alternative
59 impact on ES availability and establishing specific ES associations will therefore depend more on
60 changes in the global political context than in individual practices.

61
62 **Keywords:** Socioecological systems, multiple ecosystem service, deforestation, family
63 agriculture, sustainable agriculture, Brazilian Amazon.

64
65 **1 Introduction**

66
67 In tropical forests in general, deforestation is caused by timber felling and colonization for
68 agricultural purposes (FAO, 2012), so that farmers are among the most important agents of
69 deforestation (Pasquis 1999; Arnauld de Sartre 2006; Davidson et al. 2012; Théry 2012).
70 Agricultural activities cause changes to the natural environment, including biodiversity (Baker et

71 al. 1995) and ecosystem services (Erle and Pontius 2007). In the Brazilian Amazon, issues
72 relating to the impacts of family farmers on their environment are of crucial importance: these
73 farmers occupy areas in which they have to preserve the natural environment in order to continue
74 their activities (Soares-Filho et al. 2006; Davidson et al. 2012). At the same time, they need the
75 same space for social and economic functions, to live and work and produce maximum benefits
76 (Rodrigues et al. 2009). But to develop and use this space, family farmers are actively
77 contributing to deforestation, which allows them to own land on which to live and work, while
78 causing its degradation (Grimaldi et al. 2014).

79
80 In the Brazilian Amazon, a variety of deforestation processes can be observed at local scales
81 (Théry 1997). Hervé Théry (2012) described the two main types of agricultural production at
82 work: traditional family farming and large-scale capitalist agriculture. Traditional agriculture
83 covers a wide variety of situations (Lena 1986; Arnauld de Sartre 2006; Le Tonneau et al. 2010;
84 Oszwald et al. 2012). It is practiced by smallholders who settled in the area either spontaneously
85 or under State-supervised colonization programmes in the 1970s (Oszwald et al. 2012). The
86 diversity of settlers arises from their production methods and their very disparate socio-economic
87 situations (Hostiou et al. 2003). Capitalist agriculture is practiced by large-scale producers, for
88 both domestic and international markets. It is characterized by large farms (*fazendas*) covering up
89 to several thousand hectares and devoted to cattle ranching (Arvor 2009).

90
91 In these areas, deforestation results in the formation of pioneer fronts. The dynamics of these
92 pioneer fronts fluctuate according to demographic and economic variables related to the territory
93 (Lena 1986). Pioneer front areas are affected by extreme tension between environmental
94 protection and economic development, which translates into intense and rapid changes in the

95 environment. They are therefore of great interest for studies of the relationships between human
96 beings and their environment, and hence for the identification of statistical methodologies that
97 make it possible to investigate an extremely complex scientific question. In this context, the
98 question is whether the direct link between people's practices and their impact on the
99 environment is significantly important, compared to other broader factors such as the political
100 context or the history of colonization.

101
102 At the interface between societies and their environment, ecosystem services (ES) may be seen as
103 an integrated framework through which both natural and anthropogenic dimensions can be
104 addressed. Up to now, quantitative research has been conducted to assess the impact of farming
105 practices on environmental sustainability (Benton et al. 2002; Pretty et al. 2006; Firbank et al.
106 2008; Godfray et al. 2014; Poppy et al. 2014; Pywell et al. 2015; Smith et al. 2017) but still very
107 little quantitative assessment of the impacts of farming activities and farmers' characteristics on
108 ES supply in the Brazilian rainforest. There are two ways in which to consider relationships
109 between human activities and ES supply: by studying either the influence of ES supply on human
110 activities, or the reverse, i.e. the influence of human beings on ES supply. In this article, we
111 decided to use the second approach in areas of high tension between environmental protection
112 and economic development that characterize the pioneer fronts. We thus applied the concept of
113 ES in order to identify to what extent farmers have an impact on ES supply through their
114 presence on the land and their activities: how do different patterns of farming practice and
115 different sociological characteristics and living conditions influence the supply of ES?

116
117 To better understand the relationships between the socioeconomic characteristics of farmers and
118 ES supply, a two-stage methodology was designed :

- 119 • An initial series of analyses was performed for each sample plot in order to understand how
120 socioeconomic factors can influence the establishment of ES associations,
121 • Analyses were then performed at the farm level in order to identify socioeconomic factors
122 with an impact on ES supply and more specifically on the spatial structure of ES.

123

124 **2 Material and methods**

125

126 *2.1 Study sites*

127

128 This article is based on three local case studies conducted at Maçaranduba, Pacajá and Palmares
129 II, located in the Brazilian Amazon rainforest, in the state of Pará (Fig 1). In tropical forests,
130 especially the Amazon rainforest, the ecological issues of biodiversity and ES are well known
131 and documented (Metzger et al. 2006). Deforestation is extremely intense in these areas.
132 Worldwide, more than 100 million hectares of tropical forests were cleared between 1996 and
133 2010 (FAO 2015). Pará has one of the highest deforestation rates of all Brazilian states in the
134 Amazon forest (INPE Prodes 2014).

135

136 *Fig 1*

137

138 Site selection was guided by the need to take into account different local contexts, as the
139 importance of the latter in the implantation of the pioneer fronts to understand the forms of
140 evolution of these fronts has already been emphasized (Albaladejo and Veiga 2002). The three
141 study sites were chosen for three main reasons: 1) they are experiencing deforestation dynamics;
142 2) These dynamics of deforestation are differentiated in time and in their socio-economic and

143 political origins; and 3) These three sites present various biophysical characteristics (e.g.
144 topography, nature of the soil).

145
146 The institutional context (public policies) but also the location (distance from roads) and
147 socioeconomic characteristics of the farms, their physical environment (topography, nature of the
148 soil) and the history of colonization, differ widely from one study site to another (Costa et al.
149 2012; Grimaldi et al. 2014).

150
151 Located in the municipality of Nova Ipixuna, the Maçaranduba site covers approximately 220
152 km². This site has been logged since the 1970s, but the forest cover is still relatively well
153 preserved, mainly thanks to the implementation of sustainable development practices based on
154 extractivism. Covering 175 km², the Pacajá site is located about 60 km from the urban centre, on
155 one of the “fishbone” tracks (Traversão 338 south) perpendicular to the Trans-Amazon highway.
156 Deforestation has occurred since the early 1990s through spontaneous settlement. Forest cover
157 was still plentiful in 2007 (63%). The 160 km² Palmares II *assentamento* (settlement) is located
158 near the Carajas iron mine, close to the former gold mine of Eldorado do Carajas. It is
159 emblematic of the agrarian reform and results from the struggles between the Landless Workers
160 Movement, the government and the Vale mining company. As the land was divided into similar-
161 sized lots, the area is highly fragmented.

162

163

164 **2.2. Data**

165 Our study was based on the analysis of two datasets, collected during field campaigns (ANR
166 AMAZ, 2007-2008, coord. Patrick Lavelle) from measurements (indicators of potential

167 ecosystem services supply - Grimaldi et al. (2014)) or interviews (socioeconomic characteristics -
168 Lavelle et al. (2016)):

169 • An indicator of ES associations. The calculation of this indicator has been described in
170 another study (Le Clec'h et al. 2016). Six indicators of ES potential supply were measured
171 during field campaigns and used to create an indicator of ES associations. We decided to
172 analyse impacts on multiple ES indicators, rather than on a few individual ES indicators, in
173 order to obtain an overall view of ES supply. From this indicator of ES associations, we
174 calculated other multiple ES indicators at the farm level.

175 • Three types of socioeconomic indicators based on the characterization of agricultural
176 production, life trajectories and quality of life (Arnauld de Sartre and Seville 2008; Arnauld
177 De Sartre et al. 2011). The necessary information was obtained from surveys conducted with
178 all the farms of the three study sites (110 farmers).

179

180 ***2.2.1. An indicator of ES associations***

181

182 Since land use changes have a considerable impact on ES supply (Polasky et al. 2011; Keller,
183 Fournier, and Fox 2015), we analysed the relationships between societies and their environment
184 through a study of landscapes. Landscape is the product of economic and cultural practices (
185 Beroutchavili and Bertrand 1978) and its spatial organization is strongly related to the way
186 societies use their environment (Burel and Baudry 1999). The analyses were then based on six
187 land cover classes derived from Landsat TM images, reflecting the degree of human disturbance
188 of the environment (Fig 2).

189

190

Fig 2

191
192 The indicator of ES associations was built up from six indicators of potential ES supply:
193 vegetation carbon stock (service of climate regulation), soil carbon stock (service of primary
194 production), rate of water infiltration into the soil (water regulation service and soil erosion
195 control), chemical soil quality (service of support to production), a standardized index of
196 biodiversity (cultural service) and species richness of 70 pollinator moths (*Sphingidae* –
197 pollination service - Table 1). We decided to use spatial indicators of the biophysical processes to
198 characterize ES because defining indicators of the biophysical processes that provide the services
199 is one way to map ES (Oszwald et al. 2014). These six indicators of potential ES supply studied
200 were measured *in situ*. All indicators were assessed using field data collected from 27 farms (nine
201 per site). On each of the 27 farms, five sampling points were spaced equally along a transect
202 corresponding to the longest diagonal of the farm on a north-south axis (for more details about
203 the calculation of the indicators, see Grimaldi et al. (2014)).

204
205 *Table 1*
206 To build up an indicator of ES associations, we applied a method developed by Le Clec'h et al.
207 (2016). This involved bundling categories of a remote sensing variable, the land cover
208 classification, according to their similarities in the provision of each individual ES. For the 135
209 sampling points, for each of the six land-cover classes of the Landsat TM-based classification, we
210 averaged each ES indicator (field data - arithmetic mean with equal weights). We used the
211 average values to calculate a distance matrix among the land-cover classes. We then applied
212 Ascending Hierarchical Clustering (AHC) to the distance matrix to determine groups of land-
213 cover profiles that provided homogeneous levels of ES. The land-cover groups corresponded to
214 associations of the six ES indicators and could be mapped. In this way, we built up information

215 about ES associations for the 135 sampling points but also for the whole area of the three study
216 sites.

217
218 We discriminated between four profiles of ES associations (Fig 3). The first profile,
219 corresponding to forested areas, has a high vegetation carbon stock, a high rate of water
220 infiltration and chemically poor soil. The second profile, corresponding to areas of burned forest
221 and forest edges, has lower vegetation carbon stocks and a lower rate of water infiltration than the
222 first profile, and chemically richer soil. The third profile is a combination of pastures and fallow
223 lands (juquira-capoeira) characterized by low ES supply, except for the chemical soil quality
224 index. The fourth profile, associated with bare soils, is characterized by low vegetation carbon
225 stocks and chemically rich soils. The bare soils category in fact corresponds to two different
226 realities that cannot be discriminated by remote sensing images acquired during the dry season: it
227 may correspond to actual bare soils, such as roads, tracks and their surroundings, but also to
228 fields for annual crops with no plant cover at this time of the year. The heterogeneity of this class
229 produces wide differences in ES supply.

230

231 *Fig 3*

232

233 ***2.2.2 Socioeconomic data***

234

235 Socioeconomic data were collected to characterize 110 farms within the three study sites.
236 Interviews were conducted with the farmer-householders. To address this question on the
237 Amazonian pioneer fronts, and thus to investigate the impacts of farmers on the environment,
238 three points have been emphasized as of particular importance (Arnauld de Sartre 2006; Caldas et

239 al. 2007): the economic function of the farms (absolute and relative value of different types of
240 production), quality-of-life indicators (e.g. household equipment) and the personal characteristics
241 of the farmers (demography, life trajectory¹, level of education, etc.). Consequently, different
242 variables were extracted from the interviews (for more information, see Arnauld de Sartre and
243 Sebille (2008); Arnauld De Sartre et al. (2011)): information on agricultural production, the
244 sociology of the farmers and their quality of life (Table 2).

245

246 *Table 2*

247

248 ***2.2.3 Analysis of data associated with different statistical units (farms and sampling points)***

249

250 The different data should be studied for the same statistical units. However, the statistical units
251 for the ES indicators dataset and the socioeconomic datasets were not the same: for the ES
252 dataset, the units were the sampling points and for the socioeconomic data, the units were the
253 farms. To perform the analyses, we therefore had to build up the datasets for the same individual
254 statistics. Two methods were used:

- 255 • Replicating socioeconomic values for the sampling points. We considered that a farm is a
256 homogeneous entity from the perspective of each socioeconomic variable. We therefore
257 attributed the same socioeconomic value to each of the sampling points within one farm.
258 Consequently, the 135 sampling points were characterized by a specific profile of ES
259 association and socioeconomic information.

¹ Life trajectory of an individual refers to his multiple biographical components such as residential, professional or familial components (Hélandot 2006; Noël et al. 2017). These data are collected within a biographical questionnaire; year by year, the informant indicates where he was living, what he did and what the composition of his /her family was.

260 • Obtaining a multiple ES profile for each farm. To do so, we created a synthetic index. Since
261 this approach is less natural, we describe it below in detail.

262
263 As previously explained, we built up an indicator of ES associations at the sampling points from
264 the land use classification. This indicator was subsequently extended to each satellite image pixel
265 for the three sites. In fact, to get information about the provision of ES at the farm level, we had
266 to bundle the data. However, each single situation (each farm) encompasses many different
267 statistical and spatial realities. To synthesize these, we created spatial indicators, using landscape
268 ecology and spatial analysis indicators. These quantitative indicators, called landscape metrics,
269 are designed to draw up a detailed inventory of the distribution and spatial variability of a given
270 phenomenon (McGarigal et al. 2002). They have been widely used in tropical contexts (Oszwald
271 et al. 2012; Almeida-Gomes and Rocha 2014; Carrara et al. 2015). They are often based on land
272 use data but it is also possible to incorporate other information into their calculation, such as ES
273 association types in this case. The calculation of landscape metrics enabled us to synthesize the
274 spatial distribution of ES associations within the 110 farms for which socioeconomic data are
275 indicated. These metrics can be divided into three groups:

- 276 - The first group includes diversity metrics that quantify the ES richness of the farms, or the
277 dominance of a particular profile of ES association on a given a farm (Shannon diversity
278 index - SD, Shannon evenness - SE and dominance index - D).
- 279 - The second group includes the metrics used to quantify the complexity of ES association
280 forms and their edges (fragmentation - edge density - ED).
- 281 - The last group informs about the composition of ES associations, i.e. the proportion of the
282 area for each profile of ES association (class area – $CA_{profile1, \dots, CA_{profile4}}$).

283 These eight landscape metrics were calculated with the V-Late extension (ArcGIS 10.1).

284
285 Once all the farm level information was collected (the eight landscape metrics, the spatial
286 structure of ES associations and the socioeconomic data), statistical analyses were performed.

287

288 **2.3 Statistical analyses**

289

290 The analyses were based on the hypothesis that socioeconomic characteristics influence the
291 creation of specific ES associations. To analyse the relationship between the socioeconomic
292 datasets and the multiple ES indicator, predictive methods were chosen. First, we based our
293 analyses on the sampling point level to understand how the socioeconomic observations might
294 explain (in the statistical sense) ES supply (estimated via an indicator of ES associations). We
295 thus used predictive methods to explain, using these socioeconomic data, why each sampling
296 point belongs to one of the four profiles of ES associations. To do so, we applied two statistical
297 methods: a decision tree (Breiman et al. 1984) and multinomial logistic regression (Venables and
298 Ripley 2002). We analysed the class of ES associations predicted with each method, compared it
299 to the initial class and calculated the percentage of misclassification (cross-validation procedure).
300 The class with the best performance was retained.

301

302 A second set of analyses was performed for the farm level, to find out whether the socioeconomic
303 characteristics have an impact on the spatial structure of ES associations. First, the eight
304 landscape metrics were synthesized into a single indicator of multiple ES. This synthetic variable
305 was constructed by applying a PCA to the metrics. The values of this variable match the
306 individual coordinates on the first factorial axis. We combined the socioeconomic dataset with
307 the multiple ES index using regression methods. The multiple ES indicator was then considered

308 as the response variable (Y), while the socioeconomic data were considered as explanatory
309 variables (X), since regression methods assume the existence of a function f that links the
310 response variable Y to the explanatory variables X_1, \dots, X_p (Cornillon and Matzner-Lober 2011).
311 Because we assume that the function f is linear, the model is written as follows:

$$312 \quad Y = \beta_0 + \beta_1 X_1 + \dots + \beta_p X_p + \varepsilon$$

313 With β_j , the parameters to be estimated and ε , a random variable.

314
315 Three multiple linear regressions enabled us to identify the agricultural production, sociology and
316 quality-of-life characteristics that explain the variations in the synthetic ES index.

317

318 **3 Results and discussion**

319

320 ***3.1. Low correlation between ES supply and socioeconomic datasets at the sampling point level***

321 The cross-validation procedures highlight two main points (Table 3). First, they show the most
322 appropriate method for each specific dataset, which is mainly the decision tree (agricultural
323 production and quality-of-life datasets). Second, as the rates of misclassification are high, they
324 illustrate how small the effects of socioeconomic characteristics on the creation of specific ES
325 associations are.

326 *Table 3*

327

328 ***3.2. A strong negative correlation between ES supply and incomes at the sampling point level***

329 The socioeconomic characteristics that most influence the establishment of ES associations are
330 related to agricultural production (misclassification rate =0.37). The distribution of sampling
331 points within the ES association groups is mostly explained by factors related to incomes (Table

332 4). However, these results should be considered with caution because the error rates
333 (misclassification rates based on mismatches between the predictions and the original values) are
334 quite high.

335

336

Table 4

337

338 The analyses conducted on the sociological and quality-of-life datasets are more difficult to
339 interpret. They generally show a strong effect of context, expressed by the significance of the
340 “Site” variable and also the presence of other variables (number of migrations, living conditions,
341 demographic structure) whose values differ considerably among sites (Table 4). To better
342 understand the role of the different data in the establishment of ES associations, we represented
343 the decision tree resulting from the agricultural production dataset and the trends of the variables
344 from the sociological and quality-of-life dataset (Fig 4. a and b).

345

346 In general, the higher the income from a farm, the more limited the supply of ES (profile 1 - low
347 supply of most ES – Fig 4. a.). Clearly, the lowest incomes correspond to areas with significant
348 ES supply: forested or transition areas (burned forest or juquira-capoeira) that usually belong to
349 small farmers. Sampling points characterized by profile 3 ES associations (pastures where ES
350 supply is generally very low) and profile 4 (bare soil) correspond to high total incomes. These
351 sampling points are on farms that have been severely deforested and where ES supply is
352 consequently very low. They mainly belong to Maçaranduba and Palmares II, and although the
353 decision tree does not retain the variable related to the site, the results illustrate the importance of
354 the effect of context.

355

356 The results for the sociological and quality-of-life characteristics illustrate the negative impact of
357 an improvement in living conditions on ES supply. Moreover, a large number of migrations is
358 positively correlated with ES supply whereas a large number of family members is negatively
359 correlated with ES supply.

360

361 *Fig 4*

362

363 ***3.3. At the farm level, impact of context and agricultural incomes***

364 At the farm level, the PCA performed on the eight indicators of the structure and spatial
365 composition of ES associations shows the relationships between these variables (**Fig 5**). The first
366 factorial plan explains about 64 % of the total inertia. The first factorial axis, used as a synthetic
367 indicator of the spatial composition of ES associations, explains about 33 % of the inertia. It is
368 mainly built up from the contrast between forested farms characterized by specific ES
369 associations (high supply of almost all ES) and farms that have already been deforested and are in
370 various stages of canopy opening (profile 2, 3 and 4 of ES associations). In other words, the
371 indicator has high positive values for farms with low ES supply, mainly located in Palmares II,
372 and negative values for farms with high ES supply, except for the chemical soil quality index.
373 These negative values essentially correspond to farms located in Pacajá. The graph for individual
374 farms shows that the spatial landscape composition (and therefore ES associations) varies
375 according to the study site. The farms located in Pacajá, where the deforestation dynamics are
376 more recent, have more forest and provide more ES than the two other study sites.

377

378 *Fig 5*

379

380 Three linear regressions were performed to explain the variations of this synthetic indicator built
381 up from the coordinates of the farms on the first PCA axis. The low values of the three R^2 show
382 the relative capacity of socioeconomic data to explain the variations of the ES indicator (Table 5).

383

384 *Table 5*

385

386 The establishment of ES associations is more the result of agricultural production characteristics
387 than of sociological and quality-of-life factors. The linear regression model built up from the
388 agricultural production data underlines the influence of incomes on ES supply (Fig 6). An
389 increase in incomes causes a decrease in forest cover (profile 1 of ES associations) providing
390 many ES and an increase in other areas (profiles 2, 3 or 4 of ES associations) providing fewer ES.
391 The linear regressions produced from sociological variables and the quality-of-life dataset mainly
392 reflect the site effect: for example, ES supply tends to be lower in Palmares II than in the two
393 other sites.

394

395 *Fig 6*

396

397 **4. Discussion**

398

399 This case study on the Amazonian pioneer fronts aimed to bring a better understanding of the
400 links between human practices and the state of the environment, by identifying the human factors
401 that govern the supply of multiple ES. From a methodological point of view, we highlighted two
402 points:

- 403 • the value of spatial information to link data from two different spheres of study,

404 • the contribution of statistical methods to link these data.

405
406 Mapping multiple ES indicators makes it possible to obtain generalized information for a whole
407 area (3 local study sites in our case). These maps can produce information at the farm level that
408 can then possibly be linked with information about farmers' personal characteristics or their
409 farming practices. In order to link information from different spheres (natural and social), we
410 applied various statistical methodologies (logistic regression, linear regression). Although the
411 statistical correlations measured are weak, our results are consistent with the literature. The
412 weakness of these statistical correlations reflects the difficulty of linking realities belonging to
413 different spheres (mainly social or mainly natural sciences). However, the ability to highlight
414 relationships between the datasets demonstrates the relevance of the methods implemented and
415 the quality of the datasets. Moreover, we used in this study multiple ES indicators that are based
416 on a land use classification and on our ability to understand how the different land use classes
417 provide ES. This raises the question of the benefit of using the ES concept to analyse
418 relationships between human beings and their environment, instead of relying directly on the
419 landscape. With a shared lexicon, the concept of ecosystem services (ES) has the potential to
420 nourish debates among actors from different disciplines.

421
422 From a more thematic point of view, our analyses bring out three main points that are coherent
423 with the scientific literature (Arnauld de Sartre 2013; Arnauld de Sartre et al. 2016):

- 424 1. The reality of relationships between the socioeconomic characteristics of farmers and the
425 supply of multiple ES;
- 426 2. ES supply is influenced more by the characteristics of agricultural production (increase the
427 total incomes) than by sociological or quality-of-life characteristics;

428 3. These relationships are inconspicuous and mainly express a strong effect of context,
429 especially due to differences in the temporalities of the deforestation.

430
431 Over and above these three points, this study improved our knowledge of the impact of
432 deforestation on ES supply and on the development of specific associations, since these
433 associations are influenced by:

- 434 • farmers' incomes from agricultural production.
- 435 • broader phenomena, probably related to the historical depth of the deforestation front and
436 public policies implemented in each study site.

437
438 Our results show that the establishment of specific ES associations is strongly influenced by
439 agricultural production characteristics while quality-of-life and sociological characteristics have
440 less impact. Since high agricultural production brings a decrease in ES supply, we have
441 highlighted the economic importance of deforestation and ES degradation for family farmers.
442 More environmentally friendly practices are not profitable because a decrease in deforestation
443 activities is synonymous with lower incomes. Our results point to the limits of environmental
444 management based on bad conscience and education, in other words on individual responsibility.
445 They could also suggest that payments for environmental services could reduce environmental
446 pressures on the forests, as it has been demonstrated in other studies (Kaczan et al, 2013; Saami
447 et al, 2014; Karsenty, 2015). Therefore, according to sustainable development theories, in order
448 to change practices that are responsible for unsustainable development, it is essential to raise
449 awareness about practices with negative impacts on the environment (Salles 2006). However,
450 thinking globally to act locally does not seem to be enough, because despite the recognition of
451 environmental issues arising from deforestation in the Amazon rainforest, it is continuing. It has

452 been shown (Lavelle et al. 2016) that the loss of ES is accompanied by a better quality of life and
453 more economically efficient agricultural production. In the current context, the persistence of
454 environmental degradation due to deforestation is explained by its profitability.

455
456 Besides the influence of agricultural production characteristics, these analyses showed a very
457 strong site effect. This site effect is directly illustrated by the statistical analyses that reveal the
458 site as a significant variable or indirectly when the significant explanatory variables are all site-
459 dependant (e.g. Pacajá is characterized by poor living conditions, a large number of migrations
460 and small families, whereas Maçaranduba and Palmares II are characterized by a smaller number
461 of migrations and larger families). The site effect is by no means anecdotal, as it not only
462 expresses the heterogeneity of the biophysical environment but also the importance of the
463 historical depth of deforestation and/or public policies for ES supply. In the context of a pioneer
464 front, wealth accrues in principle from the degradation of the natural environment. The
465 differences in impacts on the environment that are due to the diversity of socioeconomic
466 characteristics are insignificant in comparison with this major overall factor. And yet, this factor
467 is directly correlated with the site. The influence of farmers' characteristics on the environment is
468 not as decisive as their distribution among the three study sites, but it is dependent on global
469 dynamics that are typically underpinned by public policies. In each site, we tried to set aside this
470 site effect in order to identify the socioeconomic factors that govern ES supply. Each site is
471 characterized by its history of deforestation and the implementation of specific public policies.
472 These two factors can explain the high ES supply in Pacajá, where no environmental public
473 policy has been implemented but where deforestation activities are relatively new and farms are
474 characterized by the presence of many forested areas. Similarly, although Maçaranduba has been
475 deforested since the 1970s, ES supply is high in some areas, due to the implementation of

476 extractivist practices. Some farmers have chosen to use state credits to develop sustainable
477 activities. Others have relied on forest products such as Brazil nuts, through marketing networks
478 developed by sustainable development programs. This locality is therefore characterized by a
479 dichotomy in farming choices. Spatially, this translates into farms that in some cases are mainly
480 structured by forests and in others by pastures. By investigating these two factors further,
481 differences appear among the sites, although they are faint compared to major global trends. In
482 particular, these differences in ES supply reflect differences in the type of agriculture
483 (commercial or family farming). Smallholdings, which are characterized by low income and a
484 small total number of livestock animals, thus have high ES supply regardless of the study site,
485 particularly Pacajá and Maçaranduba. In Palmares II, there are fewer differences among farms as
486 regards ES supply than in the two other sites. However, in this site, ES supply tends to increase
487 when incomes from non-agricultural activities and perennial crops increase.

488

489 **5. Conclusion**

490

491 The analysis of the influence of societies on their environment is an object of study for many
492 disciplines and different schools of thought within them. For example, in Geography, cultural or
493 human ecology and political ecology are frequently presented as opposites. While cultural
494 ecology and human ecology researchers argue that human beings, at the individual or household
495 level, have a strong impact on the environment in which they evolve (Zimmerer 2004), especially
496 in tropical forests (Walker 2003; Coomes 2004; Vance et al. 2004; Perz, Walker, and Caldas 2006;
497 Caldas et al. 2007), other researchers, in political ecology for example, argue that environmental
498 degradation is more a consequence of global phenomena such as public policies (Benjaminsen
499 and Svarstad 2009). Our analyses show that, for our case study, the impact of such individual

500 human characteristics on the natural environment is not that obvious. Our data illustrate the
501 difficulties involved in making quantitative estimations of the impact of individual dynamics on
502 ecosystems: although there is a relationship between agricultural production characteristics and
503 ES supply, it is very tenuous. These results are critical to understand the conditions for the
504 success or failure of political projects that aim to reconcile environmental conservation and
505 agricultural production for local populations in the pioneer front area. Yet, in the Brazilian
506 Amazon, a conservationist project has been developed since the mid-1980s to create protected
507 areas and, in this way, to counter the advance of the pioneer front (Pinton and Aubertin 2005;
508 Soares-Filho et al. 2006)

509
510 With more in-depth knowledge on the history of deforestation activities, we could implement an
511 analysis based on the identification of regime shifts and tipping points in ES supply (Scheffer et
512 al. 2009). Some studies have indeed suggested the existence of ecological thresholds, called
513 tipping points, beyond which a system becomes unstable and evolves into a new system (Scheffer
514 et al. 2001; Groffman et al. 2006). The underlying processes are likely to change or degrade
515 different ecosystem services (Chazdon 2003; Grau et al. 2003; Lewis 2009), especially in a
516 context of forest degradation (van Wilgen et al. 2001; Chazdon 2003; Grau et al. 2003; Lewis
517 2009). Geographical analyses of the regime transitions should continue to increase our
518 understanding of such process and their variation across spatial scales. A better knowledge of
519 these processes should be of interest for policies and management opportunities.

520

521

522 **6 References**

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702
703

Spatial indicator	Unit / measurement range	ES provided	MEA category	Variables used to calculate the indicator
Vegetation carbon stock	Mg/ha	Climate regulation	Regulation	Aboveground dry biomass of trees, bushes and herbaceous plants
Soil carbon stock	Mg/ha	Climate regulation and soil fertility	Regulation	Bulk density and total C content at 0-10, 10-20 and 20-30 cm depths
Rate of water infiltration into the soil	mm/h	Water cycle regulation and soil erosion control	Regulation	Infiltration rate
Soil chemical quality index	0.1-1.0	Support to production	Support	Exchangeable Ca_2^+ , Mg_2^+ , K^+ , Al_3^+ and NH_4^+ , and extractable P contents at a 0-10 cm depth
Biodiversity index	Mean of species - 0.1-1.0	Supply chain support and biodiversity for biodiversity's sake	Cultural and Support	Number of moths, birds, bees, fruit flies, spiders, ants, soil macrofauna, termites, earthworms, and small, medium and tall plants
Richness of pollinators	Total number of <i>Sphingidae</i> collected	Support to production and pollination	Support and regulation	Number of <i>Sphingidae</i>

704 Table 1. Description of the 6 ES indicators used to build up the indicator of ES associations
705

Description and unit	Dataset
Number of working days per farm worker on the farm	Agricultural production
Income per deforested hectare – dollars	
Proportion of gross product from annual crops	
Proportion of gross product from beef production	
Proportion of gross product from other livestock	
Proportion of gross product from perennial crops	
Total agricultural gross product – dollars	
Proportion of gross product per family worker	
Proportion of non-agricultural incomes	
Deforestation rates	
Proportion of pasture	
Livestock unit - number of animals of 250 kg per hectare	
Family work unit in terms of full-time equivalents	
Typology of migration trajectories (4 types)	Sociological characteristics
Typology of professional trajectories (5 types)	
Educational level achieved	
Typology of demographic structure	
Quantitative index for household equipment	Quality of life
Number of migrations divided by age	
Educational level achieved	

Measure of isolation	
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706 *Table 2. Names and descriptions of socioeconomic variables*
707

	Logistic regression	Decision tree
<i>Agricultural production</i>	1 (0.45)	0.89 (0.37)
<i>Sociological characteristics</i>	0.93 (0.51)	1 (0.54)
<i>Quality-of-life</i>	1 (0.46)	0.8 (0.43)

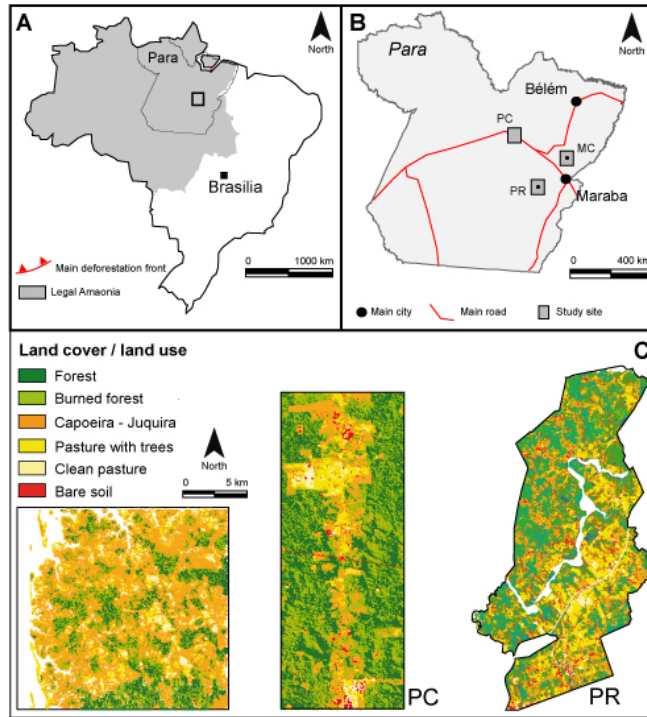
708 *Table 3. For each method implemented, rate of misclassification (prediction of a class that differs*
709 *from the initial class) standardized by the maximum value of the series. In brackets, the raw rates*
710 *of misclassification. In bold, the method that presents the best predictive capacities and that we*
711 *used in our further analyses.*
712

	Impacting factors	Selected statistical method
<i>Agricultural production</i>	Total gross product, Gross product per cultivated hectare, Livestock unit, Family work unit	Decision tree
<i>Sociology</i>	Site, Typology of demographic structure	Logistic regression
<i>Quality-of-life</i>	Number of migrations, Living conditions, Site	Logistic regression

713 *Table 4. At the sampling plot level, presentation of the factors that impact the establishment of ES*
714 *associations.*
715

Socioeconomic datasets	Significant explanatory variables	R ²
Agricultural production	Total income and Site	0.20
Sociology	Site	0.11
Life quality	Site	0.17

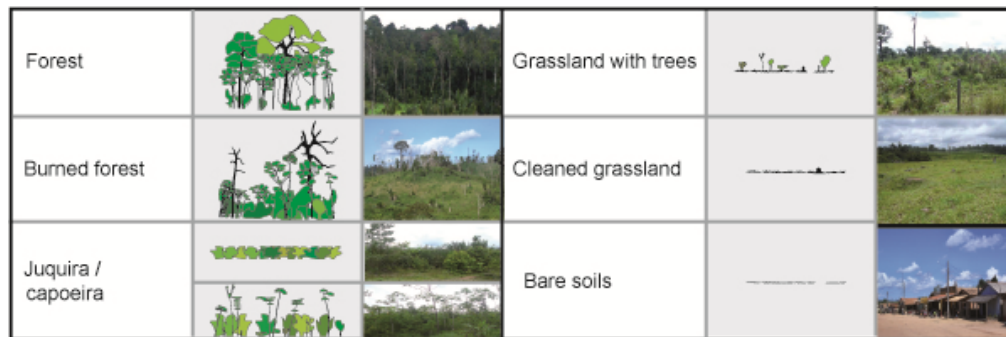
717 *Table 5. At the farm level, results of multiple linear regressions that aim to explain the indicator*
718 *of the spatial composition of ES associations from socioeconomic characteristics. All R² tests*
719 *were significant (p-value < 0.05).*
720



721
 722
 723 *Fig 1 Location of Pará State (a) and the study sites of Macaranduba (MC), Pacajá (PC) and*
 724 *Palmares II (PR - b). Zoom on the three study sites (c). The coloured maps show land use in the*
 725 *study sites in 2007.*

726

727

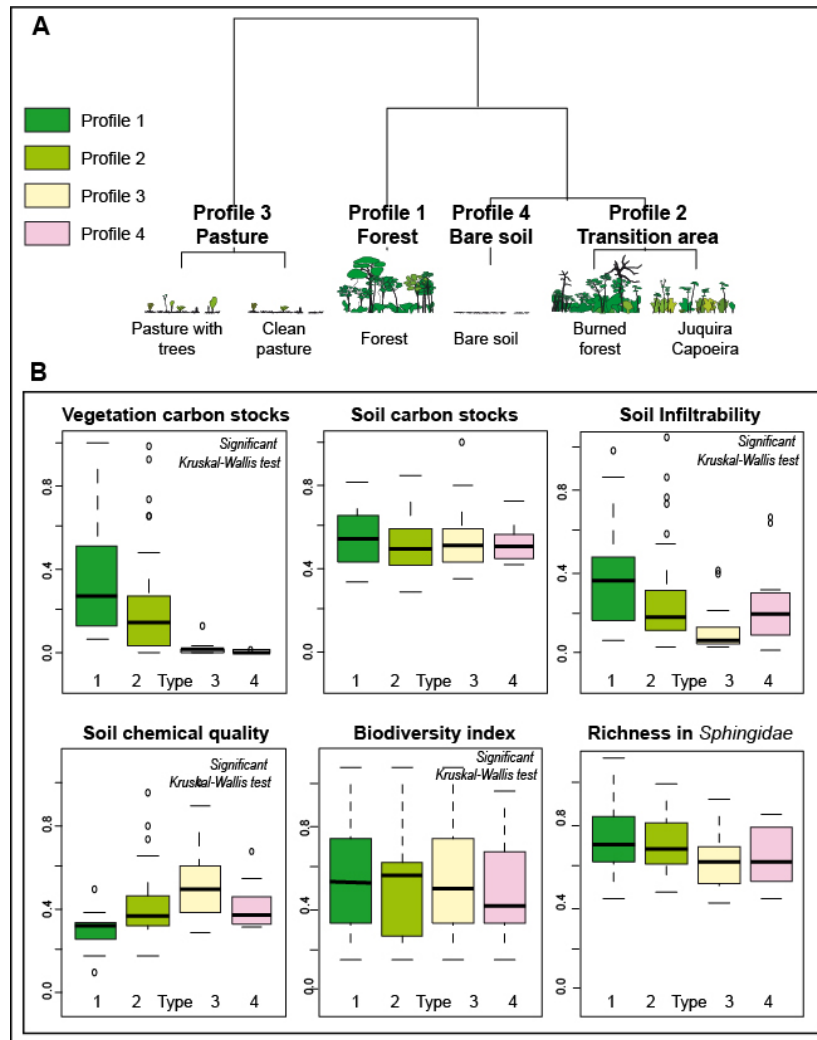


728
 729
 730 *Fig 2 Six land cover classes derived from Landsat TM images, used to create the indicator of ES*
 731 *associations. Juquira-Capoeira: Capoeira (upper picture) is fallow land dominated by*
 732 *herbaceous plants. Bushes are more dominant in juquira lands (lower picture).*

733

734

735

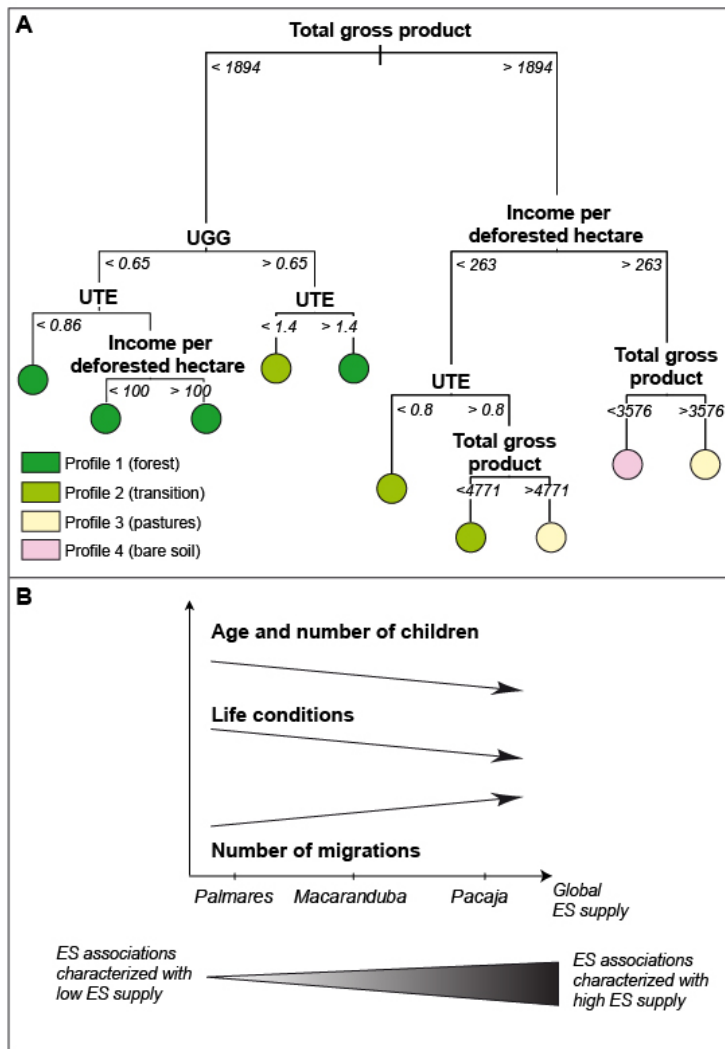


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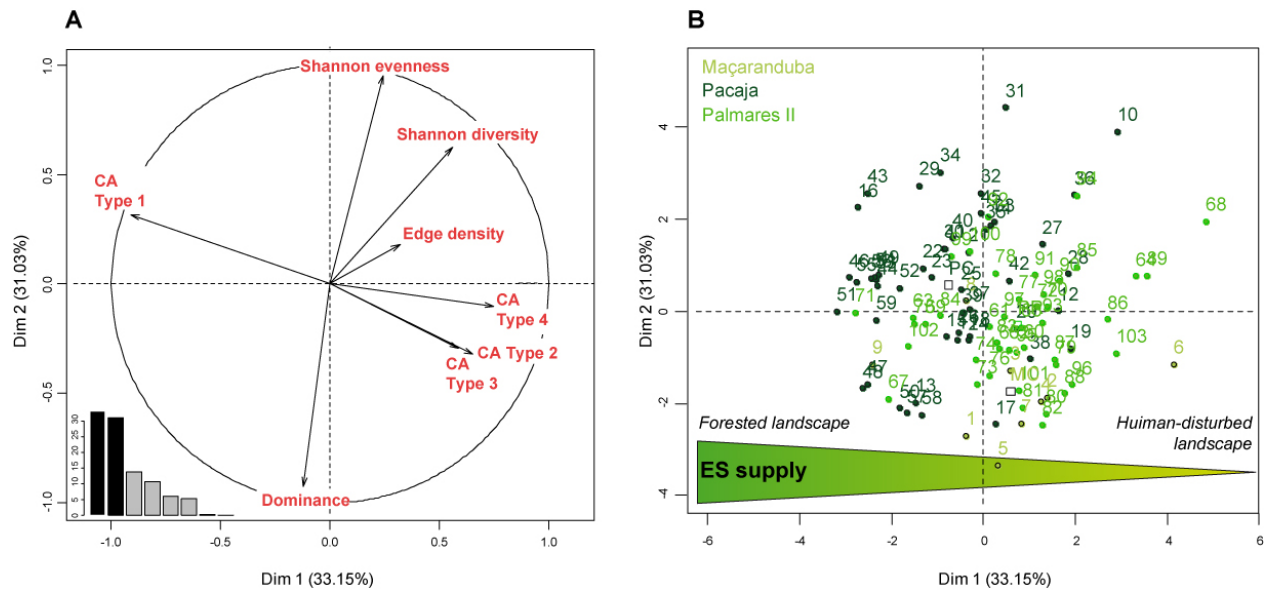
738

739 *Fig 3. a. The four land-cover groups resulting from the Ascending Hierarchical Clustering*
 740 *dendrogram; b. Description of the ecosystem services provided by the four types of associations*
 741 *provided by each of these groups.*

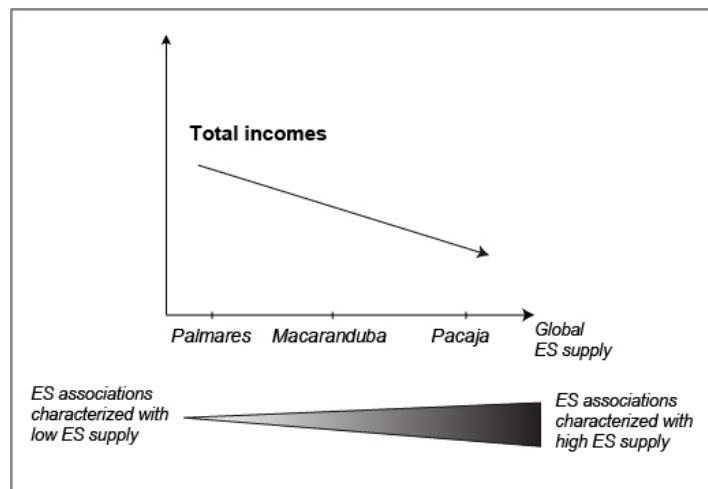
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743
 744 Fig 4 (a) Decision tree explaining the establishment of ES associations from the agricultural
 745 production dataset. Acronyms: UGG = Livestock unit (number of 250 kg animals per hectare);
 746 UTE = Family work unit in terms of full-time equivalents. (b) Relations between the significant
 747 variables from the sociological and quality-of-life datasets and the ES associations. The direction
 748 of the arrows reflects the trends followed by the variable when the ES associations are
 749 characterized by an increasing ES supply (from profile 4 to 1). “Age and number of children”
 750 indicates the demographic structure.
 751



752
 753 *Fig 5 a. Correlation circles showing the correlation of each indicator of structure and spatial*
 754 *composition of ES associations with the first two Principal Component Analysis (PCA) axes (the*
 755 *arrows point in the direction of highest values of the indicators). The insert shows the*
 756 *distribution of variance among PCA axes. b. Graph of individuals (farms): the colours vary*
 757 *according to the study site they belong to.*
 758



759
 760 *Fig 6. Relations between the significant variables from the socioeconomic datasets and the ES*
 761 *associations. The direction of the arrows reflects the trends followed by the variable when the ES*
 762 *associations are characterized by an increasing ES supply (from profile 4 to 1)*
 763

764 ***Biodiversity Index***

765 To study biodiversity we calculated a standardized indicator of species richness which indicates
766 the mean of several species richness for each of the 135 sampling points from 12 groups of
767 organisms: moths, birds, bees, fruit flies, ground spiders, ants, termites, earthworms, other soil
768 macro-invertebrates, and lower, medium and higher strata of the vegetation. For each taxonomic
769 group, the species composition and the number of individuals observed for each species were
770 recorded. For each group, we first normalized the species richness as a proportion (0–1) of the
771 highest richness observed (of the same group) in the 135 sampling points. The final index of
772 species results from the average of the normalized richness for each sampling point.

773

774 ***Richness of Pollinators***

775 *Sphingidae* moths were collected following the methodology described in Lamarre et al. (2015).
776 We used a light trapping, for each transect, at the closest point to the largest forest present in the
777 agricultural zone. The moths were attracted by a 175-W mercury vapor bulb—powered by a
778 small portable generator. A white sheet 2 m high 9 3 m wide was used as a reflector. At each
779 point, the collection was carried out over a single night, from 18:00 to 06:00. The moths were
780 then killed by injection of ammonia, stored and dried in marked paper envelopes and taken to the
781 laboratory for identification and enumeration.

782

783 ***Soil Chemical Quality Index***

784 The index was calculated from a PCA performed on several soil chemical proprieties (pH, H₂O,
785 cation exchange capacity—CEC—at soil pH; exchangeable Al³⁺, Ca²⁺, Mg²⁺ and K⁺;
786 exchangeable N⁴⁺ and extractable P- Velasquez, Lavelle, and Andrade (2007)) measured using
787 standard methods (Pansu and Gautheyrou 2006).

788 Measurements were performed from a composite from two pits using particle size distribution
789 and chemical properties of the 0- to 10-cm soil horizon that were measured.

790

791 *Soil Carbon Stocks*

792 Soil carbon stocks were calculated from bulk density measurements in the 0- to 30-cm horizon
793 (CHNS analyzer in three samples from each plot).

794

795 *Rate of Water Infiltration into the Soil*

796 Rate of water infiltration into the soil was measured on the field, using a Beerkan infiltration test.
797 The test was implemented with a fixed water volume of 250 cm³ poured into a 20-cm-diameter
798 simple ring inserted at the soil surface to a depth of approximately 1 cm.

799

800 *Vegetation Carbon Stocks*

801 Samples were made for plots of 50x9x10 m² for forests and 50x9x5 m² for fallows. Vegetation
802 species were identified. Then, the team measured the diameter and height of individuals and
803 water content at 70°C of corresponding biomass aliquots (all individuals with dbh < 5 cm) and
804 implemented allometric equations to estimate aboveground dry plant biomass for forests
805 (Gerwing 2002) and fallows (Nelson et al. 1999). If some individuals had dbh above 5 cm, the
806 factor 0.603 was applied, and if carbon analysis of plant samples was missing, a factor of 0.5 was
807 used (Markewitz et al. 2004).

808

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