



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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Abstract

In tropical forests farmers are among the most important agents of deforestation. At the interface between societies and their environment, ecosystem services (ES) is an integrated working framework through which natural and anthropogenic dimensions can be addressed. Here, we aimed to understand to what extent farmers impact ES availability. Based on case studies in three locations in the Brazilian Amazon rainforest, we performed statistical analyses at 135 sampling points and 110 farms to link socioeconomic and ES data, both derived from field work. The socioeconomic data characterized agricultural production, sociological characteristics, and quality of life. ES data were obtained from statistical analyses that yielded a multiple ES indicator for each sampling point and farm. Our results produced three main findings: first, the establishment of ES associations is due more to agricultural production characteristics than to sociological and quality-of-life factors. Second, the impact of agricultural production on ES availability depends on the level of total incomes. An increase in incomes causes a decrease in the forest cover that provides many ES and an increase in other areas that provide fewer ES. Finally, our analyses show a very strong site effect that probably expresses the heterogeneity of the biophysical contexts, but also the importance for ES availability of the historical depth of deforestation and/or the role of specific public policies. Finding ways of producing an alternative impact on ES availability and establishing specific ES associations will therefore depend more on changes in the global political context than in individual practices.

Keywords Socioecological systems · Multiple ecosystem service · Deforestation · Family agriculture · Sustainable agriculture · Brazilian Amazon

Introduction

In tropical forests in general, deforestation is caused by timber felling and colonization for agricultural purposes

(FAO 2012), so that farmers are among the most important agents of deforestation (Pasquis 1999; Arnauld de Sartre 2006; Davidson et al. 2012; Théry 2012). Agricultural activities cause changes to the natural environment, including biodiversity (Baker et al. 1995) and ecosystem services (ES) (Erle and Pontius 2007). In the Brazilian Amazon, issues relating to the impacts of family farmers on their environment are of crucial importance: these farmers

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occupy areas in which they have to preserve the natural environment in order to continue their activities (Soares-Filho et al. 2006; Davidson et al. 2012). At the same time, they need the same space for social and economic functions, to live and work and produce maximum benefits (Rodrigues et al. 2009). But to develop and use this space, family farmers are actively contributing to deforestation, which allows them to own land on which to live and work, while causing its degradation (Grimaldi et al. 2014).

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

In these areas, deforestation results in the formation of pioneer fronts. The dynamics of these pioneer fronts fluctuate according to demographic and economic variables related to the territory (Lena 1986). Pioneer front areas are affected by extreme tension between environmental protection and economic development, which translates into intense and rapid changes in the environment. They are therefore of great interest for studies of the relationships between human beings and their environment, and hence for the identification of statistical methodologies that make it possible to investigate an extremely complex scientific question. In this context, the question is whether the direct link between people's practices and their impact on the environment is significantly important, compared to other broader factors such as the political context or the history of colonization.

At the interface between societies and their environment, ES may be seen as an integrated framework through which both natural and anthropogenic dimensions can be addressed. Up to now, quantitative research has been conducted to assess the impact of farming practices on environmental sustainability (Benton et al. 2002; Pretty et al. 2006; Firbank et al. 2008; Godfray et al. 2014; Poppy et al. 2014; Pywell et al. 2015; Smith et al. 2017) but still very little quantitative assessment of the impacts of farming activities and farmers' characteristics on ES supply in the Brazilian rainforest. There are two ways in which to consider

relationships between human activities and ES supply: by studying either the influence of ES supply on human activities, or the reverse, i.e., the influence of human beings on ES supply. In this article, we decided to use the second approach in areas of high tension between environmental protection and economic development that characterize the pioneer fronts. We thus applied the concept of ES in order to identify to what extent farmers have an impact on ES supply through their presence on the land and their activities: how do different patterns of farming practice and different sociological characteristics and living conditions influence the supply of ES?

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

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

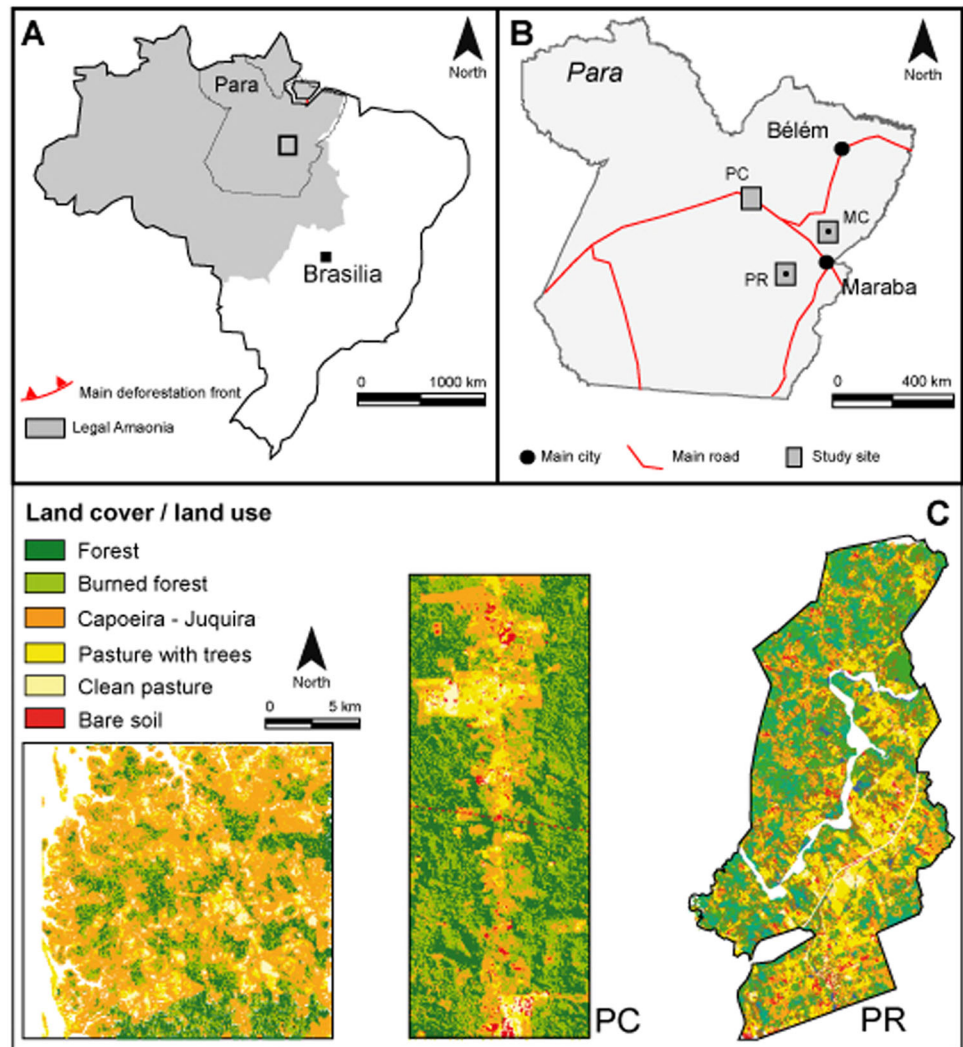
Materials and Methods

Study Sites

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

Site selection was guided by the need to take into account different local contexts, as the importance of the latter in the implantation of the pioneer fronts to understand the forms of evolution of these fronts has already been emphasized (Albaladejo and Veiga 2002). The three study sites were chosen for three main reasons: (1) they are experiencing deforestation dynamics; (2) These dynamics of deforestation are differentiated in time and in their socioeconomic and political origins; and (3) These three sites present various biophysical characteristics (e.g., topography, nature of the soil).

Fig. 1 Location of Pará State (a) and the study sites of Maçaranduba (MC), Pacajá (PC) and Palmares II (PR—b). Zoom on the three study sites (c). The colored maps show land use in the study sites in 2007



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

Located in the municipality of Nova Ipixuna, the Maçaranduba site covers approximately 220 km². This site has been logged since the 1970s, but the forest cover is still relatively well preserved, mainly thanks to the implementation of sustainable development practices based on extractivism. Covering 175 km², the Pacajá site is located about 60 km from the urban centre, on one of the “fishbone” tracks (Traversão 338 south) perpendicular to the Trans-Amazon highway. Deforestation has occurred since the early 1990s through spontaneous settlement. Forest cover was still plentiful in 2007 (63%). The 160 km² Palmares II *assentamento* (settlement) is located near the Carajas iron mine, close to the former gold mine of Eldorado do Carajas.

It is emblematic of the agrarian reform and results from the struggles between the Landless Workers Movement, the government and the Vale mining company. As the land was divided into similar-sized lots, the area is highly fragmented.

Data

Our study was based on the analysis of two datasets, collected during field campaigns (ANR AMAZ, 2007–2008, coord. Patrick Lavelle) from measurements (indicators of potential ES supply—Grimaldi et al. (2014)) or interviews (socioeconomic characteristics—Lavelle et al. (2016)):

- An indicator of ES associations. The calculation of this indicator has been described in another study (Le Clec’h et al. 2016). Six indicators of ES potential supply were measured during field campaigns and used to create an indicator of ES associations. We decided to analyse

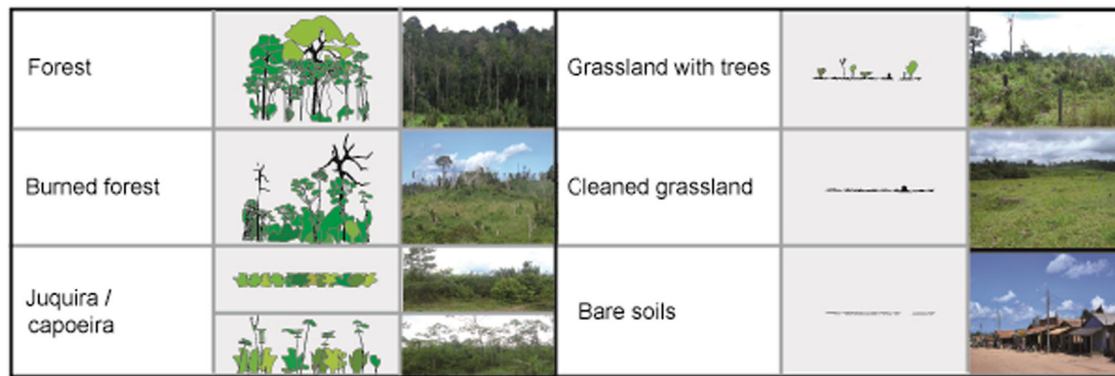


Fig. 2 Six land-cover classes derived from Landsat TM images, used to create the indicator of ES associations. Juquira-Capoeira: Capoeira (upper picture) is fallow land dominated by herbaceous plants. Bushes are more dominant in juquira lands (lower picture)

impacts on multiple ES indicators, rather than on a few individual ES indicators, in order to obtain an overall view of ES supply. From this indicator of ES associations, we calculated other multiple ES indicators at the farm level.

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

An indicator of ES associations

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

The indicator of ES associations was built up from six indicators of potential ES supply: vegetation carbon stock (service of climate regulation), soil carbon stock (service of primary production), rate of water infiltration into the soil (water regulation service and soil erosion control), chemical soil quality (service of support to production), a standardized index of biodiversity (cultural service), and species richness of 70 pollinator moths (*Sphingidae*—pollination service—Table 1). We decided to use spatial indicators of the biophysical processes to characterize ES because defining indicators of the biophysical processes that provide the services is one way to map ES (Oszwald et al. 2014).

These six indicators of potential ES supply studied were measured in situ. All indicators were assessed using field data collected from 27 farms (nine per site). On each of the 27 farms, five sampling points were spaced equally along a transect corresponding to the longest diagonal of the farm on a north–south axis (for more details about the calculation of the indicators, see Grimaldi et al. 2014).

To build up an indicator of ES associations, we applied a method developed by Le Clec’h et al. (2016). This involved bundling categories of a remote sensing variable, the land-cover classification, according to their similarities in the provision of each individual ES. For the 135 sampling points, for each of the six land-cover classes of the Landsat TM-based classification, we averaged each ES indicator (field data—arithmetic mean with equal weights). We used the average values to calculate a distance matrix among the land-cover classes. We then applied Ascending Hierarchical Clustering (AHC) to the distance matrix to determine groups of land-cover profiles that provided homogeneous levels of ES. The land-cover groups corresponded to associations of the six ES indicators and could be mapped. In this way, we built up information about ES associations for the 135 sampling points but also for the whole area of the three study sites.

We discriminated between four profiles of ES associations (Fig. 3). The first profile, corresponding to forested areas, has a high vegetation carbon stock, a high rate of water infiltration, and chemically poor soil. The second profile, corresponding to areas of burned forest and forest edges, has lower vegetation carbon stocks and a lower rate of water infiltration than the first profile, and chemically richer soil. The third profile is a combination of pastures and fallow lands (juquira-capoeira) characterized by low ES supply, except for the chemical soil quality index. The fourth profile, associated with bare soils, is characterized by low vegetation carbon stocks and chemically rich soils. The bare soils category in fact corresponds to two different

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

Spatial indicator	Unit/measurement range	ES provided	MEA category	Variables used to calculate the indicator
Vegetation carbon stock	Mg/ha	Climate regulation	Regulation	Above ground 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>

realities that cannot be discriminated by remote sensing images acquired during the dry season: it may correspond to actual bare soils, such as roads, tracks, and their surroundings, but also to fields for annual crops with no plant cover at this time of the year. The heterogeneity of this class produces wide differences in ES supply.

Socioeconomic data

Socioeconomic data were collected to characterize 110 farms within the three study sites. Interviews were conducted with the farmer-householders. To address this question on the Amazonian pioneer fronts, and thus to investigate the impacts of farmers on the environment, three points have been emphasized as of particular importance (Arnauld de Sartre 2006; Caldas et al. 2007): the economic function of the farms (absolute and relative value of different types of production), quality-of-life indicators (e.g., household equipment) and the personal characteristics of the farmers (demography, life trajectory¹, level of education, etc.). Consequently, different variables were extracted from the interviews (for more information, see Arnauld de Sartre and Sebillé (2008); Arnauld De Sartre et al. (2011)): information on agricultural production, the sociology of the farmers and their quality of life (Table 2).

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

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

- Replicating socioeconomic values for the sampling points. We considered that a farm is a homogeneous entity from the perspective of each socioeconomic variable. We therefore attributed the same socioeconomic value to each of the sampling points within one farm. Consequently, the 135 sampling points were characterized by a specific profile of ES association and socioeconomic information.
- Obtaining a multiple ES profile for each farm. To do so,

¹ Life trajectory of an individual refers to his multiple biographical components such as residential, professional or familial components (Hélarlot 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.

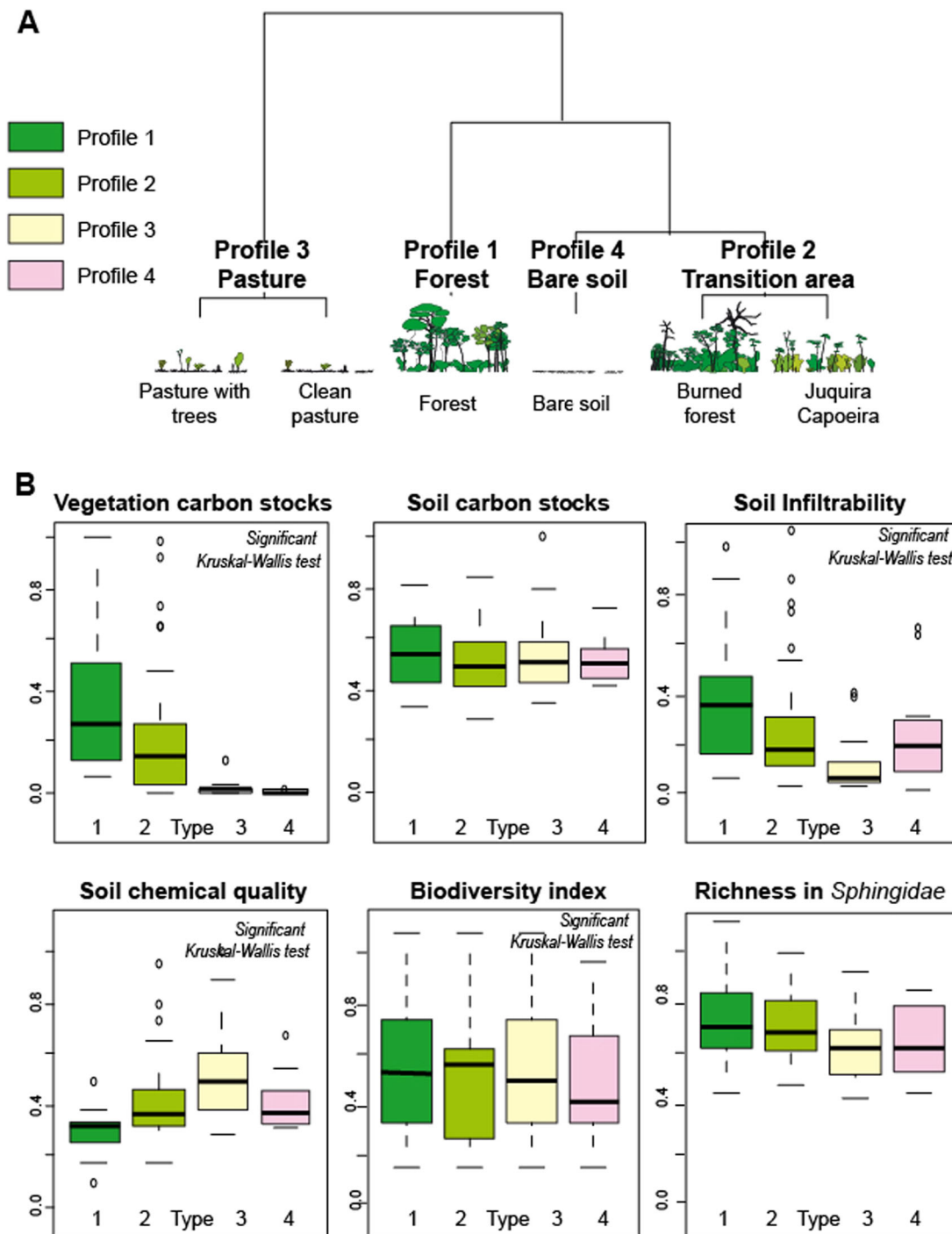


Fig. 3 a The four land-cover groups resulting from the Ascending Hierarchical Clustering dendrogram; b Description of the ecosystem services provided by the four types of associations provided by each of these groups

we created a synthetic index. Since this approach is less natural, we describe it below in detail.

As previously explained, we built up an indicator of ES associations at the sampling points from the land use classification. This indicator was subsequently extended to each

satellite image pixel for the three sites. In fact, to get information about the provision of ES at the farm level, we had to bundle the data. However, each single situation (each farm) encompasses many different statistical and spatial realities. To synthesize these, we created spatial indicators, using landscape ecology and spatial analysis indicators.

Table 2 Names and descriptions of socioeconomic variables

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)	
Typology of professional trajectories (5 types)	
Educational level achieved	
Typology of demographic structure	Quality of life
Quantitative index for household equipment	
Number of migrations divided by age	
Educational level achieved	
Measure of isolation	

These quantitative indicators, called landscape metrics, are designed to draw up a detailed inventory of the distribution and spatial variability of a given phenomenon (McGarigal et al. 2002). They have been widely used in tropical contexts (Oszwald et al. 2012; Almeida-Gomes and Rocha 2014; Carrara et al. 2015). They are often based on land use data but it is also possible to incorporate other information into their calculation, such as ES association types in this case. The calculation of landscape metrics enabled us to synthesize the spatial distribution of ES associations within the 110 farms for which socioeconomic data are indicated. These metrics can be divided into three groups:

The first group includes diversity metrics that quantify the ES richness of the farms, or the dominance of a particular profile of ES association on a given a farm (Shannon diversity index—SD, Shannon evenness—SE and dominance index—D).

The second group includes the metrics used to quantify the complexity of ES association forms and their edges (fragmentation—edge density—ED).

The last group informs about the composition of ES associations, i.e., the proportion of the area for each profile of ES association (class area— $CA_{profile1, \dots, CA_{profile4}}$).

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

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

Statistical Analyses

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

A second set of analyses was performed for the farm level, to find out whether the socioeconomic characteristics have an impact on the spatial structure of ES associations.

First, the eight landscape metrics were synthesized into a single indicator of multiple ES. This synthetic variable was constructed by applying a PCA to the metrics. The values of this variable match the individual coordinates on the first factorial axis. We combined the socioeconomic dataset with the multiple ES index using regression methods. The multiple ES indicator was then considered as the response variable (Y), while the socioeconomic data were considered as explanatory variables (X), since regression methods assume the existence of a function f that links the response variable Y to the explanatory variables X_1, \dots, X_p (Cornillon and Matzner-Lober 2011). Because we assume that the function f is linear, the model is written as follows:

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

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

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

Results and Discussion

Low Correlation between ES Supply and Socioeconomic Datasets at the Sampling Point Level

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

A Strong Negative Correlation between ES Supply and Incomes at the Sampling Point Level

The socioeconomic characteristics that most influence the establishment of ES associations are related to agricultural

Table 3 For each method implemented, rate of misclassification (prediction of a class that differs from the initial class) standardized by the maximum value of the series

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

In brackets are shown the raw rates of misclassification. In bold is shown the method that presents the best predictive capacities and that we used in our further analyses

production (misclassification rate = 0.37). The distribution of sampling points within the ES association groups is mostly explained by factors related to incomes (Table 4). However, these results should be considered with caution because the error rates (misclassification rates based on mismatches between the predictions and the original values) are quite high.

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

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

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

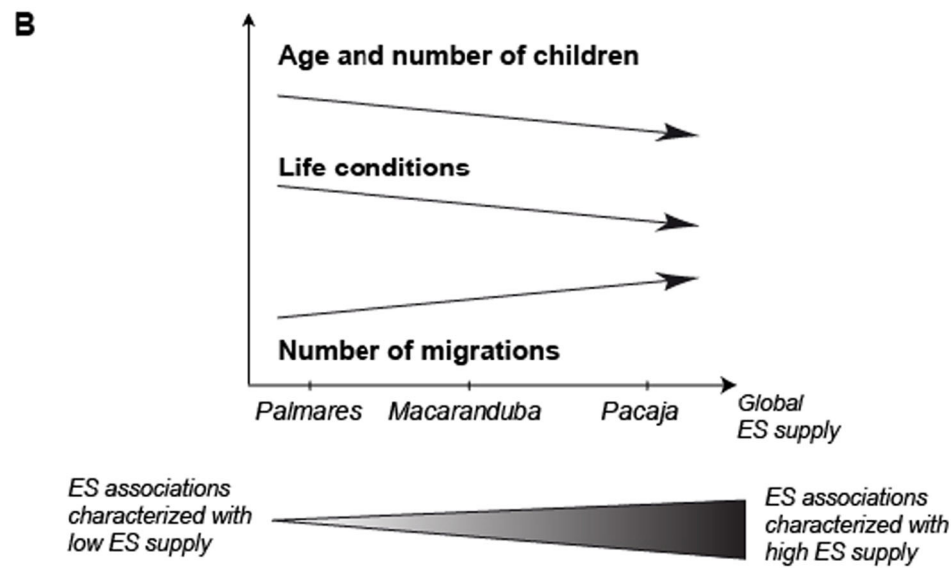
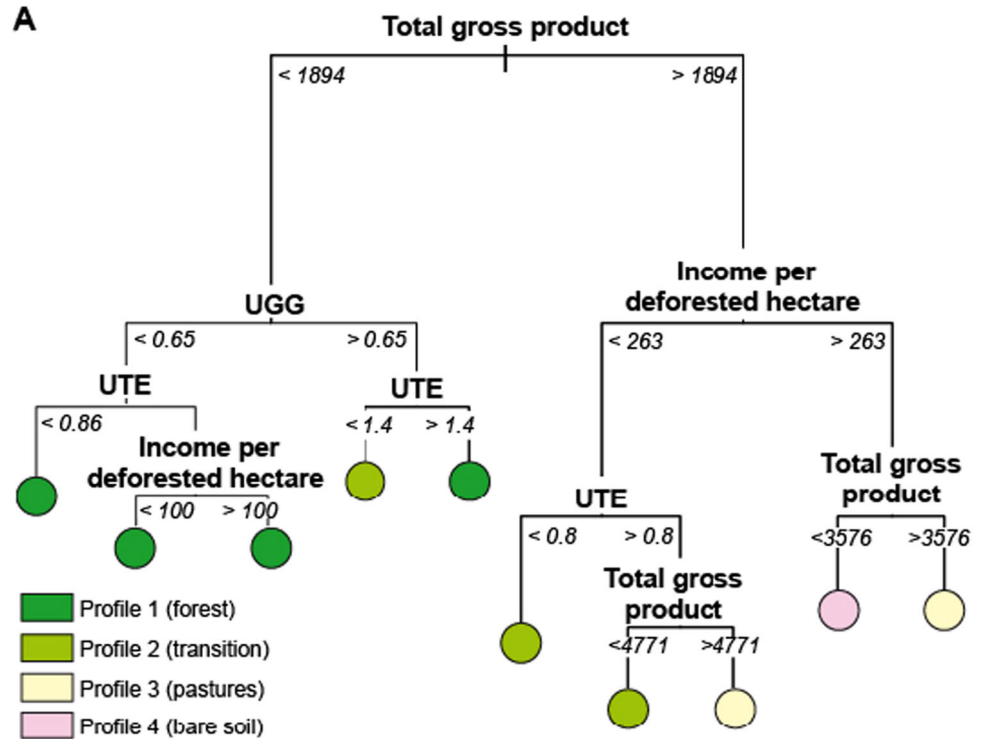
At the Farm Level, Impact of Context, and Agricultural Incomes

At the farm level, the PCA performed on the eight indicators of the structure and spatial composition of ES associations shows the relationships between these variables (Fig. 5). The first factorial plan explains about 64% of the total inertia. The first factorial axis, used as a synthetic indicator of the spatial composition of ES associations, explains about 33% of the inertia. It is mainly built up from the contrast between forested farms characterized by specific ES associations (high supply of almost all ES) and farms that have already been deforested and are in various stages of canopy opening (profile 2, 3, and 4 of ES

Table 4 At the sampling plot level, presentation of the factors that impact the establishment of ES associations

	Impacting factors	Selected statistical method
Agricultural production	Total gross product, gross product per cultivated hectare, livestock unit, family work unit	Decision tree
Sociology	Site, typology of demographic structure	Logistic regression
Quality-of-life	Number of migrations, living conditions, site	Logistic regression

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



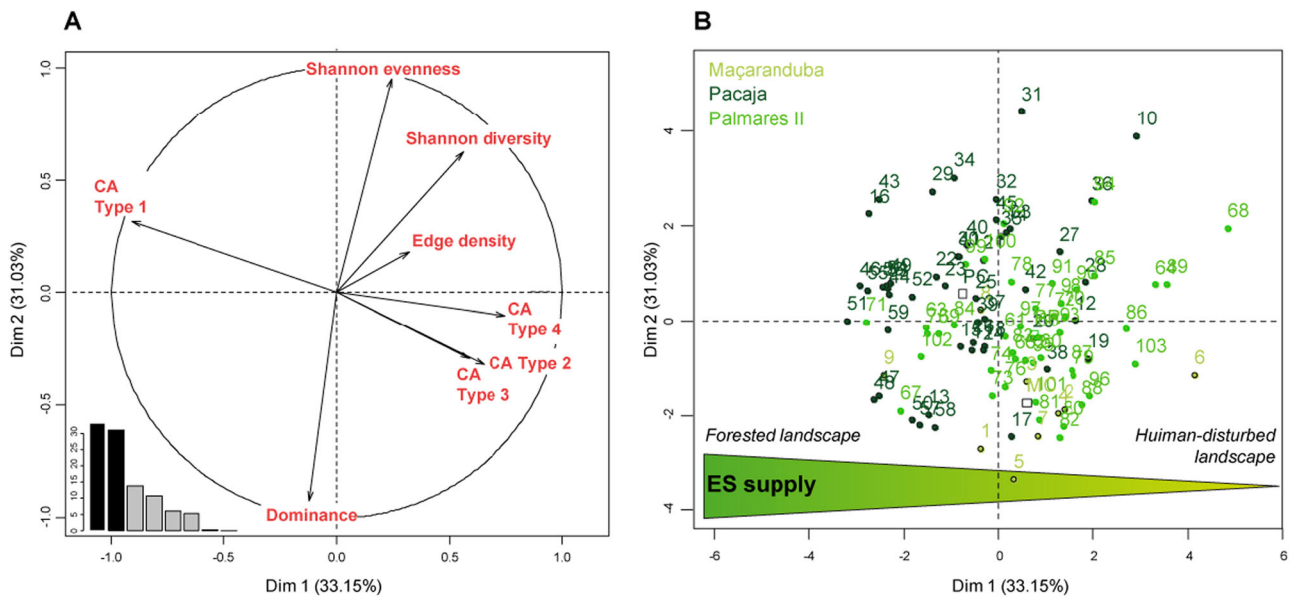


Fig. 5 a Correlation circles showing the correlation of each indicator of structure and spatial composition of ES associations with the first two Principal Component Analysis (PCA) axes (the arrows point in the

direction of highest values of the indicators). The insert shows the distribution of variance among PCA axes. **b** Graph of individuals (farms): the colors vary according to the study site they belong to

Table 5 At the farm level, results of multiple linear regressions that aim to explain the indicator of the spatial composition of ES associations from socioeconomic characteristics

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

All R² tests were significant (*p*-value < 0.05)

associations). In other words, the indicator has high positive values for farms with low ES supply, mainly located in Palmares II, and negative values for farms with high ES supply, except for the chemical soil quality index. These negative values essentially correspond to farms located in Pacajá. The graph for individual farms shows that the spatial landscape composition (and therefore ES associations) varies according to the study site. The farms located in Pacajá, where the deforestation dynamics are more recent, have more forest and provide more ES than the two other study sites.

Three linear regressions were performed to explain the variations of this synthetic indicator built up from the coordinates of the farms on the first PCA axis. The low values of the three R² show the relative capacity of socioeconomic data to explain the variations of the ES indicator (Table 5).

The establishment of ES associations is more the result of agricultural production characteristics than of sociological and quality-of-life factors. The linear regression

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

Discussion

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

- the value of spatial information to link data from two different spheres of study,
- the contribution of statistical methods to link these data.

Mapping multiple ES indicators makes it possible to obtain generalized information for a whole area (three local study sites in our case). These maps can produce information at the farm level that can then possibly be linked with information about farmers’ personal characteristics or their farming practices. In order to link information from

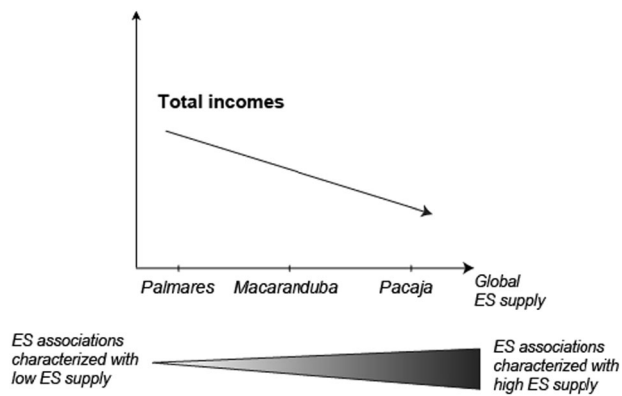


Fig. 6 Relations between the significant variables from the socio-economic datasets and the ES associations. The direction of the arrows reflects the trends followed by the variable when the ES associations are characterized by an increasing ES supply (from profile 4 to 1)

different spheres (natural and social), we applied various statistical methodologies (logistic regression, linear regression). Although the statistical correlations measured are weak, our results are consistent with the literature. The weakness of these statistical correlations reflects the difficulty of linking realities belonging to different spheres (mainly social or mainly natural sciences). However, the ability to highlight relationships between the datasets demonstrates the relevance of the methods implemented and the quality of the datasets. Moreover, we used in this study multiple ES indicators that are based on a land use classification and on our ability to understand how the different land use classes provide ES. This raises the question of the benefit of using the ES concept to analyse relationships between human beings and their environment, instead of relying directly on the landscape. With a shared lexicon, the concept of ES has the potential to nourish debates among actors from different disciplines.

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

1. The reality of relationships between the socioeconomic characteristics of farmers and the supply of multiple ES;
2. ES supply is influenced more by the characteristics of agricultural production (increase the total incomes) than by sociological or quality-of-life characteristics;
3. These relationships are inconspicuous and mainly express a strong effect of context, especially due to differences in the temporalities of the deforestation.

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

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

Our results show that the establishment of specific ES associations is strongly influenced by agricultural production characteristics while quality-of-life and sociological characteristics have less impact. Since high agricultural production brings a decrease in ES supply, we have highlighted the economic importance of deforestation and ES degradation for family farmers. More environmentally friendly practices are not profitable because a decrease in deforestation activities is synonymous with lower incomes. Our results point to the limits of environmental management based on bad conscience and education, in other words on individual responsibility. They could also suggest that payments for environmental services could reduce environmental pressures on the forests, as it has been demonstrated in other studies (Kaczan et al. 2013; Samii et al. 2013; Karsenty 2015). Therefore, according to sustainable development theories, in order to change practices that are responsible for unsustainable development, it is essential to raise awareness about practices with negative impacts on the environment (Salles 2006). However, thinking globally to act locally does not seem to be enough, because despite the recognition of environmental issues arising from deforestation in the Amazon rainforest, it is continuing. It has been shown (Lavelle et al. 2016) that the loss of ES is accompanied by a better quality of life and more economically efficient agricultural production. In the current context, the persistence of environmental degradation due to deforestation is explained by its profitability.

Besides the influence of agricultural production characteristics, these analyses showed a very strong site effect. This site effect is directly illustrated by the statistical analyses that reveal the site as a significant variable or indirectly when the significant explanatory variables are all site-dependant (e.g., Pacajá is characterized by poor living conditions, a large number of migrations and small families, whereas Maçaranduba and Palmares II are characterized by a smaller number of migrations and larger families). The site effect is by no means anecdotal, as it not only expresses the heterogeneity of the biophysical environment but also the importance of the historical depth of deforestation and/or public policies for ES supply. In the context of a pioneer front, wealth accrues in principle from the degradation of the natural environment. The differences in impacts on the environment that are due to the diversity of socioeconomic characteristics are insignificant in comparison with this major overall factor. And yet, this factor is directly correlated with the site. The influence of farmers' characteristics on the environment is not as decisive as their distribution

among the three study sites, but it is dependent on global dynamics that are typically underpinned by public policies. In each site, we tried to set aside this site effect in order to identify the socioeconomic factors that govern ES supply. Each site is characterized by its history of deforestation and the implementation of specific public policies. These two factors can explain the high ES supply in Pacajá, where no environmental public policy has been implemented but where deforestation activities are relatively new and farms are characterized by the presence of many forested areas. Similarly, although Maçaranduba has been deforested since the 1970s, ES supply is high in some areas, due to the implementation of extractivist practices. Some farmers have chosen to use state credits to develop sustainable activities. Others have relied on forest products such as Brazil nuts, through marketing networks developed by sustainable development programs. This locality is therefore characterized by a dichotomy in farming choices. Spatially, this translates into farms that in some cases are mainly structured by forests and in others by pastures. By investigating these two factors further, differences appear among the sites, although they are faint compared to major global trends. In particular, these differences in ES supply reflect differences in the type of agriculture (commercial or family farming). Smallholdings, which are characterized by low income and a small total number of livestock animals, thus have high ES supply regardless of the study site, particularly Pacajá and Maçaranduba. In Palmares II, there are fewer differences among farms as regards ES supply than in the two other sites. However, in this site, ES supply tends to increase when incomes from non agricultural activities and perennial crops increase.

Conclusion

The analysis of the influence of societies on their environment is an object of study for many disciplines and different schools of thought within them. For example, in Geography, cultural or human ecology and political ecology are frequently presented as opposites. While cultural ecology and human ecology researchers argue that human beings, at the individual or household level, have a strong impact on the environment in which they evolve (Zimmerer 2004), especially in tropical forests (Walker 2003; Coomes 2004; Vance et al. 2004; Perz et al. 2006; Caldas et al. 2007), other researchers, in political ecology for example, argue that environmental degradation is more a consequence of global phenomena such as public policies (Benjaminsen and Svarstad 2009). Our analyses show that, for our case study, the impact of such individual human characteristics on the natural environment is not that obvious. Our data illustrate the difficulties involved in making

quantitative estimations of the impact of individual dynamics on ecosystems: although there is a relationship between agricultural production characteristics and ES supply, it is very tenuous. These results are critical to understand the conditions for the success or failure of political projects that aim to reconcile environmental conservation and agricultural production for local populations in the pioneer front area. Yet, in the Brazilian Amazon, a conservationist project has been developed since the mid-1980s to create protected areas and, in this way, to counter the advance of the pioneer front (Pinton and Aubertin 2005; Soares-Filho et al. 2006)

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

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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