Shifting cultivation in decline : An analysis of soil fertility and weed pressure in intensified cropping systems in Eastern Amazon

Agriculture, Ecosystems and Environment

Abrell, Thomas; Naudin, Krishna; Bianchi, Felix J.J.A.; Aragao, Debora Veiga; Tittonell, Pablo et al

https://doi.org/10.1016/j.agee.2023.108793

This publication is made publicly available in the institutional repository of Wageningen University and Research, under the terms of article 25fa of the Dutch Copyright Act, also known as the Amendment Taverne.

Article 25fa states that the author of a short scientific work funded either wholly or partially by Dutch public funds is entitled to make that work publicly available for no consideration following a reasonable period of time after the work was first published, provided that clear reference is made to the source of the first publication of the work.

This publication is distributed using the principles as determined in the Association of Universities in the Netherlands (VSNU) 'Article 25fa implementation' project. According to these principles research outputs of researchers employed by Dutch Universities that comply with the legal requirements of Article 25fa of the Dutch Copyright Act are distributed online and free of cost or other barriers in institutional repositories. Research outputs are distributed six months after their first online publication in the original published version and with proper attribution to the source of the original publication.

You are permitted to download and use the publication for personal purposes. All rights remain with the author(s) and / or copyright owner(s) of this work. Any use of the publication or parts of it other than authorised under article 25fa of the Dutch Copyright act is prohibited. Wageningen University & Research and the author(s) of this publication shall not be held responsible or liable for any damages resulting from your (re)use of this publication.

For questions regarding the public availability of this publication please contact
openaccess.library@wur.nl

Agriculture, Ecosystems and Environment 360 (2024) 108793

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Shifting cultivation in decline: An analysis of soil fertility and weed pressure in intensified cropping systems in Eastern Amazon

Thomas Abrell[a,b,c], Krishna Naudin[a,b], Felix J.J.A. Bianchi[c], Debora Veiga Aragao[d], Pablo Tittonell[a,b,e], Marc Corbeels[a,b,f,*]

[a] CIRAD, UPR AIDA, Montpellier F-34398, France
[b] AIDA, Univ Montpellier, CIRAD, Montpellier, France
[c] Wageningen University and Research, Farming Systems Ecology, P.O. Box 430, Wageningen 6700 AK, the Netherlands
[d] Embrapa Amazônia Oriental, Tv. Dr. Eneas Pinheiro, s/n - Marco, Belém, PA 66095-903, Brazil
[e] Groningen Institute of Evolutionary Life Sciences, Groningen University, P.O. Box 72, Groningen 9700 AB, the Netherlands
[f] IITA, Nairobi, Kenya

ARTICLE INFO

Keywords:
Swidden agriculture
Brazil
Sustainable production
Weed control
Soil conservation
Cassava

ABSTRACT

Reconciling forest preservation and agricultural production is a major challenge. In Brazil, environmental laws have been introduced to reduce forest degradation associated with the expansion of agriculture. However, these laws are constraining small-scale family farmers who rely on cassava produced in shifting cultivation. Faced by scarcity of land, farmers are reducing the fallow periods on their farms. In this study, our hypothesis was that the reduction of the fallow period in shifting cultivation systems leads to a depletion of soil fertility and an increase in weed pressure. In the Brazilian Eastern Amazon region, soil fertility and weed infestation indicators were assessed in 36 cassava fields under shifting cultivation with different land-use histories. The frequency of cultivation of the fields in the past 10 years ranged from 1 to 7 and averaged 3.7 ± 2.3. The results show that the most frequently cultivated fields had lower soil fertility, indicated by lower soil organic carbon, total nitrogen and exchangeable potassium and pH. In addition, labor input for weeding and weeding frequency increased with the frequency of cultivation of the fields, indicating that weed pressure increased with intensified crop cultivation and shorter fallow periods. The findings of this study make clear that the current trend of reducing the fallow period in the Eastern Amazon is a threat to the sustainability and productivity of the local shifting cultivation systems. There is an urgent need for alternative production systems that allow for a better weed control and that contribute to restoring and maintaining soil fertility.

1. Introduction

The Brazilian Amazon forest represents one third of the world's tropical rainforest, but deforestation and the associated land degradation are major threats to its conservation (Lapola et al., 2023; Lewinsohn and Prado, 2005). Whilst between 2005 and 2015 deforestation declined as a response to the Brazilian policies and regulations on the protection and sustainable use of native forests (i.e. Forest Code, law no. 12.651/2012), more recently deforestation rates have surged, reflecting the reversal in the public policies on forest protection and the deliberate obstructions towards environmental agencies enforcing the regulations under the previous presidency (Ferrante and Fearnside, 2019). In 2021 deforestation was at its highest level since 2006, reaching 13 235 km^2 between 1st of August, 2020 and 31th July, 2021 (INPE, 2023).

The Forest Code stipulates the obligation of landholders in the Amazon region to maintain 80% of the forest cover on their farms, the so-called Legal Reserve (Area de Reserva Legal, in Portuguese) (Azevedo et al., 2017). It also forbids uncontrolled fire use, while some state and municipal laws (e.g., in the state of Acre and in the municipality of Paragominas in the Pará state) forbid all forms of fire use (Cammelli et al., 2019). However, despite these policies and because of the lack of practical fire-free alternatives, small-scale family-owned farmers continue 'pioneer' slash-and-burn practices, including the clearing of new areas of forest (Carmenta et al., 2019; Godar et al., 2012; Schons et al., 2019). Slash-and-burn is a type of shifting cultivation that entails the burning of the natural vegetation for non-permanent crop

---

* Correspondence to: IITA, Icipe Office, Duduville Complex, Kasarani off Thika Road, P.O. Box 30772-00100, Nairobi, Kenya.
E-mail address: corbeels@cirad.fr (M. Corbeels).

https://doi.org/10.1016/j.agee.2023.108793
Received 15 April 2023; Received in revised form 18 July 2023; Accepted 21 October 2023

cultivation (Conklin, 1961). This practice on the small-scale family farms was estimated to contribute to about 15% of the total deforestation in the Brazilian Amazon (Godar et al., 2014).

In shifting cultivation systems, fields are cultivated temporarily, then abandoned and allowed to recover to their natural vegetation as fallow. The sustainability of shifting cultivation largely relies on fallowing and allowing the natural vegetation to regenerate from stumps and roots that survived the cultivation period (e.g. Guillemin, 1956; Uhl and Jordan, 1984). In the Amazon region, population growth and the associated increasing demand for farmland have, however, caused a reduction in the length of the fallow periods in the context of forest conservation (Jakovac et al., 2017; Van Vliet et al., 2012). For example, it was reported that farmers in the northeastern region of the Pará state have gradually reduced the length of the fallow periods to about three to seven years (Gehring et al., 1999). Reduced lengths of fallows have an impact on several ecological processes of the shifting cultivation system (Wood et al., 2017), affecting soil fertility and crop yields (e.g. Jakovac et al., 2016), and also leading to lowered biodiversity (e.g. Metzger, 2003; Villa et al., 2018) and higher emissions of carbon dioxide into the atmosphere (e.g. Shimizu et al., 2014). Secondary forest recovery during the fallow period plays an important role in partially recapturing through deep root uptake the nutrients that have been leached to deep soil layers (e.g. Sommer et al., 2004). Moreover, the closed canopy of the regenerating secondary forest helps breaking the reproduction cycle of weeds, especially herbaceous ones, that built up in the field during the crop cultivation period (De Rouw, 1995). Therefore, management of the length of the fallow period is important, particularly for cash-constrained farmers who have limited access to fertilizers and herbicides.

While the importance of the fallow period for maintaining the long-term productivity of shifting cultivation systems is widely acknowledged, there is no consensus on the length of the fallow period required to keep the system sustainable and ecologically sound (Kleinman et al., 1995; Mertz et al., 2008). This is mostly because of the large diversity of shifting cultivation systems (Fujisaka et al., 1996). For sustainable regeneration of soil fertility, it is generally assumed that the length of the fallow period has to range between five to 15 years or more, depending on the local climate and soil conditions, as well as the cultivation practices (Bruun et al., 2006; Hepp et al., 2018; Nye and Greenland, 1964; Schmidt-Vogt et al., 2009). On the other hand, the effect of the length of the fallow period on weed dynamics and weed pressure is still poorly studied (Jakovac et al., 2016), but is also important with regard to the productivity and sustainability of the shifting cultivation system; weed control constitutes a major time investment for small-scale family farmers in the Amazon region (Vissoh et al., 2007).

In the Eastern Amazon region, cassava (*Manihot esculenta* Crantz) is the main staple food crop for family farmers (Díaz et al., 2018) and is mostly produced in shifting cultivation systems based on slash-and-burn. Maintaining cassava productivity with short fallow cycles is challenging; the productivity in these systems without external inputs depends mainly on the inherent soil fertility along with the nutrients released from the slashed (and burned) fallow biomass, and on the natural levels of weed and pathogen infestations.

The aim of this study is to assess the consequences of reduced fallow periods on soil fertility and weed pressure in shifting cultivation systems of small-scale family farmers in Paragominas, Eastern Amazon. In general, the provision of ecosystem services by fallows and secondary forests in shifting cultivation systems remains poorly understood (Mertz, et al., 2021), and few studies have examined the effect of fallow duration on soil or vegetation properties across cultivation cycles in the Amazon (Wood et al., 2017). A comprehensive understanding of the factors controlling soil fertility and weed pressure is essential for the successful management of shifting cultivation. We compared soil fertility, weed pressure and weed control in farmers' cassava fields with different cultivation frequencies, and thus fallow lengths. The study provides important new insights that can aid in the development of alternatives to slash-and-burn systems. These alternatives have the potential to break the vicious circle of reduced fallow periods, soil fertility depletion, increasing weed pressure, and crop productivity loss.

2. Materials and methods

2.1. Study sites

The study was conducted in the rural region of Paragominas, Pará state, Brazil, from December 2015 to March 2018 (Fig. 1). The region is characterized by a monsoonal equatorial climate (Am, Köppen classification), with an average annual temperature of 26.6°C and annual precipitation of 1800 mm. The wet season (defined as those months when rainfall is above 60 mm) spans from January to June; the dry season from July to December. Soils in the study region are mainly yellow dystrophic Latosols (Brazilian Soil Classification) or xanthic Ferralsols (World Reference Base for Soil Resources). The original vegetation in the region is ombrophilous dense forest.

The study was done in three sites: the village of Nazaré (2°40.92'S, 47°53.35'W), and the communities of Paragonorte and Patrimônio, both situated in the Luiz Inácio Lula da Silva settlement (2°32.03'S, 46°57.25'W) (Fig. 1). The main characteristics of the study sites are shown in Table 1. The village of Nazaré hosts a community of traditional farmers that is older than the creation of the municipality of Paragominas in 1964. It is the least developed site in terms of infrastructure, and farmers have no access to tractors or herbicides. The Luiz Inácio da Silva settlement was created at the end of the 1990 s as part of the Brazilian agrarian reform to free land in the Amazon region for landless farmers. Paragonorte is a village located in this settlement and hosts a population of 'colonists', i.e. farmers with land allocated by the government to cultivate it. In a part of the settlement, called "Patrimônio", the land has not yet been officially attributed and has been informally occupied by spontaneous settlers, i.e. self-sponsored farmers who cultivate the land on their own initiative. Cassava is the main staple crop in these three study sites. It is mostly used for self-consumption.

2.2. Field selection and previous land use

In each study site a number of cassava fields were randomly selected, depending on the willingness of farmers to contribute to monitoring their fields. Eighteen fields were selected in Nazaré (from 10 farms), five fields in Paragonorte (three farms), and 13 fields in Patrimônio (five farms). Seventeen fields (10 in Nazaré, 3 in Paragonorte and 4 in Patrimônio) were monitored during 2015–2017 and 19 fields (8 in Nazaré, 2 in Paragonorte and 9 in Patrimônio) during 2017–2018. Cassava was planted at the onset of rains at the end of December 2015 (first cassava cropping cycle) and in January 2017 (second cycle) and managed according to the local farmer practices. Field sizes were between 0.15 and 4.4 ha, and 10 of the 36 selected fields were intercropped with maize. To account for within-field heterogeneity, five square-shaped experimental plots (25 m^2) were demarcated in an "X" pattern (i.e., one plot in the center of the field and four plots in between the center and each field corner) within each field.

Interviews with the farmer of each field were conducted to reconstruct the land-use history since the initial clearing of the native forest. Complementary interviews with neighbors or previous occupants of the fields were also conducted to triangulate the data. Three land-use categories were distinguished to characterize the land use/land cover of the fields: cropland, regenerative fallow, or forest. The interviews allowed the reconstruction of the full land-use history of all selected fields up to 10 years back in time. Finally, the frequency of fallow and cultivation of the fields during that 10-years period was quantified.

2.3. Field management data

Data on cassava management were collected for each field by

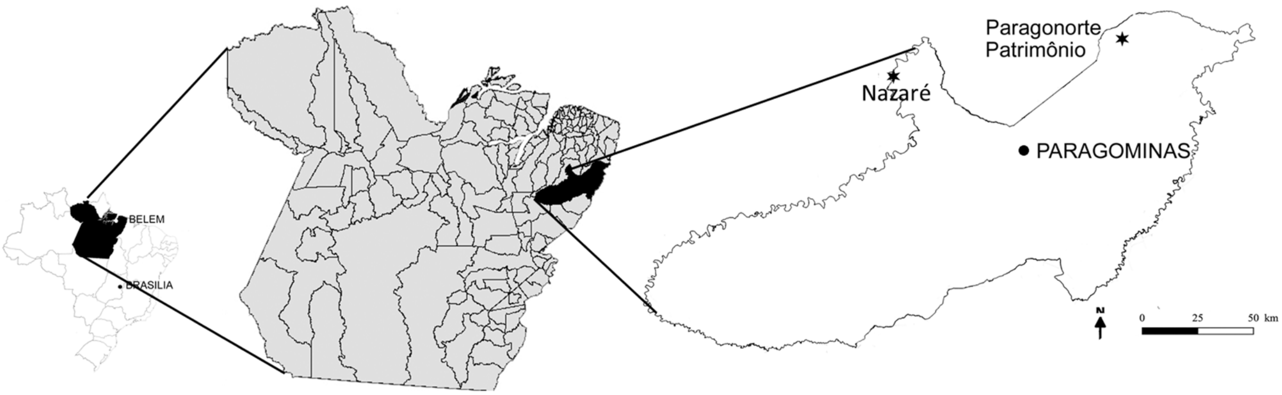

Fig. 1. Location of the study sites in the in Paragominas Municipality within the Pará state in Brazil.

Table 1
Main characteristics of the three study sites. Values represent means and standard errors.

	Paragonorte	Patrimônio	Nazaré
Number of farms	3	5	10
Number of fields	5	13	18
Number of observation plots	25	65	90
Population density (people km^{-2})	75	300	12
Farmer/settler type	government-sponsored colonist	spontaneous settler	indigenous
Soil type	yellow dystrophic Latosol	yellow dystrophic Latosol	yellow dystrophic Latosol
Rainfall recorded during cassava cropping cycle (mm)	2390	2390	2590
Vegetation cover preceding cultivation	secondary forest	secondary forest	primary forest
First land clearing	20 years ago	20 years ago	>40 years ago
Farm size (ha)	62.5 ± 4.2	2.2 ± 0.2	40.2 ± 2.5
Legal reserve size (ha)	17.0 ± 1.4	none	16.8 ± 1.3
Fallow period (yrs)	3.7 ± 0.6	0.58 ± 0.03	5.2 ± 0.3
Cassava area per farm in 2015 (ha)	1.6 ± 0.4	0.93 ± 0.14	0.69 ± 0.10
Silt + clay content (0–30 cm) (%)	37.9 ± 4.1	24.4 ± 3.5	48.6 ± 12.1
Soil bulk density (0–30 cm) (g cm^{-3})	1.40 ± 0.05	1.40 ± 0.05	1.39 ± 0.09
Soil pH (0–5 cm)	5.4 ± 0.7	4.7 ± 0.3	4.8 ± 0.6
Soil organic carbon (0–30 cm) (Mg C ha^{-1})	27.3 ± 6.0	25.7 ± 6.3	34.5 ± 6.4
Soil total nitrogen (0–30 cm) (Mg N ha^{-1})	2.4 ± 0.5	2.3 ± 0.5	3.0 ± 0.6
Exchangeable soil potassium (0–30 cm) (mg K kg^{-1})	28.2 ± 15.1	13.3 ± 7.2	26.1 ± 12.0

conducting monthly interviews with the farmers during the 2015–2017 and 2017–2018 cropping cycles. Management activities were classified as: land preparation, planting, weeding, and harvest. For each activity, the start and end date, the labor inputs as well as the amount and cost of other inputs were recorded. The land preparation consisted of slash-and-burn, mechanical plowing or herbicide application. Land preparation with plows or herbicides was performed for fields with fallow periods of 0–2 years. Slashing was conducted with a chainsaw for big trees and with machete and hoes for the residual plant cover. Mechanical land preparation was performed by tractors with a disc plow. In the case of herbicide clearing, glyphosate was commonly used. The crops were always planted within a two-week time window after the land preparation, and no extra weeding was done in between vegetation clearing and cassava planting. Weeding after planting was conducted manually with hoes. All crop management activities were performed by family labor, with the exception of the weeding for which extra labor was occasionally hired and for the mechanical land clearing and preparation that was done by hired tractor services.

2.4. *Soil sampling and analyses*

Soil sampling was conducted on each experimental plot (five plots per field) during the dry seasons of 2016 and 2017. In each plot, undisturbed soil samples were collected using volumetric steel rings (100 cm^3) at depths of 0–5, 5–10, 10–20, and 20–30 cm, resulting in five replicate samples per field for each soil depth. The samples were air dried for several days and weighted to determine soil bulk density. A 50 g sub-sample of each sample was dried in an oven at a temperature of 105 °C for 48 hours to determine dry soil weight, and to correct the bulk density for residual moisture. The remaining soil of the sample was manually crushed to pass through a 2 mm sieve. Samples were analyzed for organic carbon (Schollenberger method), total nitrogen (Kjeldhal method), texture (pipette method), pH ($CaCl_2$) and exchangeable K+ (extraction with ammonium acetate, NH_4OAc, pH 7.0 and flame photometry), as described in Elisabeth and Claessen (1997).

2.5. *Assessment of weed pressure*

Weed growth and weeding activities by farmers were monitored in all selected fields during the 2017–2018 cropping cycle. Farmers weeded their fields according to their usual practices, but were asked not to weed the five experimental plots established in their fields. Prior to each weeding event and at harvest, proportional weed cover (% of soil covered by weed) in the experimental plots was determined with the Canopeo® smartphone application (Patrignani and Ochsner, 2015), using five replicate pictures per plot. The weed cover development rate (% day^{-1}) was calculated by dividing the measured weed cover by the number of days since the last weeding (or since land preparation for the first assessment). The aboveground biomass of all monocotyledonous and dicotyledonous weeds was then measured in the experimental plots. Weeds were cut at soil level and fresh biomass of monocotyledonous and dicotyledonous weeds was determined. 300 g sub-samples were oven dried at 70°C for 72 h to determine dry weight (Da Silva, 2009). For each plot, an average monocotyledonous-to-dicotyledonous weed biomass ratio for the whole cropping cycle was calculated. The weed biomass growth rate (g dry weight m^{-2} day^{-1}) was determined by dividing the dry weight weed biomass by the number of days since the last weeding event (or since land preparation). To determine the average rates of weed cover development and weed biomass growth for the whole cropping cycle, rates were weighed over the successive weed assessments.

2.6. Cassava yield measurements

Fresh root weights were measured from all cassava plants in the experimental plots when farmers decided to harvest i.e., after between 12 and 20 months of growing cycle. In some experimental plots, cassava plants died due to root rot diseases; yield was recorded as zero in these cases.

2.7. Statistical analyses

The effects of the frequency of cultivation in the 10 years prior to the start of the experiments on soil fertility and weed pressure (response variables) were quantified using linear mixed modeling. Five indicators of soil fertility were used: organic carbon, total nitrogen, exchangeable potassium, pH, and bulk density. Weed pressure was characterized by the number of weeding events, the labor time dedicated to weeding and the average weed cover development and weed biomass growth rates during the cassava cropping cycle. The clay plus silt content of the 0–30 cm soil layer was included as an additional explanatory variable because soil texture affects soil carbon content and may also influence weed growth dynamics. Since several fields were located on the same farm, and farms were nested within sites, 'Farm within Sites' and 'Site' were set as random factors in the models. All statistical analyses were conducted in R (Core Team, 2020), using the *lme* function of the *lme4* package for mixed models.

3. Results

3.1. Site and farm characteristics

The selected study sites represent different shifting cultivation farms of the region of Paragominas in Eastern Amazon (Table 1). In Paragonorte and Patrimônio, the clearing of (secondary) forest for cultivation took place about 20 years ago, whilst the fields in Nazaré are considerably older than 20 years; initial (primary) forest clearing for cultivation occurred in the early 1960s. Farms in Patrimônio are much smaller (2.2±0.2 ha) than in Nazaré and Paragonorte (40.2±2.5 ha and 62.5±4.2 ha, respectively). In fact, in Patrimônio farmers cultivate small plots of land that were not officially attributed to them. Obviously, these farms do not have areas of Legal Reserves. Patrimônio has also by far the highest population density (300 persons km^{-2}, Table 1) and land scarcity is acute, resulting in short lengths of fallow periods, i.e. on average 0.58 ± 0.03 years, compared to 3.7 ± 0.6 and 5.2 ± 0.3 years in respectively Paragonorte and Nazaré (Table 1). Farms in Paragonorte had the largest areas cultivated with cassava, namely on average 1.6 ±0.4 ha compared to 0.7±0.1 ha and 0.9±0.1 ha in Nazaré and Patrimônio, respectively (Table 1). In Nazaré farmers also grow other (perennial) crops, such as chili peppers (*Capsicum spp.*), açaí palm (*Euterpe oleasea* Mart.), cashew tree (*Anacardium occidentale* L.) or cupuaçu (*Theobroma grandiflorum* (Willd.ex. Spreng.) Schum.).

3.2. Cultivation frequency and land preparation type

All fields of the study had either been cultivated or left fallow over the last 10 years; there were thus no recently converted fields from forest. The cultivation frequency of the selected fields during this period varied widely, i.e. from one to seven years out of 10 years, averaging 2.2, 6.0 and 2.1 in Paragonorte, Patrimônio and Nazaré, respectively (Fig. 2). Twenty-eight of the 36 monitored cassava fields were prepared for cultivation through traditional slash-and-burn practices (Table 2). In eight cases, i.e. the fields established after 0–2 years of fallow, the regenerated vegetation was not slash-and-burned but cleared by mechanical plowing or herbicide application.

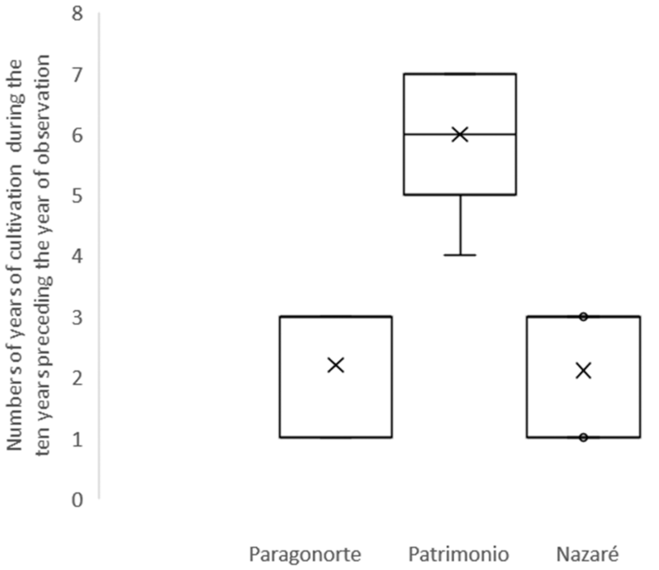

Fig. 2. Box plots of numbers of years of cultivation during the 10 years preceding the first year of observations (2016 or 2017) on the selected farmers' cassava fields at the three study sites, Paragonorte, Patrimônio and Nazaré in Eastern Amazon. The crosses indicate the mean values. n (number of fields) = 5 for Paragonorte, n = 13 for Patrimônio, n = 18 for Nazaré.

3.3. Soil fertility

The carbon stocks of the 0–30 cm soil layer were on average higher at Nazaré (34.5±6.4 Mg C ha^{-1}) than at the two other sites, Paragonorte and Patrimônio, situated in the Luiz Inácio Lula da Silva settlement (27.3±6.0 and 25.7±6.3 Mg C ha^{-1}, respectively) (Table 1). The total nitrogen stocks of the 0–30 cm soil layer showed a similar trend. The average higher soil carbon and nitrogen contents at Nazaré can be related to the higher clay plus silt content of the soils at Nazaré (48.6 ±12.1%) than at the two other sites (37.9±4.12% and 24.4±3.5%). Exchangeable potassium concentration in the 0–30 cm soil layer was on average lowest in the fields of Patrimônio (13±7 mg K kg^{-1} soil), i.e. half of the values observed in Nazaré and Paragonorte. All three sites had acidic soils with average pH values between 4.7 and 5.4 (Table 1). Average soil bulk density values did not differ between the sites.

3.4. Weed pressure and weeding

The lowest weed growth rate and weed cover at harvest were recorded in the fields in Paragonorte. Additionally, the average weed growth rate during the cassava cropping cycling in Paragonorte was at least half the observed growth rates in Patrimônio and Nazaré (Table 2). Similarly, weed cover at harvest in the slash-and-burn fields was almost 50% lower in Paragonorte than in the two other sites. Besides, in Patrimônio a lower weed growth rate was observed in the slash-and-burn fields than in the fields cleared with herbicides (17±8 versus 28±14 g dry weight ha^{-1} day^{-1}). Yet, the weed cover at harvest was higher in the slash-and-burn fields than in the cleared fields with herbicides (47±17 versus 38 ±7%). The average monocotyledonous-to-dicotyledonous weed biomass ratio varied from 0.36 (herbicide clearing at Patrimônio) to 0.42 and 0.49 (slash-and-burn systems at the three sites), suggesting that dicotyledonous weeds were more dominant in systems cleared with herbicides.

Labor time for weeding was highest in Patrimônio, namely in the fields prepared with slash-and-burn or with herbicides (on average 108 ±54 and 89±31 worker days ha^{-1}, Table 2). In Patrimônio, farmers weeded their fields on average 2.8±0.7 times during the entire cassava cropping cycle, about twice as much as in Nazaré (1.4±0.6) and Paragonorte (1.5±0.5). Weeding activities also spanned over a longer part of

Table 2

Crop management and labor input, productivity and weed pressure of the selected cassava fields in Paragonorte, Nazaré, and Patrimônio. Harvest labor data are not presented because these were strongly dependent on the productivity of the fields. Values represent means with standard errors. DAP: days after planting.

		Crop management								Cassava productivity		Weed pressure			
Site	Land preparation type	number of fields	field preparation (worker day ha^{-1})	planting (worker day ha^{-1})	weeding (worker day ha^{-1})	number of weeding events	time of first weeding (DAP)	time of last weeding (DAP)	harvest date (DAP)	average daily root growth rate (kg ha^{-1} day^{-1})	fresh root yield (Mg ha^{-1})	number of observational plots	average weed growth rate (g ha^{-1} day^{-1})	weed cover at harvest (%)	average monocotyledonous to dicotyledonous weed biomass ratio
Paragonorte	Slash-and-burn	4	40 ± 4	24 ± 7	19 ± 14	1.5 ± 0.5	44 ± 14	57 ± 30	379 ± 16	24 ± 5	10.6 ± 4.0	20	9 ± 6	28 ± 8	0.49 ± 0.04
	Mechanical plowing	1		21	9	2	45	132	491	21	10.3	0			
	Herbicide clearing	0										0			
Patrimônio	Slash-and-burn	6	41 ± 6	50 ± 11	108 ± 54	2.8 ± 0.7	46 ± 51	185 ± 102	392 ± 27	11 ± 15	4.2 ± 5.6	30	17 ± 8	47 ± 17	0.42 ± 0.16
	Mechanical plowing	2		19 ± 0	8 ± 0	1 ± 0	17 ± 11	23 ± 11	453 ± 4	25 ± 1	11.3 ± 0.5	0			
	Herbicide clearing	5	4 ± 8	23 ± 5	89 ± 31	2.8 ± 0.8	39 ± 16	223 ± 103	502 ± 98	23 ± 9	10.1 ± 3.1	25	28 ± 14	38 ± 7	0.36 ± 0.14
Nazaré	Slash-and-burn	18	33 ± 14	30 ± 13	29 ± 16	1.4 ± 0.6	90 ± 40	129 ± 32	436 ± 93	13 ± 9	5.1 ± 3.4	90	21 ± 15	49 ± 27	0.43 ± 0.27
	Mechanical plowing	0										0			
	Herbicide clearing	0										0			

the cropping cycle in Patrimônio as compared to Nazaré and Paragonorte. For instance, the first weeding of the slash-and-burn fields in Patrimônio occurred on average at 46±51 days after planting (DAP) and the last weeding at 185±102 DAP. In comparison, in Nazaré and Paragonorte the last weeding in the slash-and-burn fields took on average place at 129±32 and 57±30 DAP, respectively. Finally, total labor time for weeding was much lower in the fields prepared with mechanical plowing than in the ones prepared with slash-and-burn, both in Paragonorte and Patrimônio (Table 2).

3.5. Effect of cultivation frequency on soil fertility and weed pressure

Soil organic carbon and total nitrogen stocks, exchangeable potassium concentration and pH were significantly negatively associated with the frequency of cultivation of the fields in the past 10 years (Fig. 3, Table 3). For each additional year of cultivation, soil organic carbon and total nitrogen decreased by 1.38±0.42 Mg C ha^{-1} and 0.11±0.04 Mg N ha^{-1}, respectively. Exchangeable potassium declined with 1.6±0.6 mg 100 g^{-1} soil and pH with 0.07± 0.03. In contrast, there was no significant association between the frequency of cultivation and soil bulk density. Besides, the above soil fertility indicators were not significantly associated with the clay plus silt content of the soils (Table 3).

Labor time dedicated to weeding and number of weedings during the cropping cycle were positively associated with the frequency of cultivation of the fields (Fig. 4, Table 3). For each additional year of cultivation, the number of weedings and the labor time dedicated to weeding increased by 0.21±0.04 and 5.6±2.2 worker days ha^{-1}, respectively. Besides, the number of weedings was negatively associated with the clay plus silt content of the soils, but there was no significant relationship between the clay plus silt content and total weeding labor time (Table 3). The average weed cover development and weed biomass growth rate during the cassava cropping cycle were not significantly associated with the frequency of cultivation of the fields, but the weed cover growth rate was significantly associated with the clay plus silt content of the soils (Table 3).

3.6. Field size effects

Fields with a high frequency of cultivation, mostly corresponding to the site of Patrimônio, were generally smaller in size than fields with relatively low frequency of cultivation (Fig. 5A). The negative association between weeding labor and clay plus silt content of the soils (Fig. 5B) was mostly driven by the fields of Patrimônio that had a high weeding labor input and were relatively sandy. While there was no significant relationship between the size of the field and the clay plus silt content of its soil (Fig. 5C), weeding labor was negatively associated with field size as the fields with the most intensive weeding also tended to be the smallest (Fig. 5D).

3.7. Cassava root yields

Average cassava fresh root yield across fields and sites was 7.2±0.4.6 Mg ha^{-1} and ranged from 0 to 15.5 Mg ha^{-1}. The average yields in Paragonorte, Patrimônio and Nazaré were, respectively, 10.6±3.4, 7.6 ±5.2 and 5.1±3.4 Mg ha^{-1} (Fig. 6). Consequently, average root growth rate was noticeably smaller in Nazaré and Patrimônio than in Paragonorte (13±9 and 11±15 g fresh weight ha^{-1} day^{-1} vs. 24±5 g fresh weight ha^{-1} day^{-1} in the slash-and-burn fields) (Table 2).

Cassava yield was strongly associated with the plant density at harvest. At a given plant density level, differences in cassava root yields were largely explained by weed pressure and soil texture (see for details, Abrell et al., 2022).

4. Discussion

Limited available agricultural land in the context of forest

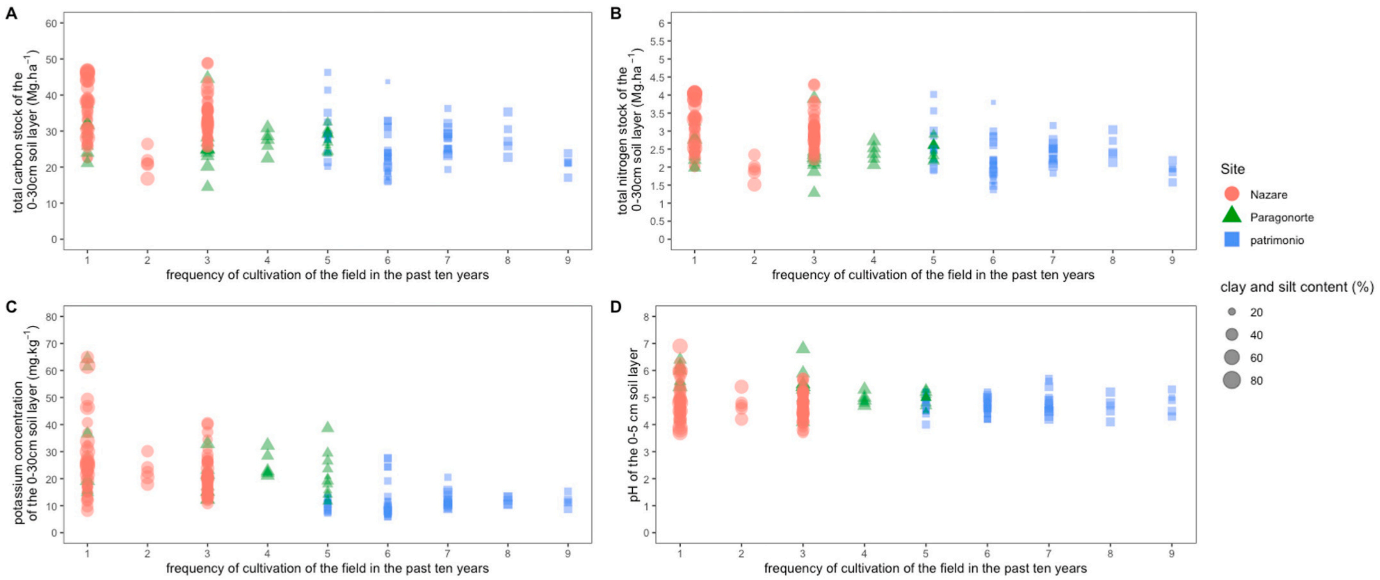

Fig. 3. Relationships between the frequency of cultivation of the fields in the past 10 years and organic carbon (A), total nitrogen (B) and exchangeable potassium (C) of the 0–30 cm soil layer, and the pH of the 0–5 cm soil layer (D). The type/color of the symbols indicates the study site and the size of the symbols indicates the clay plus silt content of the 0–30 cm soil layer.

Table 3

Linear-mixed model estimates of fixed effects (and standard errors) of the frequency of cultivation in the past 10 years and the clay plus silt content (0–30 cm soil layer) on soil fertility and weed pressure indicators for selected cassava fields on farms in Paragonorte, Nazaré, and Patrimônio. Sites and Farms within Sites were random factors.

Response variable	**Explanatory variables** **Frequency of cultivation of the field**	**Clay plus silt content of soil**
Soil fertility		
Carbon stock (Mg C ha^{-1})	**-1.38 ± 0.42** **	0.014 ± 0.062
Nitrogen stock (Mg N ha^{-1})	**-0.11 ± 0.036** **	0.0013 ± 0.0052
Exchangeable potassium concentration (mg K100 g^{-1} of dry soil)	**-1.60 ± 0.65** **	0.050 ± 0.093
pH	**-0.073 ± 0.035***	-0.0093 ± 0.0054˙
Bulk density (g dm^{-3})	0.0015 ± 0.0046	0.0011 ± 0.00071
Weed pressure		
Number of weedings	**0.21 ± 0.04** ***	**-0.019 ± 0.006** **
Total weeding labor (worker day ha^{-1})	**5.60 ± 2.20***	-0.54 ± 0.30˙
Average weed biomass growth rate during the cropping cycle (g day^{-1})	0.000098 ± 0.0030	-0.00063 ± 0.00035˙
Average weed cover development rate during the cropping cycle (% day^{-1})	-0.020 ± 0.019	**-0.0053 ± 0.0023***

*indicates a p-value<0.05, ** p-value<0.01 and *** p-value<0.001.

conservation and the need for increased local food production associated with population growth have led to an intensification of small-scale family farming in the Amazon region of Brazil, which is reflected in a high frequency of cultivation in the shifting cultivation systems, along with short fallow periods (Fig. 2, Table 1). This type of agricultural intensification, although with limited use of external inputs, threatens the sustainability of the crop production systems. This study showed that the more frequently cultivated fields are less fertile and undergo higher weed pressure, the latter resulting in a higher labor demand for weed control (Figs. 4 and 5, Table 3).

4.1. Soil fertility decline

A consistent pattern of lower soil organic carbon, total nitrogen, exchangeable potassium and pH was observed in fields with higher cultivation frequency, indicating the negative impact of intensified crop cultivation on soil fertility in cassava-based low-input shifting cultivation systems of the Amazon (Fig. 4, Table 3). These results are in line with a global review of studies that found that the negative effects of slash-and-burn on soil chemical, physical and biological properties are to a great extent related to the frequency of cultivation cycles (Ribeiro Filho et al., 2013). Although a surge of nutrients to the soil from burning fallow vegetation along with an increase in pH initially occurs, thereafter a decline in soil organic matter is typically observed (Ewel et al., 1991; Hepp et al., 2018; Kleinman et al., 1995; Sanchez et al., 1983). This decline in soil organic matter generally leads to lower soil nutrient levels and increased acidity (Ahn, 1974; Hattori et al., 2019). Nutrients released from burning the fallow vegetation become available for crop uptake but can also be lost via volatilization, leaching or surface runoff (Uhl and Jordan, 1984; N'Dri et al., 2019). For example, negative nutrient balances during the cultivation period were reported in shifting cultivation systems in the Amazon region, especially after short fallow periods of three to five years (Sommer et al., 2004). Nutrient losses are accelerated during the cultivation period, because of increased soil surface temperatures causing higher rates of organic matter decomposition and nitrogen volatilization (Agbeshie et al., 2002). Besides, as the soil becomes also more exposed to rain and wind erosion during the cultivation period, soil surface sealing or crusting can take place provoking losses of nutrients through surface runoff (Da Silva Neto et al., 2019).

In contrast to the above findings, some studies from other regions of the world did not find a relationship between the cultivation frequency

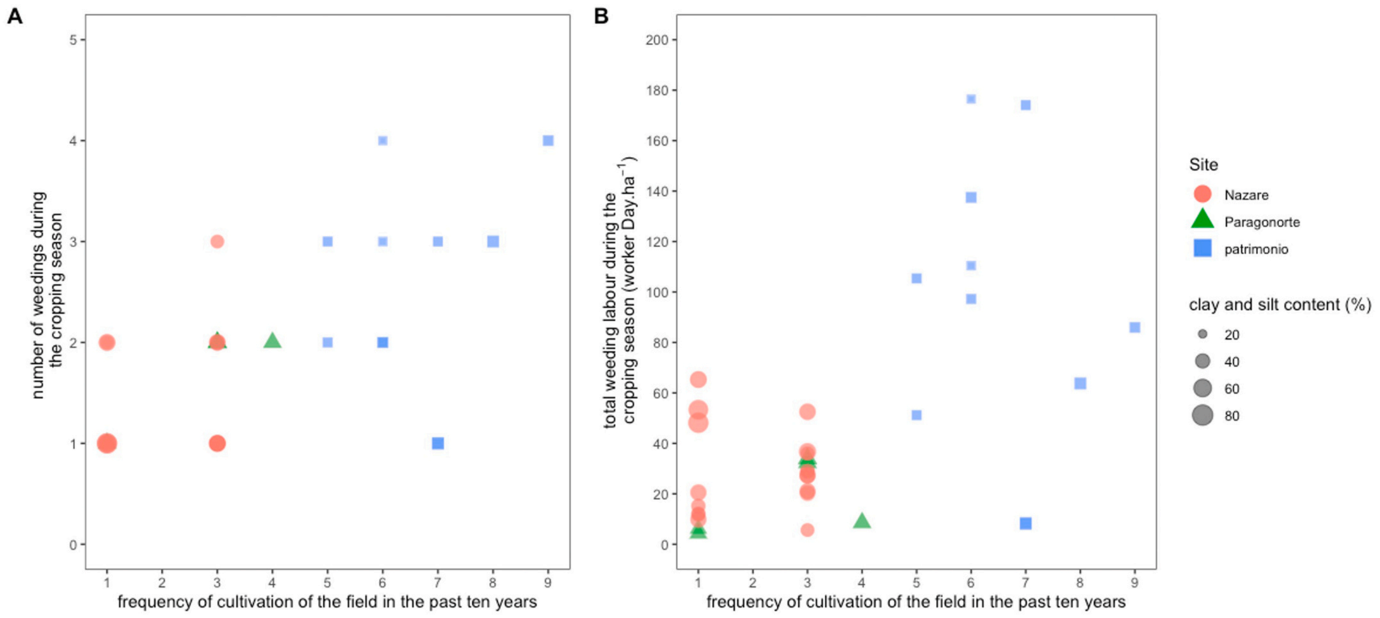

Fig. 4. Relationships between the frequency of cultivation of the fields in the past 10 years and the number of weedings (A) and the total weeding labor time (B) during the cassava cropping cycle. The type/color of the symbols indicates the site and the size of the symbols indicates the clay plus silt content of the 0–30 cm soil layer.

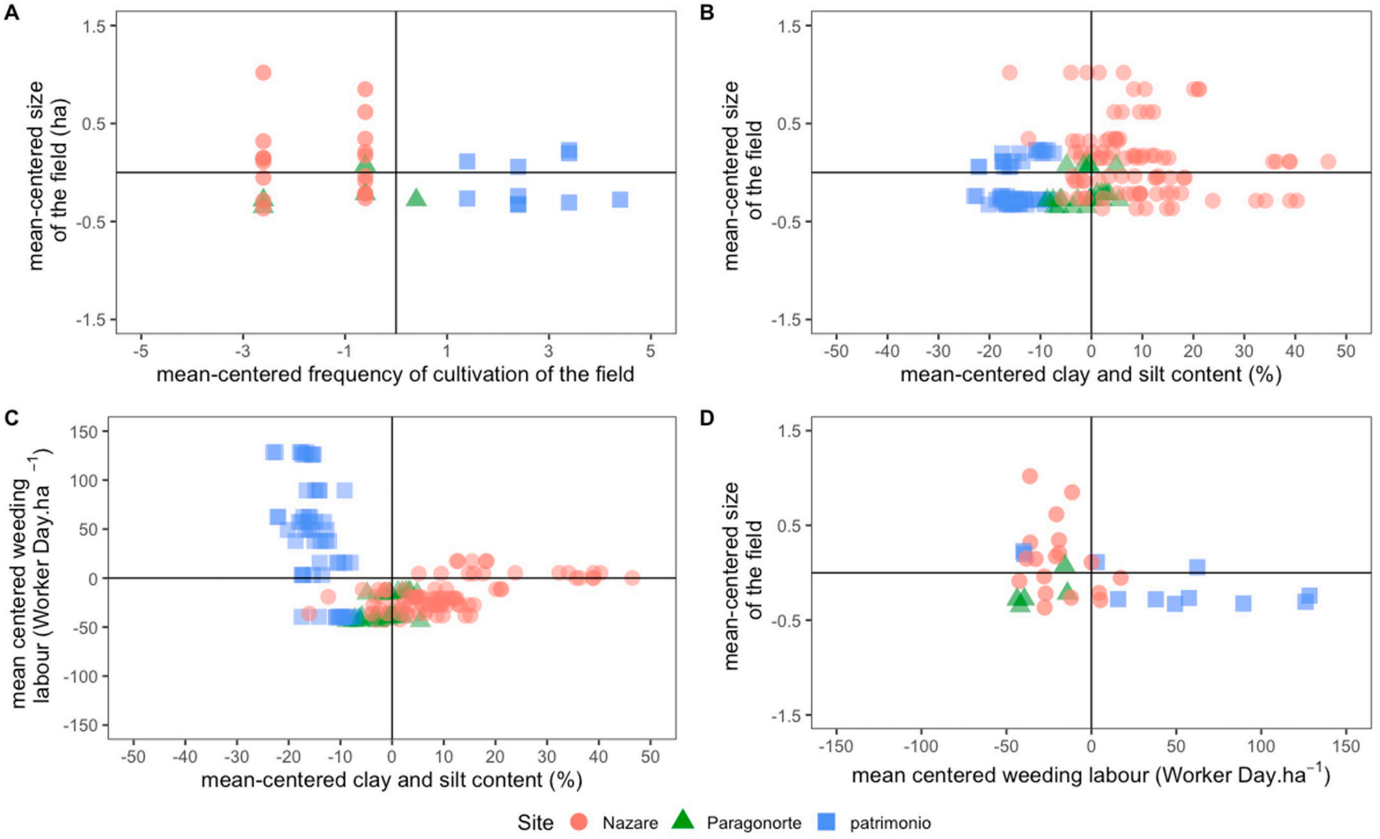

Fig. 5. Relationships between mean-centered variables: size of the field and frequency of cultivation of the fields in the past 10 years (A), total weeding labor time during the cassava cropping cycle and silt plus clay content of soils (B), size of the field and silt plus clay content of soils (C), and size of the field and total weeding labor time during the cassava cropping cycle (D). The type/color of the symbols indicates the site.

and soil organic carbon content (e.g. Bruun et al., 2017, 2021 in Southeast Asia; Kukla et al., 2019 in New Guinea). This can to a certain extent be explained by differences in pedo-climatic conditions between study sites. However, cropping practices vary widely between regions, and may be equally or even more important for maintaining soil fertility in shifting cultivation systems than the cultivation frequency or duration

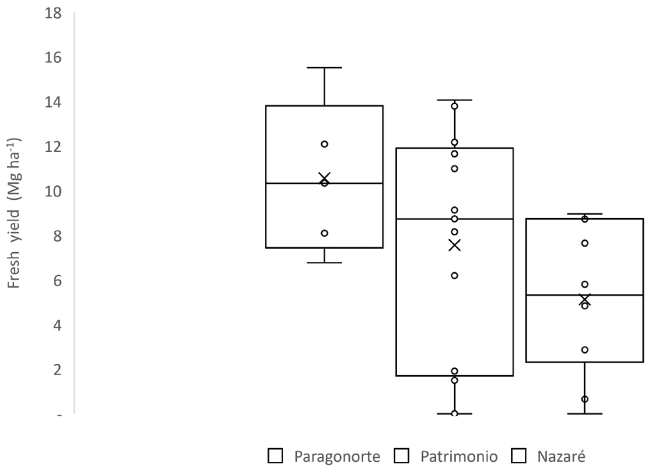

Fig. 6. Box plots of the cassava fresh root yields on the selected farmers' fields at the three study sites, Paragonorte, Patrimônio and Nazaré in Eastern Amazon. The crosses indicate the mean values. n (number of fields) = 5 for Paragonorte, n = 13 for Patrimônio, n = 18 for Nazaré.

of the fallow period (Mertz et al., 2008).

The short fallow periods and associated decline in soil fertility in this study are certainly contributing to the decline in cassava productivity claimed by the farmers over the last decade (see Abrell et al., 2022). In particular, the observed decrease in exchangeable soil potassium concentrations is expected to have an important effect on cassava root productivity (Howeler, 1991), because potassium regulates the synthesis of starch and its accumulation in the storage roots.

4.2. *Increased weed pressure*

Whilst observed weed cover and biomass were not significantly associated with the frequency of cultivation of the fields, both labor input for weeding and weeding frequency exhibited a significant association with the frequency of cultivation (Table 3), indicating that weed pressure increased with intensified crop cultivation and shorter fallow periods in this study. Increased weed infestation is one of the main causes of increased labor demand on small-scale family farms, and a strong reason for farmers to abandon their fields for fallow. Weeding labor was higher in Patrimônio than in the other two study sites, which could be explained by the high cultivation frequency of the fields and the associated higher weed pressure (Table 2, Fig. 2). On the other hand, in Nazaré weeding was commonly delayed at the start of the cropping cycle (Table 2), resulting in more challenging weed management later in the cropping season. We observed that in some cases farmers in Nazaré failed to properly weed their cassava fields because of labor commitments to other perennial crops on their farm. This may have led to lower cassava yields (Fig. 6) despite the longer fallow periods and overall better soil fertility in Nazaré.

Other studies have also reported increased weed pressure with shorter fallow periods (e.g. Jakovac et al., 2016; Uhl et al., 2009 for the Amazon region, De Rouw, 1995 for sub-Saharan Africa and Roder et al., 1997 for Southeast Asia). In this study no relationship was found between the frequency of cultivation of the fields and the monocotyledonous-to-dicotyledonous weed biomass ratio. Some studies have, however, shown that the reduction of the fallow period generally leads to an increase of graminoids (e. g. Jakovac et al., 2016; Uhl et al., 2009) and invasive species with self-propagating root systems, such as *Imperata brasiliensis* (Lojka et al., 2011). Furthermore, declining soil fertility conditions under more frequently cultivated fields may favor the growth of particular weed species that are characteristic of the study region, such as *Rottboellia cochinchinensis (Lour.) Clayton* or *Imperata brasiliensis Trin.* (Fujisaka et al., 2000).

In small-scale family farms in the Amazon, where weeding is done manually and herbicides are often unaffordable, weed infestation is a key factor for the cultivation of cassava and other crops, and is a rising challenge with the increased frequency of cultivation. Except for planting, labor availability during the cropping cycle is limited to family labor, the main activity being weeding. Therefore, weed pressure, and the required labor to control it, can to a large extent determine the size of the cropped fields, as suggested by a tendency of frequently cultivated fields (in Patrimônio) being the smallest fields (Fig. 5A). In fact, farmers experienced the need to reduce the size of their cassava fields due to the limited family labor available for weeding, which is necessary to cope with the increased weed pressure in the intensively cultivated fields. Some farmers are now in a downward spiral of reduced fallow periods, soil fertility depletion and increased weed pressure, leading to a decrease in field size, and loss of cassava production, which can compromise the farmers' livelihoods.

4.3. *The limits of the current slash-and-burn practices*

Observed cassava root yields in this study (Fig. 6) were comparable to those reported in other shifting cultivation studies in the Amazon region (e.g. Jakovac et al., 2016), but are relatively low, with an average yield of 7.2 ± 4.6 Mg ha^{-1} (compared to the average yield of about 14 Mg ha^{-1} in the Pará state, Embrapa Mandioca e Fruticultura, 2021). The low yields can thus to a large extent be explained by the high weed pressure and poor soil fertility conditions in the shifting cultivation systems with short fallows and without external inputs (Abrell et al., 2022; Jakovac et al., 2016). Farmers have however not the available land to support long fallows nor do they have the resources to practice permanent crop cultivation based on external inputs. Labor and cost considerations may also exert a dominant influence on the fallow length that farmers practice: the younger the fallow vegetation, the easier it is to clear it manually, and clearing costs can be excessive with the woody vegetation of long fallows. In fact, the reduction in land clearing costs over several short fallow cycles can compensate for the lower crop productivity caused by practicing short instead of long fallows (Metzger, 2002). Therefore, in a context where farmers resource endowment is low and productivity is constrained by labor availability, there is a need to find alternative cropping systems that are specifically more weed suppressive than the current slash-and-burn based shifting cultivation systems.

From this study, it is clear that the current practice of shifting cultivation in Eastern Amazon is not sustainable in terms of productivity. Besides, slash-and-burn practices can be a threat to secondary forests, by increasing risks of wild fires (Alencar et al., 2015; Barber et al., 2014; Cardoso et al., 2003), and by contributing to carbon loss (Lapola et al., 2023) and biodiversity loss (Coelho et al., 2012; Mamede and Araújo, 2008). In this context, the need for changing the local slash-and-burn practices towards fire-free production systems has been proclaimed (Kato et al., 1999; Lojka et al., 2008). At the sites of Paragonorte and Patrimônio, some farmers have started to use herbicides or plowing for clearing fallows, which can be relatively easily implemented on young herbaceous fallows. The results of this study indicated that land preparation with mechanical plowing or herbicides can contribute to higher cassava yields (Table 2), whilst requiring limited adjustments to the cropping system, with an investment of about 200 R$ (Brazilian Real) per hectare for the mechanical plowing, or with increased weeding costs of about 300–400 R$ per hectare (prices in 2018) in the case of clearing with herbicides. These practices are however only possible with herbaceous short-term fallows and do not fully resolve the problem of declining soil fertility caused by the shortened fallows.

One way of improving the current shifting cultivation systems would be through 'enriched fallows' or 'improved fallows' (Sanchez, 1999). In these fallows, selected tree species are planted into natural fallows to improve biomass and nutrient accumulation, such as with fast-growing nitrogen-fixing leguminous trees (Lojka et al., 2008), and/or to deliver economically valuable byproducts, such as with rattan palms (Calamus spp.), cacao or fruit trees (Tremblay et al., 2015). The feasibility of natural versus improved fallows is influenced by the benefit-cost ratio. It may take several years before farmers can make a profit from these systems above that from the traditional slash-and-burn shifting cultivation systems (Lojka et al., 2008; Mburu et al., 2007). Besides, the implementation of improved fallow systems requires substantial initial capital that small-scale family farmers in the Eastern Amazon region usually do not possess. Therefore, and to reduce the contribution of family farmers to deforestation and forest degradation, local and national public policies should be put in place to support this type of transformation of crop production systems (Tremblay et al., 2015).

5. Conclusions

This study indicates that short-fallow cropping systems are less fertile than the traditional shifting cultivation systems with long fallows and they experience important weed pressure, making them unsustainable. In the context of low access to external inputs, the productivity of the fields is largely determined by the quality of the fallow (nutrient stocks) and the amount of labor needed for weeding. Therefore, prime consideration of these two factors is required when developing viable alternatives to slash-and-burn shifting cultivation in the Amazon. There is a need for local and national public policies with incentives to motivate farmers to invest in improved fallows. These should be part of the wider efforts to combat forest degradation in the Amazon.

Declaration of Competing Interest

The authors declare they have no financial interests.

Data availability

Data will be made available on request.

Acknowledgments

We thank Embrapa Amazônia Oriental and its Núcleo de Apoio a Pesquisa e Transferência de Tecnologias at Paragominas for providing technical assistance and working facilities. We also thank Professor Luis da Silva Freitas of the Universidade Federal Rural da Amazônia, Campus Paragominas for providing practical support.

This study was supported by the research project 'STRADIV – System Approach from the TRAnsition to bio-DIVersified agroecosystems', funded by the Agropolis Foundation under the reference 1504-003; the research project 'Refloramaz – Forest restoration by family farmers in the Eastern Amazon', funded by the Agropolis Foundation under the reference ID 1503-011; the 'Investissements d'avenir' programme (Labex Agro: ANR-10-LABX-0001-01); and the ECOTERA (ECOefficiences et développement TERritorial en Amazonie Brésilienne), ANR-13-AGRO-0003, funded by the French National Research Agency.

References

Abrell, T., Naudin, K., Bianchi, F., Aragao, D., Tittonell, P., Corbeels, M., 2022. Cassava root yield variability in shifting cultivation systems in the eastern Amazon region of Brazil. Exp. Agric. 58, e38 https://doi.org/10.1017/S0014479722000333.

Agbeshie, A.A., Abugre, S., Atta-Darkwa, T., Awuah, R., 2002. A review of the effects of forest fire on soil properties. J. For. Res. 33, 1419–1441. https://doi.org/10.1007/s11676-022-01475-4.

Ahn, P.M., 1974. Some observations on basic and applied research in shifting cultivation. FAO Soils Bull. 24, 123–154.

Alencar, A.A., Brando, P.M., Asner, G.P., Putz, F.E., 2015. Landscape fragmentation, severe drought, and the new Amazon forest fire regime. Ecol. Appl. 25, 1493–1505. https://doi.org/10.1890/14-1528.1.

Azevedo, A.A., Rajão, R., Costa, M.A., Stabile, M.C.C., Macedo, M.N., dos Reis, T.N.P., Pacheco, R., 2017. Limits of Brazil's Forest Code as a means to end illegal deforestation. Proc. Natl. Acad. Sci. 114, 7653–7658. https://doi.org/10.1073/pnas.1604768114.

Barber, C.P., Cochrane, M.A., Souza, C.M., Laurance, W.F., 2014. Roads, deforestation, and the mitigating effect of protected areas in the Amazon. Biol. Conserv. 177, 203–209. https://doi.org/10.1016/j.biocon.2014.07.004.

Bruun, T.B., de Neergaard, A., Burup, M.L., Hepp, C.M., Larsen, M.N., Abel, C., Aumtong, S., Magid, J., Mertz, O., 2017. Intensification of upland agriculture in Thailand: development or degradation? Land Degrad. Dev. 28, 83–94. https://doi.org/10.1002/ldr.2596.

Bruun, T.B., Mertz, O., Elberling, B., 2006. Linking yields of upland rice in shifting cultivation to fallow length and soil properties. Agric. Ecosyst. Environ. 113, 139–149. https://doi.org/10.1016/j.agee.2005.09.012.

Bruun, T.B., Ryan, C.M., de Neergaard, A., Berry, N.J., 2021. Soil organic carbon stocks maintained despite intensification of shifting cultivation. Geoderma 388, e114804. https://doi.org/10.1016/j.geoderma.2020.114804.

Cammelli, F., Coudel, E., de Freitas Navegantes Alves, L., 2019. Smallholders' perceptions of fire in the Brazilian Amazon: exploring implications for governance arrangements. Hum. Ecol. 47, 601–612. https://doi.org/10.1007/s10745-019-00096-6.

Cardoso, M.F., Hurtt, G.C., Moore, B., Nobre, C.A., Prins, E.M., 2003. Projecting future fire activity in Amazonia. Glob. Chang. Biol. 9, 656–669. https://doi.org/10.1046/j.1365-2486.2003.00607.x.

Carmenta, R., Coudel, E., Steward, A.M., 2019. Forbidden fire: does criminalising fire hinder conservation efforts in swidden landscapes of the Brazilian Amazon? Geogr. J. 185, 23–37. https://doi.org/10.1111/geoj.12255.

Coelho, F.D.F.R., Miranda, I.D.S., Mitja, D., 2012. Caracterização do processo sucessional no projeto de assentamento Benfica, sudeste do estado do Pará, Amazônia oriental. Bol. Mus. Para. Emílio Goeldi Cienc. Nat. 7, 251–282. https://doi.org/10.46357/bcnaturais.v7i3.590.

Conklin, H.C., 1961. The study of shifting cultivation. Curr. Anthropol. 2, 27–61. https://doi.org/10.1086/200160.

Da Silva, F.C., 2009. Manual de análises químicas de solos, plantas e fertilizantes. Embrapa Solos, Rio de Janeiro, p. 627.

Da Silva Neto, E.C., Pereira, M.G., Frade, E.F., Da Silva, S.B., De Carvalho, J.A., Dos Santos, J.C., 2019. Temporal evaluation of soil chemical attributes after slash-and-burn agriculture in the western Brazilian Amazon. Acta Sci. Agron. 41 (1), 10. https://doi.org/10.4025/actasciagron.v41i1.42609.

De Rouw, A., 1995. The fallow period as a weed-break. Agric. Ecosyst. Environ. 54, 31–43. https://doi.org/10.1016/0167-8809(95)00590-O.

Díaz, A., Dini, C., Viña, S.Z., García, M.A., 2018. Technological properties of sour cassava starches: effect of fermentation and drying processes. LWT 93, 116–123. https://doi.org/10.1016/j.lwt.2018.03.029.

Elisabeth, M., Claessen, C., 1997. Manual de Métodos de Análise de Solo. Centro Nacional de Pesquisa de Solos, Embrapa, Rio de Janeiro, p. 212.

Embrapa Mandioca e Fruticultura, 2021. Produção brasileira de mandioca em 2021. ⟨http://www.cnpmf.embrapa.br/Base_de_Dados/index_pdf/dados/brasil/mandioca/b1_mandioca.pdf⟩. (Accessed 8 April 2023)..

Ewel, J.J., Mazzarino, M.J., Berish, C.W., 1991. Tropical soil fertility changes under monocultures and successional communities of different structure. Ecol. Appl. 1, 289–302. https://doi.org/10.2307/1941758.

Ferrante, L., Fearnside, P., 2019. Brazil's new president and "Ruralists" threaten Amazonia's environment, traditional peoples and the global climate. Environ. Conserv. 46, 261–263. https://doi.org/10.1017/S0376892919000213.

Fujisaka, S., Escobar, G., Veneklaas, E.J., 2000. Weedy fields and forests: interactions between land use and the composition of plant communities in the Peruvian Amazon. Agric. Ecosyst. Environ. 78, 175–186. https://doi.org/10.1016/S0167-8809(99)00122-X.

Fujisaka, S., Hurtado, L., Uribe, R., 1996. A working classification of slash-and-burn agricultural systems. Agrofor. Syst. 34, 151–169. https://doi.org/10.1007/BF00148159.

Gehring, C., Denich, M., Kanashiro, M., Vlek, P.L.G., 1999. Response of secondary vegetation in eastern Amazonia to relaxed nutrient availability constraints. Biogeochemistry 45, 223–241. https://doi.org/10.1023/A:1006138815453.

Godar, J., Gardner, T.A., Tizado, E.J., Pacheco, P., 2014. Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon. Proc. Natl. Acad. Sci. 111, 15591–15596. https://doi.org/10.1073/pnas.1322825111.

Godar, J., Tizado, E.J., Pokorny, B., 2012. Who is responsible for deforestation in the Amazon? A spatially explicit analysis along the Transamazon Highway in Brazil. For. Ecol. Manag. 267, 58–73. https://doi.org/10.1016/j.foreco.2011.11.046.

Guillemin, R., 1956. Evolution de l'agriculture autochtone dans les savanes de l'Oubangui. Agr. Trop. 11, 143–176.

Hattori, D., Kenzo, T., Shirahama, T., Harada, Y., Kendawang, J.J., Ninomiya, I., Sakurai, K., 2019. Degradation of soil nutrients and slow recovery of biomass following shifting cultivation in the heath forests of Sarawak, Malaysia. For. Ecol. Manag. 432, 467–477. https://doi.org/10.1016/j.foreco.2018.09.051.

Hepp, C.M., de Neergaard, A., Bruun, T.B., 2018. Short-term fallow in extensive upland shifting cultivation systems of Northern Lao PDR: its role in soil fertility restoration. Land Degrad. Dev. 29, 2911–2919. https://doi.org/10.1002/ldr.3032.

Howeler, R.H., 1991. Long-term effect of cassava cultivation on soil productivity. Field Crops Res. 26, 1–18. https://doi.org/10.1016/0378-4290(91)90053-X.

INPE, 2023. Instituto Nacional de Pesquisas Espaciais ⟨http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/rates⟩ (Accessed 8 April 2023).

Jakovac, C.C., Dutrieux, L., Siti, L., Peña-Claros, M., Bongers, F., 2017. Spatial and temporal dynamics of shifting cultivation in the middle-Amazonas river: expansion and intensification. PLoS One 12, e0181092. https://doi.org/10.1371/journal.pone.0181092.

Jakovac, C.C., Peña-Claros, M., Mesquita, R.C.G., Bongers, F., Kuyper, T.W., 2016. Swiddens under transition: consequences of agricultural intensification in the

Amazon. Agric. Ecosyst. Environ. 218, 116–125. https://doi.org/10.1016/j.agee.2015.11.013.

Kato, M.S.A., Kato, O.R., Denich, M., Vlek, P.L.G., 1999. Fire-free alternatives to slash-and-burn for shifting cultivation in the eastern Amazon region: the role of fertilizers. Field Crops Res. 62, 225–237. https://doi.org/10.1016/S0378-4290(99)00021-0.

Kleinman, P.J.A., Pimentel, D., Bryant, R.B., 1995. The ecological sustainability of slash-and-burn agriculture. Agric. Ecosyst. Environ. 52, 235–249. https://doi.org/10.1016/0167-8809(94)00531-I.

Kukla, J., Whitfeld, T., Cajthaml, T., Baldrian, P., Veselá-Šimáčková, H., Novotný, V., Frouz, J., 2019. The effect of traditional slash-and-burn agriculture on soil organic matter, nutrient content, and microbiota in tropical ecosystems of Papua New Guinea. Land Degrad. Dev. 30, 166–177. https://doi.org/10.1002/ldr.3203.

Lapola, D.M., Pinho, P., Barlow, J., Aragão, L.E.O.C., Berenguer, E., Carmenta, R., Liddy, H.M., Seixas, H., Silva, C.V.J., Silva-Junior, C.H.L., Alencar, A.A.C., Anderson, L.O., Armenteras, D.P., Brovkin, V., Calders, K., Chambers, J., Chini, L., Costa, M.H., Faria, B.L., Fearnside, P.M., Ferreira, J., Gatti, L., Gutierrez-Velez, V.H., Han, Z., Hibbard, K., Koven, C., Lawrence, P., Pongratz, J., Portela, B.T.T., Rounsevell, M., Ruane, A.C., Schaldach, R., da Silva, S.S., von Randow, C., Walker, W.S., 2023. The drivers and impacts of Amazon forest degradation. eabp8622 Science 379. https://doi.org/10.1126/science.abp8622.

Lewinsohn, T.M., Prado, P.I., 2005. How many species are there in Brazil? Conserv. Biol. 19, 619–624. https://doi.org/10.1111/j.1523-1739.2005.00680.x.

Lojka, B., Cepkova, P.H., Navratilova, L., Van Damme, P., Banout, J., Polesny, Z., Preininger, D., 2011. Methods for short-term control of Imperata grass in Peruvian Amazon. JARTS 112, 37–43.

Lojka, B., Lojkova, J., Banout, J., Polesny, Z., Preininger, D., 2008. Performance of an improved fallow system in the Peruvian Amazon—modelling approach. Agrofor. Syst. 72, 27–39. https://doi.org/10.1007/s10457-007-9079-0.

Mamede, M., Araújo, F., 2008. Effects of slash and burn practices on a soil seed bank of Caatinga vegetation in Northestern Brazil. J. Arid Environ. 72, 458–470. https://doi.org/10.1016/j.jaridenv.2007.07.014.

Mburu, J., Börner, J., Hedden-Dunkhorst, B., Mendoza-Escalante, A., Frohberg, K., 2007. Feasibility of mulching technology as an alternative to slash-and-burn farming in eastern Amazon: a cost–benefit analysis. Renew. Agric. Food Syst. 22, 125–133. ⟨http://www.jstor.org/stable/44491444⟩.

Mertz, O., Bruun, T.B., Jepsen, M.R., Hinrup, J.S., 2021. Ecosystem service provision by secondary forests in shifting cultivation areas remains poorly understood. Hum. Ecol. 49, 271–283. https://doi.org/10.1007/s10745-021-00236-x.

Mertz, O., Wadley, R.L., Nielsen, U., Bruun, T.B., Colfer, C.J.P., de Neergaard, A., Jepsen, M.R., Martinussen, T., Zhao, Q., Noweg, G.T., Magid, J., 2008. A fresh look at shifting cultivation: fallow length an uncertain indicator of productivity. Agric. Syst. 96, 75–84. https://doi.org/10.1016/j.agsy.2007.06.002.

Metzger, J.P., 2002. Landscape dynamics and equilibrium in areas of slash-and-burn agriculture with short and long fallow period (Bragantina region, NE Brazilian Amazon). Landsc. Ecol. 17, 419–431. https://doi.org/10.1023/A:1021250306481.

Metzger, J.P., 2003. Effects of slash-and-burn fallow periods on landscape structure. Environ. Conserv. 30, 325–333. https://doi.org/10.1017/S0376892903000341.

N'Dri, A.B., Kone, A.W., Loukou, S.K.K., Barot, S., Gignoux, J., 2019. Carbon and nutrient losses through biomass burning, and links with soil fertility and yam (*Dioscorea alata*) production. Exp. Agric. 55, 738–751. https://doi.org/10.1017/S0014479718000327.

Nye, P.H., Greenland, D.J., 1964. Changes in the soil after clearing tropical forest. Plant Soil 21, 101–112. https://doi.org/10.1007/BF01373877.

Patrignani, A., Ochsner, T.E., 2015. Canopeo: a powerful new tool for measuring fractional green canopy cover. Agron. J. 107, 2312–2320. https://doi.org/10.2134/agronj15.0150.

Core Team, R., 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ⟨https://www.R-project.org/⟩.

Ribeiro Filho, A.A., Adams, C., Murrieta, R.S.S., 2013. The impacts of shifting cultivation on tropical forest soil: a review. Bol. Mus. Para Emílio Goeldi. Ciênc. Hum. 8, 693–727. https://doi.org/10.1590/s1981-81222013000300013.

Roder, W., Phengchanh, S., Keoboulapha, B., 1997. Weeds in slash-and-bum rice fields in northern Laos. Weed Res. 37, 111–119. https://doi.org/10.1046/j.1365-3180.1996.d01-6.x.

Sanchez, P.A., 1999. Improved fallows come of age in the tropics. Agrofor. Syst. 47, 3–12. https://doi.org/10.1023/A:1006287702265.

Sanchez, P.A., Villachica, J.H., Bandy, D.E., 1983. Soil fertility dynamics after clearing a tropical rainforest in Peru. Soil Sci. Soc. Am. J. 47, 1171–1178. https://doi.org/10.2136/sssaj1983.03615995004700060023x.

Schmidt-Vogt, D., Leisz, S.J., Mertz, O., Heinimann, A., Thiha, T., Messerli, P., Epprecht, M., Cu, P.Van, Chi, V.K., Hardiono, M., Dao, T.M., 2009. An assessment of trends in the extent of swidden in southeast Asia. Hum. Ecol. 37, 269–280. https://doi.org/10.1007/s10745-009-9239-0.

Schons, S.Z., Lima, E., Amacher, G.S., Merry, F., 2019. Smallholder land clearing and the Forest Code in the Brazilian Amazon. Environ. Dev. Econ. 24, 157–179. https://doi.org/10.1017/S1355770×18000505.

Shimizu, M.K., Kato, O.R., Figueiredo, R. de O., Vasconcelos, S.S., Sá, T.D. de A., Borges, A.C.M.R., 2014. Agriculture without burning: restoration of altered areas with chop-and-mulch sequential agroforestry systems in the Amazon region. Glob. Adv. Res. J. Agric. Sci. 3, 415–422.

Sommer, R., Vlek, P.L.G., Deane de Abreu Sá, T., Vielhauer, K., de Fátima Rodrigues Coelho, R., Fölster, H., 2004. Nutrient balance of shifting cultivation by burning or mulching in the Eastern Amazon – evidence for subsoil nutrient accumulation. Nutr. Cycl. Agroecosyst. 68, 257–271. https://doi.org/10.1023/B:FRES.0000019470.93637.54.

Tremblay, S., Lucotte, M., Revéret, J.P., Davidson, R., Mertens, F., Passos, C.J., Romaña, C.A., 2015. Agroforestry systems as a profitable alternative to slash and burn practices in small-scale agriculture of the Brazilian Amazon. Agrofor. Syst. 89, 193–204. https://doi.org/10.1007/s10457-014-9753-y.

Uhl, C., Clark, H., Clark, K., Maquirino, P., 2009. Successional patterns associated with slash-and-burn agriculture in the Upper Rio Negro region of the Amazon Basin. Biotropica 14, 249–254.

Uhl, C., Jordan, C.F., 1984. Succession and nutrient dynamics following forest cutting and burning in Amazonia. Ecology 65, 1476–1489. https://doi.org/10.2307/1939128.

Van Vliet, N., Mertz, O., Heinimann, A., Langanke, T., Pascual, U., Schmook, B., Adams, C., Schmidt-Vogt, D., Messerli, P., Leisz, S.J., Castella, J.C., Jørgensen, L., Birch-Thomsen, T., Hett, C., Bech-Bruun, T., Ickowitz, A., Vu, K.C., Yasuyuki, K., Fox, J., Padoch, C., Dressler, W., Ziegler, A.D., 2012. Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. Glob. Environ. Change 22, 418–429. https://doi.org/10.1016/j.gloenvcha.2011.10.009.

Villa, P.M., Martins, S.V., de Oliveira Neto, S.N., Rodrigues, A.C., Martorano, L.G., Monsanto, L.D., Cancio, N.M., Gastauer, M., 2018. Intensification of shifting cultivation reduces forest resilience in the northern Amazon. For. Ecol. Manag. 430, 312–320. https://doi.org/10.1016/j.foreco.2018.08.014.

Vissoh, P.V., Mongbo, R., Gbèhounou, G., Hounkonnou, D., Ahanchédé, A., Röling, N., Kuyper, T.W., 2007. The social construction of weeds: different reactions to an emergent problem by farmers, officials and researchers. Int. J. Agric. Sustain. 5, 161–175. https://doi.org/10.1080/14735903.2007.9684820.

Wood, S., Rhemtulla, J., Coomes, O., 2017. Cropping history trumps fallow duration in long-term soil and vegetation dynamics of shifting cultivation systems. Ecol. Appl. 27, 519–531. https://doi.org/10.1002/eap.1462.