Experimental Agriculture (2022), vol. 58, e38, 1–19
doi:10.1017/S0014479722000333

RESEARCH ARTICLE

Cassava root yield variability in shifting cultivation systems in the eastern Amazon region of Brazil

Thomas Abrell[1,2,3], Krishna Naudin[1,2], Felix J.J.A. Bianchi[3], Debora Veiga Aragao[4], Pablo Tittonell[1,2,5] and Marc Corbeels[1,2,6,*]

[1]CIRAD, UPR AIDA, F-34398 Montpellier, France, [2]AIDA, University of Montpellier, CIRAD, Montpellier, France, [3]Wageningen University and Research, Farming Systems Ecology, P.O. Box, 430, Wageningen, AK 6700, the Netherlands, [4]Embrapa, Brazilian Agricultural Research Corporation, Amazônia Oriental, Tv. Dr. Eneas Pinheiro, s/n – Marco, Belém, PA 66095-903, Brazil, [5]Groningen Institute of Evolutionary Life Sciences, Groningen University, PO Box 72, Groningen, AB 9700, the Netherlands and [6]IITA, International Institute of Tropical Agriculture, PO Box 30772, Nairobi, 00100, Kenya
*Corresponding author. Email: corbeels@cirad.fr

(Received 15 March 2021; revised 11 April 2022; accepted 05 August 2022)

Summary

Cassava flour is the main source of carbohydrates for family farmers in the Amazon region of Brazil. Cassava is mainly grown under shifting cultivation, in recurrent cultivation periods initiated through slash-and-burn. Its sustainability is, however, questioned due to the associated deforestation and often rapidly decreasing crop productivity. There is an urgent need to make these cassava systems more sustainable and more profitable, but we currently lack a deep understanding of the key factors governing their productivity. We conducted an on-farm study on 37 cassava fields of smallholder farmers at three locations that spanned a range of crop-fallow frequencies, some of which were initiated through slash-and-burn while others through fire-free land clearance. First, we analysed how cassava plant density at harvest was related with pedoclimatic and management factors in slash-and-burn systems. Second, we assessed the relationship between plant density and cassava root yield at harvest and conducted a yield gap analysis to better understand which factors govern cassava productivity beyond plant density in slash-and-burn systems. Finally, we compared cassava productivity between slash-and-burn and the fire-free land clearing techniques that some farmers started to adopt in the study region. Cassava yields averaged 7.2 ± 5.4 Mg ha^{-1} (50% of the average yield of 14.2 Mg ha^{-1} in the Pará State), and ranged from 0 (in case of root rot diseases) to 24 Mg ha^{-1}. Cassava yield was associated with plant density at harvest (ranging from 0 to 10 000 plants ha^{-1}), suggesting that managing plant density is a key determinant of the attainable yield levels. In addition, differences in cassava root yields could be largely explained by differences in labour inputs for weeding and fallow clearing, the effect of the latter depending on soil texture. Therefore, our results suggest that labour is a key production factor for cassava in the shifting cultivation systems of the Eastern Amazon in which the use of external inputs, such as chemical fertilizers and herbicides, is limited. Further, root yields were influenced by the method of field preparation, whereby yields were about 50% lower (and more variable) when fields were prepared by slash-and-burn than by mechanical ploughing or herbicide application. Despite the significantly higher yields, these alternatives to burning the vegetation are, however, still hardly adopted in Paragominas. Hence, there is a need for supporting more sustainable production systems through local and national public policies. These new systems should not only focus on soil fertility management but also on weed control and, more generally, on labour productivity.

Keywords: Shifting cultivation; Yield gap; Soil fertility; Weed pressure; Brazil

Introduction

Shifting cultivation is an agricultural production system in which land is cleared of vegetation for cultivation of crops, and after a few years of cultivation abandoned for a new area whilst the land can regenerate as a fallow before it is cleared and cultivated again (Conklin, 1961). It continues being an important driver for forest structure and change in the Amazon region (Coomes *et al.*, 2011; Jakovac *et al.*, 2017). Prior to cultivation, the aboveground vegetation is normally slashed and burned, as a method of clearing the land and supplying nutrients to the soil in available form for crop uptake via the biomass ashes (e.g., Andriesse and Schelhaas, 1987; Brinkmann *et al.*, 1973; Stromgaard, 1984). The fallow period between the crop cultivation cycles plays a key role in sustaining the productivity of these systems (Jakovac *et al.*, 2016; Wood *et al.*, 2017). The re-growing vegetation during fallow accumulates nutrients (Feldpausche *et al.*, 2004; Hölscher *et al.*, 1996; Hughes *et al.*, 2002), can increase soil organic matter (Bruun *et al.*, 2021; Greenland and Nye, 1959; Lemos *et al.*, 2016), controls soil erosion (Sanchez, 1982), suppresses herbaceous weeds (De Rouw, 1995) and breaks down pest and disease cycles (Bianchi *et al.*, 2006). In the Amazon region, human population growth, increased demand for food products and the associated increased demand for land, especially in the context of forest conservation, have led to reduced lengths of fallow periods in shifting cultivation systems with an increased frequency of crop cultivation cycles (Jakovac *et al.*, 2017; Van Vliet *et al.*, 2013). Shorter fallows result in lower soil fertility, shifts in plant (weed) community composition and slower biomass regeneration (e.g., Villa *et al.*, 2018; Wood *et al.*, 2017). These processes are expected to lead to a gradual decrease in crop yields over the cultivation cycles (e.g., Jakovac *et al.*, 2016; Silva-Forsberg and Fearnside, 1997). Therefore, there is a need for appropriate fallow management, particularly aimed at farmers with low resource endowments who cannot afford the use of external inputs in the form of fertilizers and herbicides.

Cassava (*Manihot esculenta* Crantz) is commonly grown in shifting cultivation systems in the Eastern Amazon region, occasionally in combination with maize *(Zea mays* L.), common bean (*Phaseolus vulgaris* L.) or rice (*Oryza sativa* L.), with fallow periods ranging from 1 to 20 years (Jakovac *et al.*, 2016). Cassava plays an important role in providing local food security because its flour is the main source of carbohydrates for farm households in the Amazon (Díaz *et al.*, 2018). Cassava productivity and its determining factors have been studied in many parts of the tropics (e.g., Fermont *et al.*, 2009; Melifonwu, 1994; Visses *et al.*, 2018), but few studies are available for the Amazon region where declining yields jeopardise food security and livelihoods of smallholder farmers.

Cassava productivity is positively associated with planting density (Silva *et al.*, 2013) as the root storage capacity has been found to be strongly related to the crop leaf area (Cock, 1976; Sagrilo *et al.*, 2006). As a result, recommendations of best management practices for cassava production in the Amazon region revolve around the use of optimal planting densities in combination with seedling selection and weed management (Modesto and Alves, 2016). However, in practice, root yields are highly variable, and farmers have recently reported declining yields, which could partially be explained by the current trend of reduced lengths of fallow periods in the shifting cultivation systems (Jakovac *et al.*, 2016; Parsons *et al.*, 2009), and by the associated depletion of soil fertility (Sommer *et al.*, 2004; Wood *et al.*, 2017) and increase of weed pressure (De Rouw *et al.*, 2014; Uhl *et al.*, 2009).

We currently lack understanding of the relative importance of these factors and the potential interactions with other factors governing the productivity of cassava in slash-and-burn shifting cultivation systems. Besides, quantitative information is needed to compare the productivity of traditional slash-and-burn with alternative fire-free land preparation that is promoted in Eastern Amazon in the context of the zero-fire initiatives (Carmenta *et al.*, 2018).

The aim of this study was to assess the key factors that influence cassava root productivity in shifting cultivation systems in the Eastern Amazon region of Brazil. First, we analysed how cassava

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

plant density at harvest was related to pedoclimatic and management factors. Second, we assessed the relationship between cassava plant density and root yield at harvest and conducted a yield gap analysis to better understand which factors govern cassava productivity beyond plant density in slash-and-burn systems. Finally, we compared cassava productivity between slash-and-burn and the fire-free land clearing techniques that some farmers started to adopt in the study region.

Materials and Methods

Site characteristics and field selection

Our study was conducted in the rural region of Paragominas in the Pará state, Brazil. This region experiences a monsoonal equatorial climate (Am, Köppen classification) with the rainy season occurring from December to June. The average annual temperature is 26.6 °C and the average annual rainfall is 1800 mm. Soils in our study are characterised as yellow dystrophic Latosols (Brazilian Soil Classification System) or xanthic Ferralsols (World Reference Base for Soil Resources). The pedoclimatic conditions in our study sites are representative of the Eastern Amazon region.

We selected three study sites: the community of Nazaré (2°40.92' S, 47°53.35' W) and the communities of Paragonorte and Patrimônio, which both are part of the Luiz Inácio Lula da Silva village (2°32.03' S, 46°57.25' W). The farms in Nazaré, Paragonorte and Patrimônio represent different farming contexts (Table 1). Nazaré is an old settlement prior to the creation of the municipality of Paragominas in 1964. The village of Luiz Inácio da Silva is a settlement created at the end of the 1990s as part of the Brazilian agrarian reform and hosts the communities of Paragonorte and Patrimônio in spatially separated areas. Paragonorte is populated by colonists, i.e., farmers who were officially appointed by the government, while the community of Patrimônio hosts spontaneous settlers with no official status (Fujisaka *et al.*, 1996). Farms in Patrimônio are smaller than in Paragonorte and Nazaré and do not have Legal Reserves (Table 1), i.e., areas that farmers should maintain under native vegetation cover according to the Forest Code, law no. 12.651/2012 (Bandeira, 2015). The size of the Legal Reserves ranges from 20 to 80% of the total farm area, depending on the local policy context. The available labour force on the farms is mostly family labour in all three study sites.

The main staple crop in the study sites is cassava, which is typically grown in slash-and-burn systems. Cassava tubers are processed by farmers into flour that is used for subsistence food needs (Diaz *et al.*, 2018). Cassava is planted at the onset of the rains starting in December and is harvested between 12 and 20 months later. We selected cassava fields in Nazaré, Paragonorte and Patrimônio depending upon the farmers' consents to participate at a field monitoring study of several months, corresponding to the 2015–2017 and 2016–2018 cassava cropping cycles. Eighteen fields were selected in Nazaré (in 10 different farms), six fields in Paragonorte (in three farms) and 13 fields in Patrimônio (in five farms). Fields were managed by the farmers according to their usual practices. Cassava was planted in the selected fields in December 2015 in the first cropping cycle of the study and in December 2016/January 2017 in the second cycle. Field sizes ranged from 0.15 to 4.4 ha and 10 out of the 37 fields were intercropped with maize.

Data collection

Farmers were visited on a weekly basis during the two cassava cropping cycles to collect data on crop management activities. We classified the management activities as: land clearing and preparation (through slashing and burning, applying herbicides or ploughing), cassava planting, replanting of cassava (when required), maize planting (when applicable), weeding (one to four times per cropping cycle) and harvesting. For each activity, we recorded the start and end date, the family and external labour input and the amount of external inputs. The tools used by the

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

Table 1. Main characteristics of the study sites (means and standard deviations)

Selected fields/farms:	Paragonorte	Patrimônio	Nazaré
Number of farms	3	5	10
Number of fields by land preparation method:			
Slash-and-burn	5	6	18
Mechanical Ploughing	1	2	0
Herbicide cleaning	0	5	0
Total	6	13	18
Number of observation plots	30	65	9
Site characteristics:			
Vegetation cover preceding cultivation	Secondary forest	Secondary forest	Primary forest
First land clearing	20 years ago	20 years ago	>40 years
Population density (persons km^{-2})	75	300	12
Farmer type	colonists	spontaneous settlers	old settlers
Average farm size (ha)	62.5 ± 4.2	2.2 ± 0.21	40.2 ± 2.5
Main crop cultivated	Cassava	Cassava	Cassava
Average cassava area per farm in 2015 (ha)	1.6 ± 0.43	0.93 ± 0.14	0.69 ± 0.10
Other crops	Pepper	Pepper	Other perennials and pepper
Legal Reserve size (ha)	17 ± 1.4	0	16.8 ± 1.3
Average fallow period (year)	3.7 ± 0.58	0.58 ± 0.033	5.2 ± 0.33
Average rainfall during the 2015/2017 and 2016/2018 cropping cycles (16 months) (mm)	2392	2392	2587
Main soil type	Yellow dystrophic Latosol	Yellow dystrophic Latosol	Yellow dystrophic Latosol
Average silt + clay content (0–30 cm) (%)	30 ± 13	24 ± 4	49 ± 12
Average soil bulk density (0–30 cm) (g cm^{-3})	1.41 ± 0.05	1.40 ± 0.05	1.39 ± 0.09

Means and standard deviations are reported.

farmers in the slash (and burn) activities consisted of chainsaws for the largest trees and shovels and machetes for the remaining vegetation. The mechanical fire-free land clearing with a tractor was always in the form of hired services. Land clearing with herbicides was usually done with glyphosate. No additional weeding was conducted between clearing the fallow and cassava planting, as all crops were planted at most two weeks after land preparation. Weeding was the only activity between planting and harvesting and was performed with hand hoes. The fields were completely cleared from weeds at each weeding event, and the weed biomass was then left to decompose on the field. All cropping activities were conducted by family labour, except for weeding, for which sometimes additional labour was hired, and mechanical land clearing, for which tractor services were hired. The same tools and techniques were used on all fields, except for the land clearing methods (see above).

In each selected field, five georeferenced observational plots (5x5 m^2) were established in an 'X' pattern (i.e., one plot in the centre of each field and four plots in between the centre and each field corner) to account for within-field variability, mainly resulting from spatial heterogeneity in soil characteristics and residual biomass (mainly tree stumps and roots) from the fallow.

We monitored weed growth in all fields during the second cropping cycle (2016–2018). Prior to each weeding event and at harvest, we determined the weed cover of the plots using the Canopeo® Smartphone App (Patrignani and Ochsner, 2015) with five replicate images per plot. We calculated the weed cover development rate (WCDR) (day^{-1}) by dividing the measured weed cover by the number of days since the last weeding (or since planting). At each weeding event and at harvest, we also determined the total aboveground biomass of weeds in the observational plots, separated in monocotyledonous and dicotyledonous weeds. The aboveground parts of weeds were cut a ground level, fresh biomass was measured with a 15-g digital precision scale. A 300-g sub-sample was oven dried at 70 °C for 72 hours to determine the moisture content and calculate the dry weight (dw) of the weed sample. The weed (monocotyledonous and/or dicotyledonous) biomass growth rate (WBGR, g dw m^{-2} day^{-1}) was calculated by dividing the dry weight weed biomass by the number of days since the last weeding event (or since planting). Specific WBGRs were calculated for monocotyledonous and dicotyledonous weeds separately. Finally, we integrated the respective WCDRs and WBGRs over the successive weeding events and calculated the average daily rates for the period between the cassava planting and harvest.

Cassava was harvested at a date decided by the farmer, i.e., after between 12 and 20 months of growing cycle. Cassava root yields were determined in each observational plot by weighing the total fresh root biomass of all plants present in the plot. The number of plants for each variety in the plot was also recorded. In some observational plots, cassava plants suffered from root rot diseases, leading to the death of all plants; yield was then recorded as null. In the fields with maize as an intercrop, we determined the maize grain yield when farmers decided to harvest maize by collecting the grains of all plants in the observational plots. A 300-g sub-sample of grains was oven dried at 70 °C for 72 hours to determine its moisture content and calculate dry matter content.

During the dry season (August/September) of 2016 and 2017, soil was sampled in the fields at a one-meter distance from each observational plot, resulting in five replicate samples per field. Steal rings with a volume of 100 cm^3 were used to collect undisturbed soil samples at depths of 0–5, 5–10, 10–20 and 20–30 cm. After air-drying to constant weight, the soil bulk density was determined by weighing the samples, and for each sample, a 50-g sub-sample was oven dried at 110 ºC for 24 hours to determine its moisture content. The air-dried samples were ground to pass through a 2-mm sieve and analyzed for texture (pipette method), pH ($CaCl_2$), organic carbon (Schollenberger method), total nitrogen (Kjeldhal method) and exchangeable K^+ (extraction with ammonium acetate, NH_4OAc, pH 7.0 and flame photometry), according to the procedures used at Embrapa, the Brazilian Agricultural Research Corporation (Elisabeth and Claessen, 1997). pH was only determined on the 0–5 cm soil samples.

Air temperature and rainfall were monitored with an automatic weather station at each site. Total daily rainfall was calculated from 15-minute interval recordings of an automatic rain gauge.

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

Data analysis

The association between the measured environmental, management and crop variables was assessed using principal component analysis (PCA; $n = 37$). Given the strong correlations between clay plus silt content, organic carbon, total nitrogen and available potassium of the 0–30 cm soil layer, we selected soil clay plus silt content as the explanatory variable for soil fertility in the further analysis below. In addition, we used labour requirements for fallow clearing in slash-and-burn systems as a proxy for the amount of fallow aboveground biomass and the associated quantity of nutrients supplied to the soil after slashing and burning. Furthermore, temperature and cumulative rainfall during the cropping cycle were strongly correlated, and therefore we only used rainfall as explanatory variable in the analysis, and not temperature. After this first variable selection, we evaluated the correlations among pairs of the remaining explanatory variables to control for multicollinearity in the linear mixed-effects regression models that are described in the next paragraph.

We conducted the analysis of the cassava root yield variability in the slash-and-burn fields ($n = 29$) in two steps. First, as part of the yield variability was expected to be related with plant density, we analysed the variation in cassava plant density at harvest (response variable) against a set of explanatory variables (i.e., soil characteristics, management practices and rainfall, Table 2) using a linear mixed-effects model. Second, we determined the plant density-specific yield gap and explained its variability through variations in soil characteristics, weed pressure, crop management and rainfall. To do so, we first fitted a boundary line, i.e., a non-linear model of maximum yield as function of cassava plant density at harvest, as follows:

$$Maximum\ Yield = a* \left(1 - exp^{-b^* \left(plant\ density\right)}\right) \tag{1}$$

The relative yield gap at plant density i (RYGi) for each observational plot was then defined as

$$RYGi = (Maximum\ Yield\ i - Observed\ Yield\ i)/Maximum\ Yield\ i \tag{2}$$

Finally, the relationship between the relative yield gap (response variable) and a set of variables related to soil, management, rainfall and weed pressure (explanatory variables; Table 2) was explored using linear mixed models. Rainfall variables had no significant effect here and were omitted. Since some fields were located on the same farm, and farms were nested within sites, we used ‘Farm within Sites’ as a random factor. For each analysis, the individual observational plots were used as unit of observation to capture the intra-field variability (total of 114 observations). As weed growth dynamics were only assessed in the second cropping cycle (2016–2018), data on weed pressure variables were only available for 66 out of the 114 slash-and-burned observational plots. The following three models were used:

$$\text{MODEL1 : RYG} \sim f(\text{soil variables} + \text{management variables}); (n = 114)$$

$$\text{MODEL2 : RYG} \sim f(\text{weed pressure variables}); (n = 66)$$

$$\text{MODEL3 : RYG} \sim f(\text{significant explanatory variables from MODELS 1 and 2}); (n = 66)$$

In the above analysis of yield variability, we only considered fields that were prepared by slash and burn (29 out of the 37 fields, Table 1) and thus discarded eight fields that had been cleared by either ploughing or herbicide application. A Student’s t-test was used to compare the average fresh cassava root yields from fields prepared with traditional slash-and-burn to those from fields with mechanical ploughing or herbicide clearing.

All statistical analyses were conducted in R (R Core Team, 2020). We used the ade4 package for the PCA, the lme function of the lme4 package for the mixed models and the geom_signif function of the ggsignif package for the comparison of cassava root yields.

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

Table 2. List of the variables used in the linear mixed-effects model analyses of plant density at harvest and yield gap

Variable name	Variable description	Unit	Plant density analysis	Yield gap analysis
	General field information			
Farm	Identification of the farm		X	X
	Soil characteristics			
ClSi	Clay plus silt content of the 0–30 cm soil layer	%	X	X
BD1030	Bulk density of the 10–30 cm soil layer	g cm^{-3}	X	X
pH5	pH of the 0–5 cm soil layer		X	X
	Management		X	
WS	Labour force dedicated to the slashing of the fallow	worker day ha^{-1}		X
WCplI	Labour force dedicated to the first cassava planting	worker day ha^{-1}	X	
WCplII	Labour force dedicated to the second cassava planting	worker day ha^{-1}	X	
WMP	Labour force dedicated to the maize planting	worker day ha^{-1}	X	
WWt	Labour force dedicated to weeding during the cropping season	worker day ha^{-1}	X	
NCV	Number of varieties of cassava		X	X
CCl	Length of the cassava cropping cycle	days		X
	Climate			
Nwd	Number of rainy days during the cropping cycle	%	X	
Pd	Delay between cassava planting and the start of the rainy season	days	X	
	Weed pressure			
mwg2	Average monocotyledonous weed growth rate g $ha^{-1}day^{-1}$			X
Mda	Average monocotyledonous to dicotyledonous weed biomass ratio		X	
cg2	Average weed cover growth rate during cropping season	day^{-1}		X
	Crop productivity			
MaYield	Maize dry grain yield	Mg ha^{-1}		X
CDh	Cassava density at harvest	plants ha^{-1}	Y	
RYieldGap	Relative cassava yield gap	%		Y

X and Y indicate response and explanatory variables, respectively.

Table 3. Soil characteristics of the study sites (means and standard deviations)

	Soil layer (cm)	Nazaré	Paragonorte	Patrimônio
SOC (g C kg^{-1})	0–5	14.5 ± 6.2	10.8 ± 2.7	9.93 ± 4.30
	5–10	10.2 ± 2.9	8.11 ± 3.30	7.30 ± 3.25
	10–20	7.13 ± 2.08	5.54 ± 1.65	5.63 ± 1.76
	20–30	5.44 ± 1.87	4.81 ± 1.38	4.53 ± 1.44
Total N (g N kg^{-1})	0–5	1.28 ± 0.55	0.95 ± 0.26	0.86 ± 0.38
	5–10	0.89 ± 0.27	0.70 ± 0.29	0.64 ± 0.28
	10–20	0.62 ± 0.18	0.49 ± 0.13	0.50 ± 0.14
	20–30	0.48 ± 0.16	0.44 ± 0.11	0.42 ± 0.12
K^+ ($cmol_c$ dm^{-3})	0–5	0.11 ± 0.07	0.15 ± 0.10	0.06 ± 0.05
	5–10	0.07 ± 0.03	0.08 ± 0.04	0.04 ± 0.01
	10–20	0.07 ± 0.04	0.07 ± 0.04	0.04 ± 0.01
	20–30	0.06 ± 0.04	0.06 ± 0.04	0.04 ± 0.02
Clay + silt (%)	0–5	35 ± 6	27 ± 4	15 ± 3
	5–10	42 ± 6	30 ± 4	19 ± 4
	10–20	51 ± 8	37 ± 4	27 ± 4
	20–30	58 ± 8	39 ± 5	29 ± 3
pH	0–5	4.8 ± 0.6	5.2 ± 0.6	4.7 ± 0.3

Results

Soil characteristics at the study sites

On average, soils at Nazaré were inherently more fertile than at Paragonorte and Patrimônio, as indicated by the higher soil organic carbon contents in the upper soil layers (Table 3). Soils at Nazaré had also higher clay plus silt contents than at the two other sites. The sandiest soils were found at Patrimônio. Exchangeable K^+ was lowest at Patrimônio, but variable within sites. pH values
(0–5 cm soil layer) were similar across the three sites ranging from 4.7 to 5.2.

Cassava root yield

The mean cassava fresh root yield across all 37 fields was 7.2 ± 5.4 Mg ha^{-1} and yields ranged between 0 (i.e., complete crop failure due to root rot diseases) and 24 Mg ha^{-1} (Figure 1). Besides the variation in yield among fields, there was also substantial variation among plots within a field with a mean difference between minimum and maximum yield of 7.5 Mg ha^{-1}, ranging from 1.0 to 18 Mg ha^{-1} (Figure 1). Cassava root yield was influenced by the method of field preparation, whereby yields were about 50% lower (and more variable) when fields were prepared by slash and burn than by mechanical ploughing or herbicide application ($p < 0.001$; Figure 2). The fields prepared by slash and burn had significantly higher yields in Paragonorte than in Patrimônio and Nazaré (Table 4, 11.0 ± 5.0 vs. 4.5 ± 5.4 and 5.2 ± 4.6 Mg ha-^{1}, respectively; $p < 0.05$). Root yields below 5 Mg ha^{-1} occurred in the fields harvested before 450 days after planting, which corresponded to a harvest before February, and this mostly occurred in Nazaré (Figure 3a). There was no clear relationship between root yield and the total rainfall during the cropping cycle (Figure 3b). On the other hand, there was a trend of decreasing yield with higher silt plus clay content of the 0-30 cm soil layer, the latter also corresponding to site differences (Figure 3c). Fields that were intensively weeded (in Patrimônio see below), i.e., with a total weeding labour during the cropping cycle of more than 65 worker days ha^{-1}, had yields exceeding 5 Mg ha^{-1} (Figure 3d), except for two plots that were infected with root rot. There was no clear relationship between labour dedicated to the slashing of the fallow prior to cultivation and cassava yield (Figure 3e), while the variation in yields increased and higher maximum yields were attained with increasing plant density at harvest (Figure 3f).

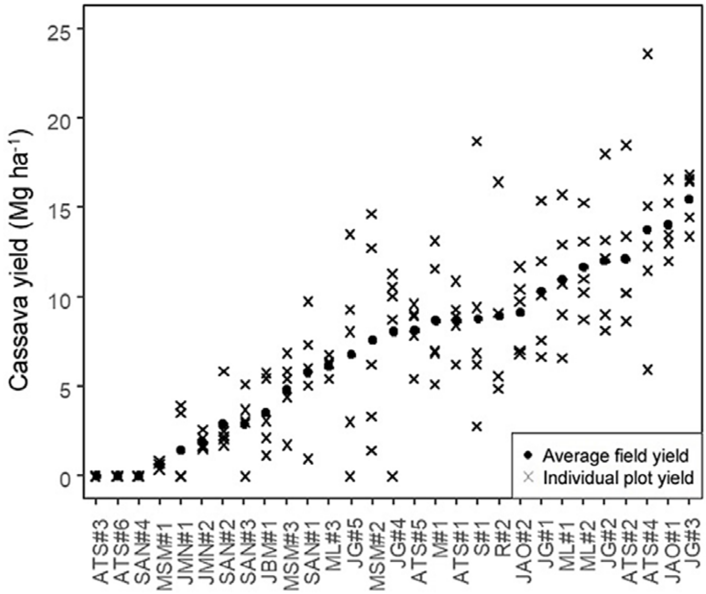

Figure 1. Average cassava fresh root yields in the slash-and-burn fields (circles) and corresponding yields in the individual observation plots (crosses). The labels of the X-as indicate the identifiers of the 29 fields of the study.

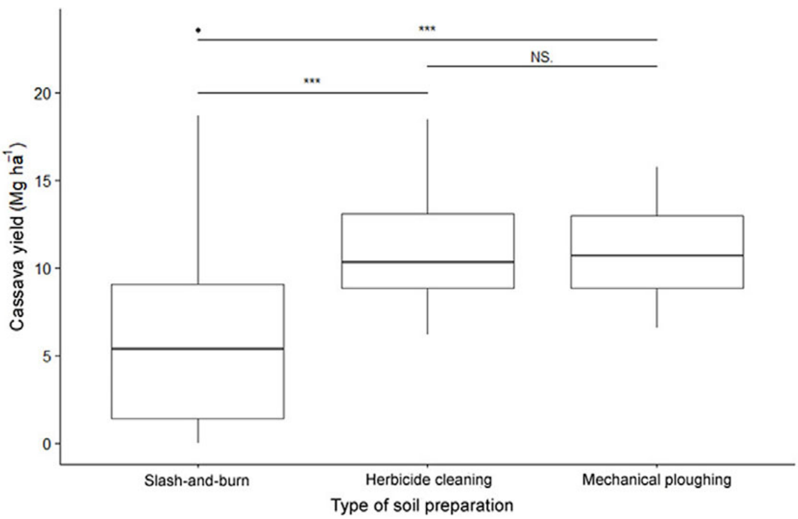

Figure 2. Boxplot of the cassava fresh root yield vs. the type of land preparation. Significance of the difference between means is represented by *** ($p < 0.001$) or NS (non-significant). $n = 100$ for slash-and-burn, $n = 20$ for herbicide cleaning, $n = 15$ for mechanical ploughing.

Weed pressure and weeding labour

Weeding labour for the slash-and-burn fields was significantly higher in Patrimônio than in Paragonorte and Nazaré, averaging 108 ± 10 vs. 19 ± 3 and 29 ± 2 workers day ha^{-1} ($p < 0.05$; Table 5), respectively, suggesting that weed pressure was highest in Patrimônio. This corresponded with the numbers of weeding events that were about twice higher in Patrimônio than in Paragonorte and Nazaré. On the other hand, the observed seasonal WBGR was

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

Table 4. Number of varieties, plant density at harvest and fresh root yield of cassava in the slash-and-burn fields at the three study sites (means and standard deviations)

Study site	Number of varieties	Plant density at harvest (plants ha^{-1})	Fresh root yield (Mg ha^{-1})
Nazaré	1.9 ± 0.1	4200 ± 730	5.2 ± 4.6
Paragonorte	1.3 ± 0.1	5320 ± 630	11.0 ± 5.0
Patrimônio	1.5 ± 0.1	5340 ± 460	4.5 ± 5.4

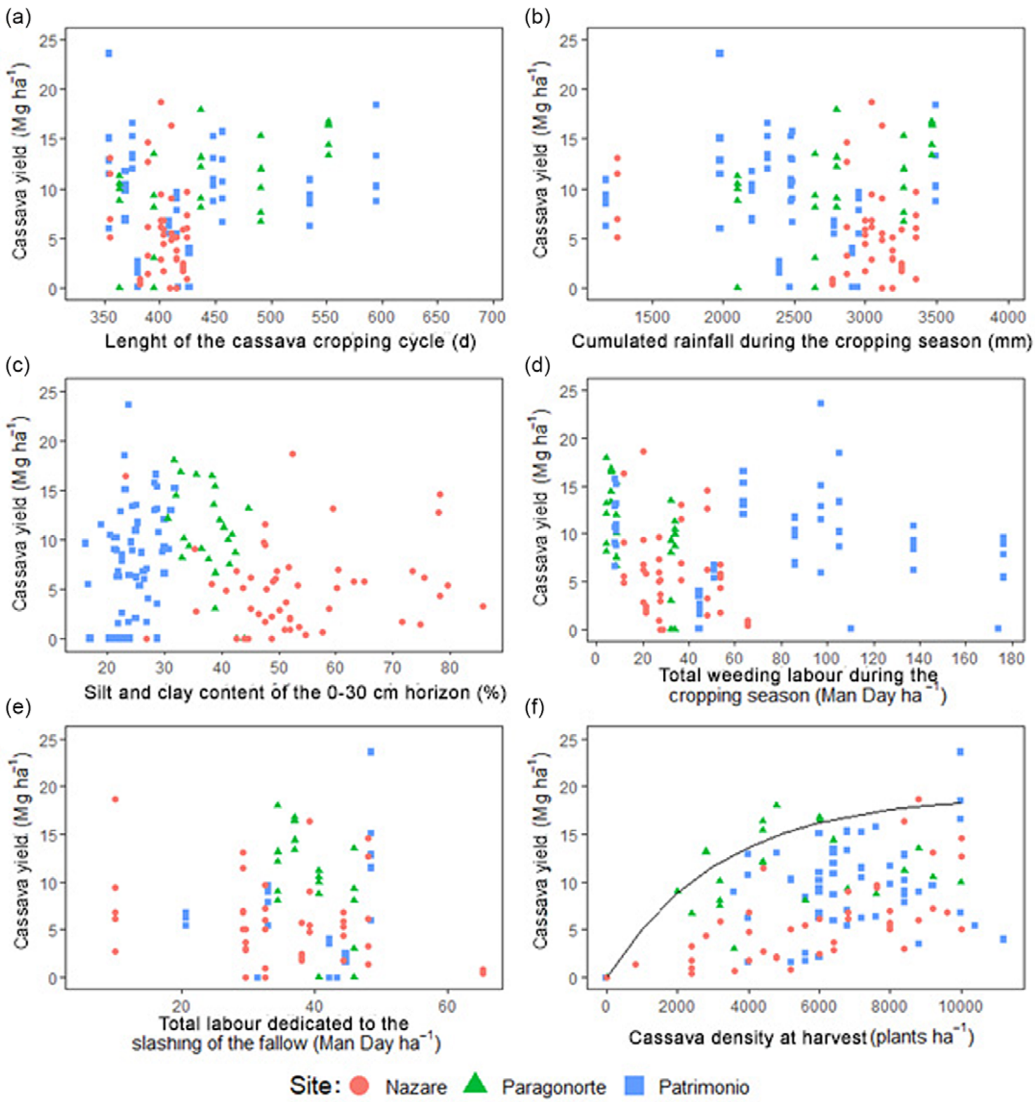

Figure 3. Relationships between cassava fresh root yield and the length of the cropping cycle (a), the cumulated rainfall during the cropping cycle (b), the silt plus clay content of soil (c), the weeding labour (d), the labour for clearing of the fallow (e), and the cassava density at harvest (f) during the cropping cycles of 2015–2017 and 2016–2018. The marker type indicates the site. The equation of the envelop curve of (f) is $y = a\left(1 - \exp^{-b*density}\right)$ with $a = 19$ Mg ha^{-1} ± 17 ($p < 0.001$) and $b = 3.1 * 10^{-4} \pm 7.6 * 10^{-5}$ ($p < 0.001$).

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

Table 5. Weeding labour and weed pressure in the slash-and-burn fields at the three study sites (means and standard deviations)

Study site	Number of weeding events	Weeding labour (worker day ha^{-1})	sWCDR (day^{-1})	sWBGR (g dw m^{-2} day^{-1})	sWBGR mono-cotyledonous	sWBGR dicoty-ledonous
Nazaré	1.4	29 ± 2	0.16 ± 0.09	20.7 ± 15.2	3.7 ± 2.4	17.0 ± 14.2
Paragonorte	1.4	19 ± 3	0.11 ± 0.08	9.4 ± 5.8	2.7 ± 1.8	6.7 ± 4.5
Patrimônio	2.9	108 ± 10	0.23 ± 0.08	17.8 ± 8.3	4.7 ± 4.1	13.1 ± 6.0

sWCDR: seasonal weed cover development rate; sWBGR: seasonal weed biomass growth rate

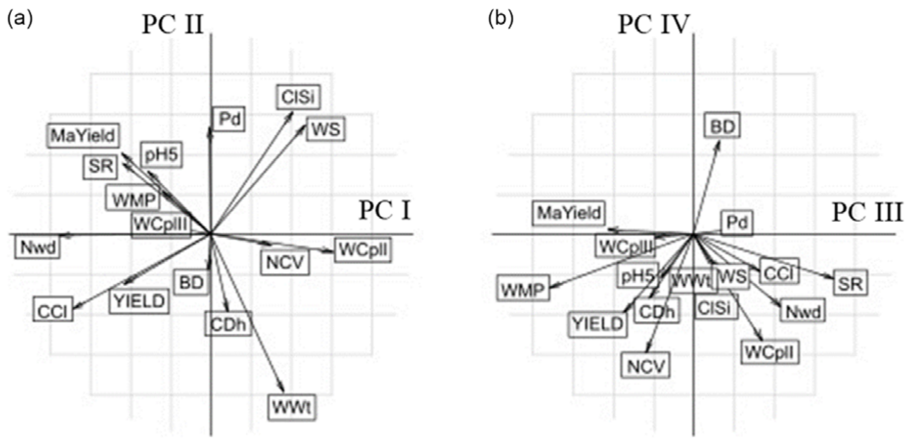

Figure 4. Plot of the principal component analysis (PCA) of variables at the plot and field level. Panel (a) shows the first and second principal component and panel (b) the third and fourth. The cumulative explained variance of the four axes is 54%. The full name of variables can be found in Table 2.

significantly higher in Nazaré and Patrimônio than in Paragonorte (20.7 ± 15.2 and 17.8 ± 8.3 versus 9.4 ± 5.8 g m^{-2} day^{-1} for the slash-and-burn fields, $p < 0.05$) (Table 5). The majority of the weeds were dicotyledonous, i.e., on average between 60 and 80% of the total weed growth at the three sites. Average WCDR during the cassava cropping cycle in the slash-and-burn fields was largest in Patrimônio (0.23 ± 0.08 day^{-1}) compared to 0.16 ± 0.09 and 0.11 ± 0.08 day^{-1}, respectively, in Nazaré and Paragonorte.

Correlations between variables

The first two principal components of the PCA indicated that the length of the cassava cropping cycle (CCl) and cassava root yield (YIELD) were negatively correlated with soil clay plus silt content (ClSi) and the amount of labour dedicated to the slashing of the fallow prior to cultivation (WS) (Figure 4a). The third principal component was associated with the bulk density of the 0–30 cm soil layer (BD) (Figure 4b). Management variables that were correlated along the first two axis were differentiated by the fourth axis of the PCA (Figure 4b). The cumulative variance explained by the first four principal components was 21 (PC1), 41 (PC1 and 2), 55 (PC1–3) and 66% (PC1–4; Figure 4).

Cassava plant density at harvest

The cassava plant density at harvest ranged from zero (in case of plant death due to root rot) to 11 000 plants ha^{-1} (Figure 3f) and was on average significantly lower in Nazaré than in

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

Paragonorte and Patrimônio (Table 4, 4200 ± 730 vs. 5320 ± 630 and 5340 ± 460 plants ha^{-1} for the slash-and-burn fields; $p < 0.05$). Fields contained on average 1.9 ± 0.15 planted cassava varieties in Nazaré, 1.3 ± 0.09 in Paragonorte and 1.5 ± 0.11 in Patrimônio (Table 4). The plant density was positively associated to the labour dedicated to weeding and to cassava replanting ($p < 0.05$; Table 6), whilst a negative association was observed to the bulk density of the 10–30 cm soil layer ($p < 0.05$) and the labour dedicated to intercropped maize planting ($p < 0.05$; Table 6). Concerning the climatic (rainfall) variables, we found that the delay between cassava planting and the start of the rainy season was positively associated to the plant density of cassava at harvest ($p < 0.05$), whilst the number of rainy days during the growing cycle was not significantly associated ($p > 0.05$). Lastly, there was no significant ($p > 0.05$) association between soil clay plus silt content, soil pH or the number of varieties planted and cassava plant density at harvest (Table 6).

Relative cassava yield gap

The plant density-specific relative yield gap ranged from 0 to 95% (Figure 3f). Model 1 (including all observational plots, $n = 114$) showed significant positive effects of the soil clay plus silt content (0–30 cm), the length of the cropping cycle and the labour dedicated to the slashing of the fallow prior to cultivation on reducing the relative cassava yield gap (Table 7). The effect of the amount of labour used for clearing the fallow depended on the soil texture of the site, as indicated by the significant interaction term (Table 7). On the other hand, a significant negative effect of soil bulk density (0–30 cm) on closing the relative yield gap was observed. Model 2 (including the observational plots with weed monitoring, $n = 66$) indicated a significant positive association between the average seasonal WCDR and the relative yield gap, indicating that weed cover negatively affected yield for a given plant density. Model 2 also indicated a significant negative association between the average (seasonal) ratio of monocotyledonous to dicotyledonous weed biomass and the relative yield gap. Moreover, this effect depended on the value of the average seasonal WCDR, as indicated by the significant interaction term between the two variables. There was no significant association between soil pH, the number of cassava varieties planted or intercropped maize grain yield and the relative yield gap. Model 3 (including the observational plots with weed monitoring, $n = 66$) confirmed the significance of the effects of soil fertility and weed pressure on the relative yield gap shown by the models 1 and 2.

Discussion

We found high variability in cassava root yields between and within farmers' fields in the Amazon region of Paragominas, which could to a large extent be explained by the variability of plant density at harvest (Figure 3f). As plant density appeared as a key determinant of attainable root yields, proper management of plant density during the cropping cycle is key to increase the yield potential of cassava. At different plant density levels, differences in cassava root yields were largely explained by differences in labour inputs for weeding and fallow clearing, the effect of the latter depending on soil type (i.e., soil texture). Thus, our results suggest that labour is a key production factor for cassava in the shifting cultivation systems of the Eastern Amazon in which the use of external inputs, such as chemical fertilizers and herbicides, is very limited.

Variability of cassava plant density at harvest

The positive association between cassava plant density at harvest and root yield (Figure 3f) highlights the importance of managing plant density to secure cassava productivity. While we were not able to find other studies reporting measurements of cassava plant density at harvest, the highest values in our study (around 10 000 plants ha^{-1}) were in the same order of magnitude as densities at

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

Table 6. Estimates and standard errors (in brackets) for variables explaining cassava plant density at harvest (plants ha^{-1}) using a linear mixed-effects model

	d.f.	Estimate (SE)	t-value	*p*-value
Intercept	84	13 600 (5510)	2.46	0.016
Soil characteristics				
Clay and silt content of the 0–30 cm soil layer	84	18 (30)	0.61	0.541
Bulk density of the 10–30 cm soil layer	84	−6400 (2500)	−2.55	0.013
pH of the 0–5 cm soil layer	84	220 (350)	0.63	0.528
Management				
Labour force dedicated to the maize planting	84	−430 (200)	−2.08	0.040
Labour force dedicated to the first cassava planting	84	−43 (26)	−1.70	0.093
Labour force dedicated to the second cassava planting	84	160 (50)	3.21	0.002
Number of cassava varieties	84	500 (310)	1.59	0.115
Labour force dedicated to weeding during the cropping cycle	84	29 (13)	2.16	0.033
Climate				
Number of rainy days during the cropping cycle	84	−1060 (6100)	−0.17	0.862
Delay between cassava planting and the start of the rainy season	84	15(7)	2.08	0.040

planting of cassava reported by e.g., Fermont *et al.* (2009) and Jakovac *et al.* (2016). The negative association between the bulk density of the 10–30 cm soil layer and the cassava plant density at harvest can be related to development of root rot, mainly caused by *Phytophthora* spp. and *Pythium* spp. (Poltronieri *et al.*, 1997). A high bulk density in subsoil layers can cause water stagnation in the upper soil layer, creating favourable conditions for fungal diseases on harvestable roots and can ultimately lead to the death of cassava plants (Boas *et al.*, 2016; Byju *et al.*, 2010). In the Amazon region, it is estimated that cassava yield losses due to root rot can reach to more than 50% in the floodplains and over 30% in the uplands. In some cases, there is a complete yield loss, especially in fields that are located on poorly drained soils that are frequently flooded (Modesto and Alves, 2016). Selecting non-sensitive areas to root rot diseases for the cultivation of cassava, or using resistant varieties when available, replanting cassava when stand reduction occurs and controlling the weed pressure can help farmers achieving the plant density of 10 000 plants ha^{-1} that is recommended in the Pará state (Modesto and Alves, 2016) and can increase the yield potential (cf. Figure 3f). Smallholder farmers in the Amazon region occasionally intercrop cassava with maize in order to maximize food production and income per area (Schons *et al.*, 2009). The negative association between the labour input for maize planting and the cassava plant density at harvest may point to strong competition for resources between maize and young cassava plants (Olutayo *et al.*, 2014), or to the occasional destruction of cassava sprouts during maize planting. In addition, the amount of labour for replanting cassava was positively associated with the plant density at harvest, highlighting the importance of a second planting in case that the first planting resulted in a suboptimal crop stand. Furthermore, the observed positive association between weeding labour and cassava plant density at harvest underlines the importance of timely weeding to avoid weed competition with young cassava plants (Staver, 1991) and even to prevent mortality of cassava plants (Aspiazú *et al.*, 2010; Fermont *et al.*, 2009). This was exemplified in one of the cassava fields in which we observed the development of a dense cover of *Acacia mangium* Willd that smothered the cassava plants. Finally, sufficient rain during the initial period after planting is important for a good cassava stand as water deficits can substantially affect sprout survival, depending upon the quality of the stem cuttings (Oka *et al.*, 1987). It was, however, difficult in our study to describe and quantify possible differences in the quality of the cassava planting material used by farmers. In our study region, farmers do not buy improved planting materials but produce their own materials, using cuttings taken from the stems of mother plants. Hereby, they all use very similar

https://doi.org/10.1017/S0014479722000333 Published online by Cambridge University Press

Table 7. Estimates and standard errors (in brackets) for variables explaining plant-density specific relative cassava root yield gap (RYG) using linear mixed-effects models

	MODEL 1	MODEL 2	MODEL 3
d.f.	96	48	51
Intercept	0.50 (0.53)	0.38 (0.11)***	−0.61 (0.99)
Soil characteristics			
Bulk density of the 0–30 cm soil layer	1.1 (0.2)***		1.1 (0.5)*
pH of the 0–5 cm soil layer	−0.050 (0.031)		
Clay and silt content of the 0–30 cm soil layer	−0.020 (0.006)***		−0.025 (0.009)*
Management			
Labour force dedicated to the slashing of the fallow	−0.017 (0.005)**		−0.025 (0.009)*
Number of cassava varieties	−0.021 (0.023)		
Length of the cassava cropping cycle	−0.0013 (0.0005)*		0.0008 (0.0014)
Weed pressure			
Average monocotyledonous weed species growth rate		−9.3 (5.1)	
Average monocotyledonous to dicotyledonous weed biomass ratio		−0.18 (0.08)*	
Average weed cover development rate		0.69 (0.23)**	0.61 (0.21) **
Crop productivity			
Maize dry grain yield	−0.11 (0.07)		
Interaction effects			
Clay and silt content of the 0–30 cm soil layer x labour force dedicated to the burning/slashing of the fallow	0.0005 (0.0001)***		0.0007 (0.0003)**
Average monocotyledonous to dicotyledonous weed biomass ratio x average weed cover development rate		0.93 (0.44)*	

MODEL 1: RYG ∼ soil fertility + management ($n = 114$), MODEL 2: RYG ∼ weed pressure ($n = 66$), MODEL 3: RYG ∼ significant explanatory variables from MODELS 1 and 2 ($n = 66$).
*Indicating $p < 0.05$, **indicating $p < 0.01$ and ***indicating $p < 0.001$.

practices, i.e. with respect to the age of the mother plants, the storage of stems, the parts of the stem used and the length of the stem cuttings.

Managing cassava plant density is a key recommendation formulated by agricultural advisors in the Brazilian Amazon region (Modesto and Alves, 2016) because a densely planted field allows to achieve a rapidly closed leaf canopy during the cropping cycle, limiting soil moisture losses during the dry season, reducing weed pressure and controlling the direct impact of rain on soil particles in causing soil erosion. Our data indicated, however, a high variability of yields for a given plant density at harvest (Figure 3f). Therefore, we performed a yield gap analysis using plant density as a first determining factor which allowed identifying what other factors determine root yields beyond plant density.

Cassava root yield gap

The cassava root yields observed in our study varied largely, ranging from 0 (in case of root rot diseases) to 24 Mg ha^{-1}, comparable with the wide yield ranges reported in slash-and-burn systems in other regions of the Amazon (Jakovac *et al.*, 2016; Vosti *et al.*, 2002). Considerable yield gaps, i.e., the difference between the water-limited yield potential and actual yields, were hence observed (Figure 3f).

Yield gap analysis is commonly used to understand variability of crop yields in smallholder farming systems (e.g., Affholder *et al.*, 2013; Fermont *et al.*, 2009; Van Ittersum *et al.*, 2013), and they may be indicative of both agronomic as well as broader socioeconomic factors affecting family agriculture (Tittonell and Giller, 2013). In yield gap analyses, crop growth simulation models are commonly used to assess the water-limited yield potential, which is defined as the maximum attainable yield per unit land area that can be achieved by a particular crop cultivar in an environment to which it is adapted when nutrients are not limiting, and pests and diseases are effectively controlled. However, the calibration of those models to local contexts often demands a significant amount of data (Affholder *et al.*, 2012), making the use of this method challenging. Our method of using plant density-based estimations of yield potential is based on upper yield boundaries and hence a practical alternative to calculate attainable yields when crop growth modelling is not practicable (e.g., Delmotte *et al.*, 2011; Tittonell *et al.*, 2008).

We did not find any significant association between the cassava yield gap and the number of varieties cultivated in the field, which is probably due to the low number of different varieties used by farmers in the three study sites. Lowest yields, i.e. less than 5 Mg ha^{-1}, were observed when the length of the cropping cycle was shorter than 450 days (Figure 3a), which corresponded to a crop harvest in the middle of the second rainy season following planting. More generally, the relative yield gap was negatively associated with the length of the cropping cycle, indicating that a longer cropping cycle gets the actual yield closer to the maximum observed yield. Cassava plants develop their canopy and root system primarily during the first rainy season, while the harvestable roots (tubers) develop mostly in the second rainy season (Carvalho *et al.*, 1993; Sagrilo *et al.,* 2006). Therefore, completing the full second rainy season is important for achieving high root yields. However, farmers often harvest some portion of their crops earlier because of food or cash needs, resulting in yields lower than those attainable.

Our data (from the site at Patrimônio) indicated a threshold for weeding labour of 60 worker days ha^{-1} above which yields below 5 Mg ha^{-1} were uncommon (Figure 3d) and corresponded to crop failures due to root rot diseases. This result suggests that good weed management is crucial in achieving high cassava yields (Albuquerque *et al.*, 2008) and was corroborated by the positive association between the WCDR and the size of the relative yield gap, which became more important in case of herbaceous weed dominancy (Table 7). A strong negative effect of herbaceous weed pressure on cassava yield was also reported in the Central Amazon region (Jakovac *et al.*, 2016). These are important findings as the current trend of reduced lengths of fallow periods in shifting cultivation systems has been associated with an increase of herbaceous weed populations (e.g., Parsons *et al.*, 2009). Our results are therefore in line with Ekeleme *et al.* (2016) and Fermont *et al.* (2009), who highlighted the importance of weed control in closing cassava yield gaps on smallholder farms.

The lower root yields in Patrimônio and Nazaré than in Paragonorte could be related to weed competition with the cassava plants, as the seasonal WBGR was substantially higher in Patrimônio and Nazaré than in Paragonorte. In Patrimônio, the relatively high human population density poses a high pressure on the land in the community resulting in short fallow cycles (Table 1), increased weed pressure and ultimately declining crop productivity, as also was observed in a study in Central Amazon (Jakovac *et al.*, 2016). In Nazaré, higher weed pressure may to a certain extent be attributed to more fertile soils at this site, but also to the fact that the farmers in this community tended not to prioritize weeding their cassava fields as they rely for their income also on other perennial crops, such as açaí palm (*Euterpe oleasea* Mart.), cashew tree (*Anacardium occidentale* L.) or cupuaçu (*Theobroma grandiflorum* (Willd.ex. Spreng.) Schum.). Thus, the strong weed competition explained to a certain extent the relatively low cassava yields in Nazaré, despite the longer average fallow period and better overall soil conditions than in Paragonorte and Patrimônio (Table 1).

The significant positive effect of labour input for fallow clearing on reducing the yield gap (Table 7) indicates that cultivating cassava on relatively old fallows with substantial aboveground biomass requires relatively high labour input for slashing, but can also support high yields. This finding is supported by Jakovac *et al.* (2016) who also reported higher cassava yields associated with longer fallow periods and decreased frequency of cultivation of the fields.

Based on the above findings, we suggest that besides managing plant density, optimal (late) harvest dates and proper weed and fallow management can help farmers to maximise their cassava yields. In regions such as our study area, where farmers have limited to no access to external inputs, optimal management practices in slash-and-burn systems depend, however, strongly on the availability of labour which is often constrained by the size of the family. In this context, there is an urgent need for alternative cropping systems to slash-and-burn agriculture.

The need for alternatives to slash and burn

Cassava yields in the slash-and-burned fields averaged 6.1 ± 5.5 Mg ha^{-1} (Figure 2), which is low in comparison to the average reported yield for the Para state (14.2 t ha^{-1}, IBGE, 2019). This suggests that the current slash-and-burn practices and cassava management at the study sites were not optimal for productivity. Slash-and-burn is still a common practice in the study region, despite that all fire use has been forbidden by Paragominas municipality law. Some farmers have started to use herbicides or ploughing for clearing fallows, which, if affordable, can be relatively easily implemented at the farms. Despite the significantly higher yields (Figure 2), these local alternatives to burning the vegetation are, however, still poorly represented in Paragominas. For example, in our study, only 13% of the selected fields were prepared with herbicide clearing and 8% with mechanical ploughing, against 79% with slash-and-burn (Table 1). Besides, we did not observe among the farmers who participated in our study the practice of (fire-free) slash-and-mulch (Denich *et al.*, 2004; Kato *et al.*, 1999), the use of improved fallows with e.g., leguminous trees (Lojka *et al.*, 2008), or the practice of agroforestry with e.g., rattan palms (Calamus spp.), cacao or fruit trees with an economic value (Tremblay *et al.*, 2015). These systems require, however, a considerable initial capital, which is frequently not available to the smallholder farmers in the Eastern Amazon region. Moreover, it may take several years for farmers to begin making a profit from these systems above that achievable with the traditional slash-and-burn shifting cultivation systems (Lojka *et al.*, 2008; Mburu *et al.*, 2007). In this context, and to reduce the contribution of smallholder farmers to deforestation, there is an urgent need for supporting more sustainable production systems through local and national public policies (Tremblay *et al.*, 2015). Finally, from our study, it is also clear that new practices should not only focus on soil fertility management but also on weed control and, more generally, on labour productivity.

Conclusions

Plant density, soil fertility and weed pressure are key factors governing cassava productivity in slash-and-burn systems of the Eastern Amazon. In particular, cassava plant density determined the maximum attainable yields that could be expected across soil types and labour availability levels. Plant density depended to a large extent upon the farmers' management decisions, disease incidence and labour availability. Soil fertility decline and weed pressure, on the other hand, are multi-causal and hence more difficult to manage by farmers without access to external mechanical equipment and inputs. In the absence of these, farmers cope with declining cassava productivity by shifting their fields more frequently, thereby reducing the length of the fallow period.

In the current context of low external inputs, labour availability is a key factor for closing the yield gap in cassava slash-and-burn systems. Shifting cultivation systems are facing an important risk of further soil fertility depletion and increased weed pressure because of the current trend of reduction of the length of fallow periods. Cassava productivity declines rapidly when soils become depleted and/or weed pressured increases. To break this vicious cycle, there is an urgent need for a transition from slash-and-burn agriculture to more sustainable and resilient practices, such as agroforestry or slash-and-mulch systems, which allow attaining higher cassava productivity while reducing the extent of soil depletion and weed pressure.

Acknowledgements. We thank Embrapa Amazônia Oriental and the Núcleo de Apoio a Pesquisa e Transferência de Tecnologias, Paragominas for providing technical assistance and working facilities. We also thank Reynaldo Cristo Pinheiro and Ravena Ferreira de Figueiredo for helping with the soil sampling, as well as Professor Luis da Silva Freitas of the Universidade Federal Rural da Amazônia for providing practical support.

Financial support. This study was supported by the research project 'STRADIV – System Approach from the TRAnsition to bio-DIVersified agroecosystems', funded by the Agropolis Fondation under the reference 1504-003; the research project 'Refloramaz – Forest restoration by family farmers in the Eastern Amazon', funded by the Agropolis Fondation under the reference ID 1503-011; the 'Investissements d'avenir' programme (Labex Agro:ANR-10-LABX-0001-01); and the ECOTERA project, ANR-13-AGRO-0003, funded by the French Agence Nationale de la Recherche.

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

References

Affholder F., Poeydebat C., Corbeels M., Scopel E. and Tittonell P. (2013). The yield gap of major food crops in family agriculture in the tropics: assessment and analysis through field surveys and modelling. *Field Crops Research* **143**, 106–118.

Affholder F., Tittonell P., Corbeels M., Roux S., Motisi N., Tixier P. and Wery J. (2012). Ad hoc modeling in agronomy: what have we learned in the last 15 years? *Agronomy Journal* **104**, 735–748.

Albuquerque J.A.A., Sediyama T, Silva A.A., Carneiro J.E.S., Cecon P.R. and Alves J.M.A. (2008). Interferência de plantas daninhas sobre a produtividade da mandioca (*Manihot esculenta*). *Planta Daninha* **26**, 279–289.

Andriesse J.P. and Schelhaas R.M. (1987). A monitoring study on nutrient cycles in soils used for shifting cultivation under various climatic conditions in Asia. III. The effects of land clearing through burning on fertility level. *Agriculture Ecosystems and Environment* **19**, 311–332.

Aspiazú I., Sediyama T., Rebeiro J.I. Jr., Silva A.A., Concenco G., Ferreira E.A., Galin L., Silva A.F., Borges E.T. and Araujo W.F. (2010). Atividade fotossintética de plantas de mandioca submetidas a competição com plantas daninhas. *Planta Daninha* **28**, 963–968.

Bandeira C.T. (2015). Brazilian forestry legislation and to combat deforestation government policies in the Amazon. *Ambiente & Sociedade* **18**, 215–234.

Bianchi F.J.J.A, Booij C.J.H. and Tscharntke T. (2006). Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceeding of the Royal Society of London* **273**, 1715–1727.

Boas S.A.V., Oliveira S.A.S.D., Bragança C.A.D., Ramos J.B. and Oliveira E.J.D. (2016). Survey of fungi associated with cassava root rot from different producing regions in Brazil. *Scientia Agricola* **74**, 60–67.

Brinkmann W.L.F., Nascimento J.C.D., Brinkmann W.L.F. and Nascimento J.C.D. (1973). The effect of slash and burn agriculture on plant nutrients in the Tertiary region of Central Amazonia. *Acta Amazonica* **3**, 55–61.

Bruun T.B., Ryan C.M., de Neergaard A. and Berry N.J. (2021). Soil organic carbon stocks maintained despite intensification of shifting cultivation. *Geoderma* **388**, 114804.

Byju G., Ravindran C.S., Nair R.H. and Ravi V. (2010). Tillage and planting methods on soil properties, yield, root rot and nutrient uptake in a continuously grown cassava field in a semi arid Vertisol of India. *Advances in Horticultural Science* **24**, 176–182.

Carmenta R., Coudel E. and Steward A.M. (2018). Forbidden fire: does criminalising fire hinder conservation efforts in swidden landscapes of the Brazilian Amazon? *Geographical Journal* **185**, 23–37.

Carvalho V.D., Chagas S.J.R. and Botrel N. (1993). Produtividade e qualidade de raízes em diferentes épocas de colheita de variedades de mandioca. *Revista Brasileira de Mandioca* **12**, 49–58.

Cock J.H. (1976). Characteristics of high yielding cassava varities. *Experimental Agriculture* **12**, 135–143.

Conklin H.C. (1961). The study of shifting cultivation. *Current Anthropology* **2**, 27–61.

Coomes O.T., Takasaki Y. and Rhemtulla J. M. (2011). Landuse poverty traps identified in shifting cultivation systems shape long-term tropical forest cover. *Proceeding of the National Academy of Science of the United States of America* **108**, 13925–13930.

De Rouw A. (1995). The fallow period as a weed-break. *Agriculture Ecosystems and Environment* **54**, 31–43.

De Rouw A., Casagrande M., Phaynaxay K., Soulileuth B. and Saito K. (2014). Soil seedbanks in slash-and-burn rice fields of northern Laos. *Weed Research* **54**, 26–37.

Delmotte S., Tittonell P., Mouret J.C., Hammond R. and Lopez-Ridaura S. (2011). On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. *European Journal of Agronomy* **35**, 223–236.

Denich M., Vielhauer K., Kato M.S.D.A., Block A., Kato O.R., de Abreu Sá T.D., Lücke W. and Vlek P.L.G. (2004). Mechanized land preparation in forest-based fallow systems: the experience from Eastern Amazonia. *Agroforestry Systems* **61**, 91–106.

Diaz A., Dini C., Viña S. and García M. (2018). Technological properties of sour cassava starches: effect of fermentation and drying processes. *LWT* **93**, 116–123.

Ekeleme F., Hauser S., Aster G., Dixon A., Weller S., Olorunmaiye P., Usman H., Adeyemi O. and Chikoye D. (2016). Weed management in cassava in Africa: challenged and opportunities. *Outlooks on Pest Management* **27**, 196–197.

Elisabeth M. and Claessen C. (1997). *Manual de Métodos de Análise de Solo*. Rio de Janeiro: EMBRAPA-CNPS.

Feldpausch T.R., Rondon M.A., Fernandes E.C.M., Riha S.J. and Wandelli E. (2004). Carbon and nutrient accumulation in secondary forests regenerating on pastures in Central Amazonia. *Ecological Applications* **14**, 164–176.

Fermont A.M., Van Asten P.J.A., Tittonell P., van Wijk M.T. and Giller K.E. (2009). Closing the cassava yield gap: an analysis from smallholder farms in East Africa. *Field Crop Research* **112**, 24–36.

Fujisaka S., Hurtado L. and Uribe R. (1996). A working classification of slash-and-burn agricultural systems. *Agroforestry Systems* **34**, 151–169.

Greenland D.J. and Nye P.H. (1959). Increases in the carbon and nitrogen contents of tropical soils under natural fallows. *Journal of Soil Science* **10**, 284–299.

Hölscher D., Möller R.F., Denich M. and Fölster H. (1996). Nutrient input-output budget of shifting agriculture in Eastern Amazonia. *Nutrient Cycling in Agroecosystems* **47**, 49–57.

Hughes R., Kauffman J. and Cummings D. (2002). Dynamics of aboveground and soil carbon and nitrogen stocks and cycling of available nitrogen along a land-use gradient in Rondônia, Brazil. *Ecosystems* **5**, 244–259.

Instituto Brasileiro de Geografia e Estatística. (2019). *Produção Agrícola Municipal*. http://www.sidra.ibge.gov.br/ (accessed 25 July 2021).

Jakovac C.C., Dutrieux L., Siti L., Peña-Claros M. and Bongers F. (2017). Spatial and temporal dynamics of shifting cultivation in the middle-Amazonas river: expansion and intensification. *PLoS ONE* **12**, e0181092.

Jakovac C.C., Peña-Claros M., Mesquita R.C.G., Bongers F. and Kuyper T.W. (2016). Swiddens under transition: consequences of agricultural intensification in the Amazon. *Agriculture Ecosystems and Environment* **218**, 116–125.

Kato M.S.A, Kato O.R., Denich M. and 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 Research* **62**, 225–237.

Lemos E.C.M., Vasconcelos S.S., Santiago W.R., de Oliveira M.C.M. and Souza C.M.D.A. (2016). The responses of soil, litter and root carbon stocks to the conversion of forest regrowth to crop and tree production systems used by smallholder farmers in eastern Amazonia. *Soil Use and Management* **32**, 504–514.

Lojka B., Lojkova J., Banout J., Polesny Z. and Preininger D. (2008). Performance of an improved fallow system in the Peruvian Amazon – modelling approach. *Agroforestry Systems* **72**, 27–39.

Mburu J., Börner J., Hedden-Dunkhorst B., Mendoza-Escalante A. and Frohberg K. (2007). Feasibility of mulching technology as an alternative to slash-and-burn farming in eastern Amazon: a cost–benefit analysis. *Renewable Agriculture and Food Systems* **22**, 125–133.

Melifonwu A.A. (1994). Weeds and their control in cassava. *African Crop Science Journal* **2**, 519–530.

Modesto M.D.S. and Alves R.N.B. (2016). *Cultura da Mandicoa: Apostila*. Brasilia: Embrapa.
Oka M.I., Limsila J.A. and Sarakarn S.U. (1987). Relationship between characteristics and germination ability of cuttings in cassava (Manihot esculenta Crantz). *Japan Agricultural Research Quarterly* **21**, 70–75.
Olutayo A., Olubunmi A.O., Olanipekun S.O., Olasoji J. and Aduramigba-Modupe V. (2014). Growth and yield performance of cassava/maize intercrop under different plant population density of maize. *Journal of Agricultural Science* **6**, Article 8.
Parsons D., Ramı´Rez-Aviles L. and Jerome H. (2009). Managing maize production in shifting cultivation Milpa systems in Yucatan through weed control and manure application. *Agriculture Ecosystems and Environment* **133**, 123–134
Patrignani A. and Ochsner T.E. (2015). Canopeo: a powerful new tool for measuring fractional green canopy cover. *Agronomy Journal* **107**, 2312–2320.
Poltronieri L.S., Trindade D.R., Silva H.M. and Albuquerque F.C. (1997). Patógenos associados à podridão mole de raízes de mandioca no estado do pará. *Fitopatologia Brasileira* **22**, 111.
R Core Team. (2020). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.
Sagrilo E., Soares P., Filho V., Pequeno M.G., Celeste M., Vidigal G., Scapim C.A., Kvitschal M.V., Rui R. and Rimoldi F. (2006). Effect of harvest period on foliage production and dry matter distribution in five cassava cultivars during the second plant cycle. *Brazilian Archives of Biology and Technology* **49**, 1007–1018.
Sánchez P.A. (1982). Nitrogen in shifting cultivation systems of Latin America. *Plant and Soil* **67**, 91–103.
Schons A., Streck N.A., Storck L., Adeliburiol G., Zanon A.J., Pinheiro D.G. and Kraulich B. (2009). Arranjos de plantas de mandioca e milho em cultivo solteiro e consorciado: crescimento, desenvolvimento e produtividade. *Bragantia* **68**, 155–167.
Silva T.S., Lima e Silva P.S., Braga J.D., Da Silveira L.M. and Sousa R.P.D. (2013). Planting density and yield of cassava roots. *Revista Ciência Agronomica* **44**, 317–324.
Silva-Forsberg M.C. and Fearnside P. (1997). Brazilian Amazonian Caboclo agriculture: effect of fallow period on maize yield. *Forest Ecology and Management* **97**, 283–291.
Sommer R., Vlek P., Sá T.D., Vielhauer K., Coelho R.D. and Fölster H. (2004). Nutrient balance of shifting cultivation by burning or mulching in the eastern Amazon – evidence for subsoil nutrient accumulation. *Nutrient Cycling in Agroecosystems* **68**, 257–271.
Staver C. (1991). The role of weeds in the productivity of Amazonian bush fallow agriculture. *Experimental Agriculture* **27**, 287–304.
Stromgaard P. (1984). The immediate effect of burning and ash-fertilization. *Plant and Soil* **80**, 307–320.
Tittonell P. and Giller K.E. (2013). When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. *Field Crop Research* **143**, 76–90.
Tittonell P, Vanlauwe B., Corbeels M. and Giller K.E. (2008). Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil* **313**, 19–37.
Tremblay S., Lucotte M., Revéret J.P., Davidson R., Mertens F., Passos C. and Romaña C. (2015). Agroforestry systems as a profitable alternative to slash and burn practices in small-scale agriculture of the Brazilian Amazon. *Agroforestry Systems* **89**, 193–204.
Uhl C., Clark H., Clark K. and 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.
Van Ittersum M.K., Cassman K.G., Grassini P., Wolf J., Tittonell P. and Hochman Z. (2013). Yield gap analysis with local to global relevance – a review. *Field Crop Research* **143**, 4–17.
Van Vliet N., Adams C., Vieira I.C.G. and Mertz O. (2013). Slash and burn and shifting cultivation systems in forest agriculture frontiers from the Brazilian Amazon. *Society & Natural Resources* **26**, 1454–1467.
Villa P.M., Martins S.V., de Oliveira Neto S.N., Rodrigues A.C., Martorano L.G., Monsanto L.D., Cancio N.M. and Gastauer M. (2018). Intensification of shifting cultivation reduces forest resilience in the northern Amazon. *Forest and Ecology Management* **430**, 312–320.
Visses F.D.A., Sentelhas P.C. and Pereira A.B. (2018). Yield gap of cassava crop as a measure of food security – an example for the main Brazilian producing regions. *Food Security* **10**, 1191–1202.
Vosti S.A., Witcover J. and Carpentier C.L. (2002). *Agricultural Intensification by Smallholders in the Western Brazilian Amazon: From Deforestation to Sustainable Land Use. Research Reports 130*. Washington, DC: International Food Policy Research Institute.
Wood S., Rhemtulla J. and Coomes O. (2017). Cropping history trumps fallow duration in long-term soil and vegetation dynamics of shifting cultivation systems. *Ecological Applications* **27**, 519–531.

Cite this article: Abrell T, Naudin K, Bianchi FJJA, Aragao DV, Tittonell P, and Corbeels M. Cassava root yield variability in shifting cultivation systems in the eastern Amazon region of Brazil. *Experimental Agriculture*. https://doi.org/10.1017/S0014479722000333