Fertilizer adoption by smallholders in the Brazilian Amazon: farm-level evidence

Abstract

Multiple constraints prevent smallholders from adopting fertilizers even with regional supply of agricultural inputs expanding and soils being weared-out. Using comprehensive farm-level data from the eastern Brazilian Amazon, we found that market proximity had a significant positive correlation with fertilizer adoption, even after controlling for liquidity, land tenure, education, experience and access to rural extension services. Nevertheless, few smallholders completely replaced nutrients from vegetation with fertilizers. Instead, we found that a hybrid system that combines nutrients from vegetation and fertilizers was approximately twice as common as exclusive fertilizer use. We suggest that the option for this diversified “nutrient portfolio” may result not only from a lack of capital or knowledge regarding return on fertilizer use, but also from the need to adapt to the economic constraints facing smallholders and minimize risk. Results indicate that a rural extension program aimed at supporting a rapid and complete replacement of ashes from vegetation by fertilizers could prove unsuccessful for Amazonian smallholders

1 Introduction

The Amazon region has seen a recent boom in infrastructure expansion (roads and ports), subsidized credit lines, investments in the development of high-yield crop varieties and increased domestic and international demand for agricultural commodities, including beef and soy (Garret et al., 2013; Mann et al., 2010, Pacheco and Poccard-Chapuis, 2012; Vera-Diaz et al., 2008). As a consequence, supply of inputs, including fertilizer, have increased across the region from the 1990's on (Barona et al., 2010; Brown, 2004; Carrero and Fearnside, 2011; Nepstad et al., 2006; Perz 2002 and 2003).

However, not all farmers have been able to seize the potential gains brought by the increased supply of inputs. This is particularly true for smallholders, who typically have limited access to public services, human capital and financial markets (Coomes et al., 2011; Guedes et al., 2014; Perz, 2003; Siegmund-Schultze et al., 2010; Vosti and Witcover, 1996; Vosti et al., 1998). Many of these limiting factors are further exacerbated by the large distances of many smallholdings from paved roads and urban centers (Pacheco, 2009; Perz, 2003).

Smallholders are responsible for producing a substantial share of the region´s staple crops, including maize, rice, cowpea, and manioc (Börner et al., 2007; Caviglia-Harris, 2003; Denich et al. 2005; Pokorny et al., 2013). This important role may, however, be threatened in the long term due to the depletion of the nutrient stocks in the soils of smallholdings. The replenishment of such stocks depends, in most cases, on a system of fallow. Research suggests that fallow duration has been decreasing over time as a result of population and economic growth (Kato et al., 1999, Comte et al., 2012), and there are limited options for accessing new lands through legal deforestation (Nunes et al. 2016)

In addition, results from agronomic research show that more ecologically sound systems such as chop-and-mulch land preparation and specific modalities of agroforestry require high nutrient input in initial years (Kato et al., 1999, Costa et al., 2012). For them to achieve levels of yield and economic performance comparable to existing systems in the Phosphorous-scarce soils of Amazon (Mendonça-Santos et al., 2006) fertilizer use may often be required (see, eg, Kato et al., 1999, Mburu et al., 2006, Costa et al., 2012, Moreira et al., 2013 and Joslin et al., 2013).

To sum up, both the supply of fertilizers and the demand for nutrients by smallholders are expanding. But scarce evidence exists on how fertilizer adoption is responding to such changes, and surprisingly little research has been conducted on fertilizer adoption by smallholders living in the Brazilian Amazon. To the best of our knowledge, the only published articles on the subject are Perz (2003) and Wood et al. (2001), both based on data from the 1990's and before many important changes took place across the region; and also Vera-Diaz et al. (2008), that estimated, with data from 2006, a fertilizer expenditure model without, however, any socioeconomic explanatory variable. We address this knowledge gap by assessing which are the main factors that favour or disfavour fertilizer adoption by Amazonian smallholders. Addressing this question is crucial for improving the effectiveness of rural extension programs in the region.

The next section presents the literature review that grounds empirical analysis. It follows a method section that includes details of the study region, results followed by a deepened discussion and, at last, concluding remarks.

2 Literature review

2.1 New technology adoption by smallholders

The theories and empirical results summarized by Ellis (1993, chap.11) suggest that smallholders, even if partially integrated to markets, may indeed adopt new techniques influenced by factor and output prices, but this may be hindered by market imperfections. For example, Börner et al (2007) presented a bioeconomic simulation model for a representative family of smallholders that practiced, initially, slash and burn in the Bragantina region of the eastern Amazonian state of Pará. Results show that constraints of credit, labor and land are not necessarily sufficient to hinder the adoption of a more profitable technology based on fertilizers and tractors.

Empirical research on technology choice and adoption by smallholders evidences the restrictive role of liquidity constraints, with emphasis on limited credit access (Zerfu & Larson, 2002, Croppenstedt et al, 2003, Duflo et al, 2011). Technical knowledge, experience and education were also emphasized as factors that affect the ability to manage fertilizer utilization (Schuck et al 2002, Kormawa et al, 2003, Asfaw & Admassie, 2004, Conley & Udry, 2008). The influence of market prices and subsidies has also been attested (Duflo et al 2011, Ricker-Gilbert et al, 2011). Caviglia-Harris & Kahn (2001) and Caviglia-Harris (2003) found that access to markets, credit and information on alternative practices had positive influence on the probability and extent of substitution of the traditional agriculture that rely on ashes of burnt vegetation for nutrients. What was also positively affected by other forms of liquidity such as income and cattle herd size.

From evidences that smallholders may adopt new techniques it should not be concluded that such shift occurs all-at-once. Instead, adoption may be gradual and remains partial for a significant period of time, as showed by Byerlee and Polanco (1986) for the case of the Mexican Altiplano. The authors observed that smallholders, seeking to balance risk and profitability embedded to new technological packages, adopt individual components of such packages separately and over time, with gaps of a few years between two new components. The partial adoption of new agricultural technologies by smallholders was also detected recently in other regions, such as Eastern Congo (Lambrecht et al., 2015), Mozambique (Grabowski and Kerr, 2013) and Timor Leste (Noltze et al., 2011).

Partial adoption may be explained not only by risk, but also by the cost of learning how to optimize a new set of practices. In particular, the introduction of fertilizers requires the accumulation of knowledge on the fertilizer-yield relationship (Dercon and Christiaensen, 2011, Zerfu and Lawson, 2002, p.5, Lambrecht et al., 2014). Where rural extension and technical assistance is not fully available, this is pursued in part through experimentation resulting in production losses and foregone profits, as evidenced by the recent literature on the economics of learning (Conley and Udry, 2008, Duflo et al., 2011, Wen and Stefanou, 2007, Udry, 2010).

In sum, the available literature suggests that smallholders tend to adopt, gradually, new practices when prices are favorable and constraints flexible and otherwise retain traditional farming techniques. The focus of this paper is to assess the extent to which this conclusion holds for the adoption of fertilizers by smallholders in the Amazon region.

2.2 Fertilizer adoption by smallholders

Smallholders in the Amazon are known to rely on a limited set of nutrient sources, depending primarily on burnt or decomposing vegetation from fallow areas. Organic fertilizer from cattle or poultry and chemical fertilizers are used less frequently. Here, in reviewing the literature to date on fertilizer adoption by smallholders, we refer to external chemical fertilizers simply as “fertilizer”.

Sauer and Mendoza-Escalante (2007) detected a 40% fertilizer use rate in a sample of 197 smallholders from 22 villages of an old colonization region in the Eastern Amazon in which the practice of slash-and-burn and annual crops dominated. The authors also observed the use of castor oil and poultry manure as fertilizers, in line with Siegmund-Schultze et al. (2007) detection of organic fertilizer use.

Perz (2003) surveyed 291 households that owned 347 lots on the Uruará Colony, in the eastern Amazon. The farmers most likely to use fertilizers were those that were born in south/southeastern Brazil, had access to credit and rural extension, owned larger farms whose deforested fraction was smaller upon acquisition, were closer to the nearest town and lived in older households. Also, perception of a decline in soil fertility and market orientation were positively correlated with use of fertilizers. In addition, Wood et al. (2001), based on 261 smallholders from eastern Amazon (Uruará), show that smallholders with land title are twice more likely to use fertilizers. Vera-Diaz et al. (2008) found that physical properties of soils, in particular, soil depth and pH level, are (positively) correlated with the amount of fertilizer applied by soybean growers.

Multiple studies bring evidence on the influence of smallholders’ budget constraint. Croppenstedt et al. (2003) and Zerfu and Lawson (2002) provide evidence that credit constraint is a limiting factor to fertilizer adoption by Ethiopian farmers. Duflo et al. (2006 and 2011) show that when liquidity is insufficient to finance both consumption plans and purchase of fertilizers, Kenyan smallholders tend to prioritize the former, procrastinating fertilizer adoption. Lambrecht et al. (2014) found a positive significant correlation of a dummy indicating off-farm income with the decision to adopt fertilizers, controlling for other socioeconomic characteristics of Congolese farmers.

According with the review of African studies by Druilhe and Barreiro-Hurlé (2012), the main drivers of fertilizer adoption were wealth, education, access to markets, rural extension, prices of outputs and inputs, farmers’ age and gender. With data from Malawi, Ricker-Gilbert et al. (2011) estimated the impact of fertilizer subsidy on fertilizer adoption. In addition to the factors already mentioned, the authors found that farmers closer to paved roads, with access to credit, receiving larger subsidies and holding larger farms tended to acquire larger quantities of non-subsidized fertilizer. Rainfall and the expectation of increased output price also proved influent.

The role of education in technology adoption can be traced back to the classical hypothesis of Theodore Schultz that education shapes the ability to innovate and reallocate resources, dealing efficiently with disequilibria (Schultz, 1975). It also augments the diffusion of “new ideas and techniques” (Zerfu and Lawson, 2002).

Kormawa et al. (2012) investigated the effects of fertilizer market reforms in Bénin, Sub-Saharan Africa. The additional factors found by authors were the use of complementary inputs (seed and pesticide), social capital, and the degree of market orientation (share of production sold). Other factors that proved influential were, for the case of Eastern Congo (Lambrecht et al, 2014), off-farm income, size of livestock and household labor and, for the case of Ethiopia (Zerfu and Lawson, 2002), favorable climate, stability of prices and use of organic fertilizers.

Shakya and Flinn (1985) conducted a survey with Nepalese rice farmers in early 1980s and the only additional factor they detected was the adoption of a high-yield rice variety. Fertilizer demand of farmers located at Chaobai watershed, northern China, was estimated by Zhou et al. (2010). The covariates with significant and positive effects were the share of non-working persons in the household, irrigation, market proximity and whether farming prioritized profit. Fertilizer use was disfavored by the use of manure (organic fertilizer), a higher soil fertility and by a higher importance attached to fertilizer price while deciding on fertilizer amount. Interestingly, education and wealth did not had a significant effect and farm size had a negative significant effect.

Table 1 synthesizes the literature review just presented by listing main factors that had significant favoring (“+” sign) or disfavoring (“-”) influence on fertilizer adoption by smallholders. It also justifies the selection of explanatory factors based on the channels that, in accordance with the papers reviewed, link factors with the explained fertilizer adoption.

[Table 1: about here]

3 Data and methods

3.1 The study region

Survey data were collected during 2010 and early 2011 in two study regions, the municipality of Paragominas (PGM) and the contiguous municipalities of Santarém and Belterra (herein, Santarém-Belterra or STM-BTA), as part of the Sustainable Amazon Network (whose acronym in Portuguese is 'RAS'), (Gardner et al., 2013). This database, hereafter referred as "RASDB", contains information on agricultural practices and household characteristics of a sample of landholders. From it, 213 farmer landholders were selected for this study (as explained in 3.5 below). Staple crops comprise a significant part of the agriculture of the three municipalities (Table 2) with land-use practices ranging from fallow and fire to the use of fertilizers and tractors (Table 3).

The dominant nutrient source for the production of staple crops was ash from burnt vegetation, mainly secondary forest, with 164 of 213 farmers (77%) relying only on fallow (Table 3). Fertilizer was used by 37 farmers (~18%). Interestingly, only about half of these farmers relied solely on fertilizer, while the other half opted for a hybrid nutrient mix of fallow and fertilizers (Table 3).

Within the two study regions, human settlement and colonization are consolidated and mechanized agriculture has expanded alongside low-input and extensive cultivation dependent on nutrients from burnt vegetation. The coexistence of these technologies has given rise to a hybrid approach to fertilizer use, combining ash from burnt vegetation and fertilizers. Up-to-date data on fertilizer use in these regions are not available. However, the area planted with soybeans, a fertilizer-intensive crop, is a reasonable proxy for the relative level of fertilizer use (Brown et al., 2004; Garret et al., 2013; Richards et al., 2012; Table 2). Such proxy reveals, together with the rate of fertilizer use in 2006, that the use of fertilizers in our study regions was higher than the average for the Brazilian Amazon as a whole (Table 2, last two columns).

Smallholders dominate our sample with 197 farmers (92%) with properties no larger than 100 ha and the maximum property size being 500 ha (see Gardner et al, 2013 for details). This definition of smallholders (i.e., holders of farms up to 100 hectares) is in accordance with the literature on the state of Pará (e.g., Börner et al., 2007; Guedes et al., 2014 and; Siegmund-Schultze et al. 2007 and 2010).

Almost half of the farmers (43%) received monthly transfers from Bolsa Família (Family Grant), the main governmental program to tackle poverty alleviation, and can thus be considered poor (Table 4)[1]. Only 6% had an education level above lower secondary. Most farmers (70%) grew annual crops (mainly maize, manioc and rice) with the objective of selling to markets (Table 4).

On average, farmers that adopted the fertilizer-based technology had larger annual incomes, allocated larger areas to annual crops, were more educated but less experienced about the Amazonian environment, and had a higher probability of being integrated to the market for annuals, and of being located in Paragominas (Table 4). They also had more access to credit. Considering, more broadly, the farmers with some degree of fertilizer adoption, whether 100% fertilizers or a hybrid input, they had a lower probability of being poor and a high probability of being served by rural extension, and were also closer to markets. Hybrid technology adopters were, on average, older and more experienced with the Amazon region and also with their farm (Table 4).

[Table 2 About here]

[Table 3 About here]

[Table 4 About here]

3.2 Econometric model

The econometric model represents the process of decision on fertilizer adoption. It explains the nutrient option chosen among the three alternatives detected in the study regions (section 3.1) in the basis of influential factors identified by the literature review (section 2). The theoretical basis of the econometric model is the nutrient choice problem described in the next two paragraphs.

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[1] To be eligible for the Program, a family must earn a monthly per capita income below approximately US$35 (R$70), i.e., roughly the poverty line of the United Nations Program for Development (UNDP) of US$1.25/day (see the footnote on http://www.un.org/millenniumgoals/pdf/Goal_1_fs.pdf).

The “traditional technology”, based on nutrients from the ashes of vegetation, is represented by the production function $F_1(A,Z;\Omega)$, where A is the input of ash and Z is the vector of inputs of labor, land and tractors. Biophysical characteristics of the farm (soil quality) and socioeconomic characteristics of the farmer (access to rural extension, tenure, human capital, etc.) are captured by vector Ω. This technology will be referred, hereafter, simply as “vegetation-based”.

The fertilizer-based technology is described by the function $F_2(Q,Z;\Omega)$ with Q being the fertilizer input. The hybrid technology, combining nutrients from fertilizers and from vegetation ash is represented by $F_3(A,Q,Z;\Omega)$. For all three technologies, production factors exhibit positive but diminishing marginal product.

Let the vector of factor inputs specific to technology j be denoted by Δ_j. It can include fertilizers and ash, depending on j. Vegetation-based technology is indicated by j = 1, the hybrid, by j = 2 and fertilizer-based, by j = 3. All technologies are optimized subjected to the liquidity constraint $r\Delta_j \leq M$, where r is the vector of factor prices, including fertilizers, and M the liquidity available. If p is the vector of output prices, then the optimal profit is thus:

$$\pi_j'(\Delta_j') = g_j(p, r, M, \Omega), \text{ such that } \Delta_j' = \text{argmax}\{pF_j(\Delta_j;\Omega) - r\Delta_j\} \text{ s.t. } r\Delta_j \leq M$$

With $g_j(.)$ being the function that connects parameters of the optimization problem with the optimal profit level. Of the three technologies, rational farmers choose the one that yields the largest optimal profit under the limit imposed by M.

To conclude, it is assumed that farmers behave as if they choose nutrient source by following a two-stage procedure. In the first stage, the use of nutrient sources is optimized, revealing the maximum level of profit each of the three sources can yield. In the second stage, the source that yields the highest maximum profit is identified and then chosen.

Now, to obtain an econometric model, the approach of Schuck et al. (2002) is followed, with random disturbances being appended to the maximum profits yielded by the technologies. This way, for the i-th farmer, $\pi'_{ji} = f_{ji}(x_i) + u_{ji}$, where x_i is the vector with the exogenous variables of the profit maximization problem which were also detected in the literature review (herein, “covariates”) , i.e, $x_i = [p_i\ r_i\ M_i\ \Omega_i]$ and j = 1,2,3. Taking a linear approximation for f(.) one has $\pi'_{ji} = x_i\beta_j + u_{ji}$ (Mcfadden, 1981). Let X be the matrix with the values of x_i for all N farmers. Technology j is chosen if and only if $\pi'_{ji} > \pi'_{ki}$, k=1,2,3, then, the probability of j be chosen, conditional on the covariates of X, P(y = j|X), is equal to P($\pi'_{ji} = \max\{\pi'_{1i}, \pi'_{2i}, \pi'_{3i}\}$|X). It is generally assumed (Mcfadden, 1981, Wooldridge, 2002a, section 15.9) that the last probability is a non-linear function G(.) of only X and the parameters of the linear approximation, β_j, j=1,2,3, which can be subsumed to a three-column matrix, β , such that P(y = j|X) = G(X,β). The multinomial logit model (MNL) corresponds to the following specification for G(X,β):

$$G(X,\ \beta\,) = \begin{cases} \dfrac{\exp(X\beta_j)}{1+\exp(X\beta_2)+\exp(X\beta_3)}, if\ j = 2{,}3 \\ \dfrac{1}{1+\exp(X\beta_2)+\exp(X\beta_3)}, if\ j = 1 \end{cases} \quad (1)$$

Thus, $\sum_{j=1}^{3} \mathrm{P}(\mathrm{y} = \mathrm{j}|\mathrm{X}) = 1$.

The econometric model above establishes that the probability of a nutrient option being chosen is related to the socioeconomic characteristics of decision makers that were selected based on the literature review (vector X). The model informs whether a given characteristic is correlated in a significant and expected way with observed nutrient source choices, after correlations with all reasonable influential factors are accounted for.

To simplify the presentation and interpretation of the results, it is helpful to note that, by taking the vegetation-based technology as the base (reference) alternative, the ternary nutrient choice problem can be studied as a set of two binary choices, j = 1 vs. j= 2 and j = 1 vs. j = 3. In each pair, the probability of an alternative being chosen is $\mathrm{P}(\mathrm{y} = \mathrm{j}|\ \mathrm{y} = \mathrm{j}\ \mathrm{or}\ \mathrm{y} = 1\,, \mathrm{X}) = \frac{\exp(X\beta_j)}{\exp(X\beta_j)+1}, j = 2{,}3$ (2).

The function H(x) = $x(1+x)^{-1}$ is such that H' ≡ dH(x)/dx > 0. Then, $\frac{\partial \mathrm{P}(\mathrm{y} = \mathrm{j}|\ \mathrm{y} = \mathrm{j}\ \mathrm{or}\ \mathrm{y} = 1\,, \mathrm{X})}{\partial x_l} = H' \ \exp(X\beta_j)\,\beta_{jl}$ and, conclusively, $S\left(\frac{\partial \mathrm{P}(\mathrm{y} = \mathrm{j}|\ \mathrm{y} = \mathrm{j}\ \mathrm{or}\ \mathrm{y} = 1\,, \mathrm{X})}{\partial x_l}\right) = S(\widehat{\beta_{jl}})$, j=2,3, where S(.) is the sign function and $\widehat{\beta_{jl}}$ the point estimate for the coefficient of the l-th covariate in the equation explaining the binary choice of j versus the base-choice.

This last step considerably simplifies the refutation of the favouring or disfavouring role of the covariates suggested by literature (Table 1). It ensures that the sign of the point estimate of a coefficient can be interpreted as the direction of the effect of the associated covariate on the probability of choosing the alternative technology instead of the vegetation-based incumbent technology.

Maximum likelihood is the method best suited for estimating model above (Wooldridge, 2002a, p.498). Only results robust to heteroskedasticity and autocorrelation are considered. To mitigate the multicollinearity attested by pairwise correlations (appendix B) multiple exclusion restriction (joint significance) tests were performed for categories of covariates (Aguilera et al., 2006, Homser and Lemeshow, 2013, section 4.4). These tests are less influenced by multicollinearity among covariates than individual significance tests (Wooldridge, 2002b, section 4.5).

3.3 Dependent variable and terminology

The dependent variable identifies the option for one of the three nutrient sourcing technologies presented in section 3.1, based on the following criteria.

1. Vegetation-based technology adopters are defined as farmers that
    a. Conducted fallow and did not use fertilizers or;
    b. Did not conduct fallow and did not use fertilizers, but used fire between 2007 to 2010;
2. Hybrid technology adopters are farmers that conducted fallow and used fertilizers;
3. Fertilizer-based adopters are farmers that used fertilizers but did not conduct fallow nor used fire.

Therefore, the terms “(staple crop) technology” and “nutrient source” are interchangeable and will be used as such herein. We also use the term “incumbent” to refer to vegetation-based technology.

3.4 Robustness assessment

Robustness of multinomial logit estimates to alternative classifications of nutrient choice status (dependent variable) was assessed. For this, two probit models were run, whose dependent variables were the fertilizer and fallow dummies used to create the MNL dependent variable (section 3.3).

For each of the two binary choices, vegetation-based vs hybrid and vegetation-based vs fertilizer (only), the statistical significance and signs of covariates were compared with the probits. For easiness, the fallow dummy was inverted (i.e., turned into a no-fallow dummy) when comparing with the choice including the fertilizer (only) option. Whether the MNL estimate differed from the two probits, the status "uncertain" was assigned to the sign of corresponding coefficient. Contrariwise, the MNL sign was deemed correct. The same procedure was pursued for joint significance tests.

3.5 Econometric model covariates and sample

The covariates incorporated belong to the six classes of factors that, according with the literature, drive fertilizer adoption (Table 1). Not all factors mentioned by previous studies were included either because data for them could not be consistently collected or they were not meaningful for the particular context. One example is the case of fertilizer and output prices. Many respondents did not used fertilizers and most of others had not answered the questions on prices[2]. Therefore, prices could not be included. Table 4 provides detailed definitions for variables and their statistical summary.

The sample used in this study comes from a joint ecological-socioeconomic data collection effort that sought to represent the regional forest cover gradient (Gardner et al., 2013). This landscape-based criterion for sampling selected many landholders that did not farm their land and were therefore out of the scope of this paper. Other reasons for exclusion of landholders were missing variables and sharp

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[2] Another omission that deserves clarification is that of livestock, a measure of which works as a saving account with high liquidity in rural areas of developing countries. Siegmund-Schultze et al (2007) provide evidence that this applies to rural areas of Pará state what is also pointed out by Caviglia-Harris (2003). Unfortunately, the survey has not collected precise enough information to estimate the value of farmers' cattle herds. Among the 213 farmers of the sample, only 96 answered questions on cattle herd and among them, 37 have not provided data on the composition of the cattle herd. Notwithstanding, a dummy indicating whether a farmer has a cattle herd was positively correlated, within the sample and at the 5% level, with the credit access dummies and also with income. This attests that the liquidity measures considered are valid indicators of the liquidity available to farmers.

technological/socioeconomic differences with the rest of the sample, such as the case of a small (N~20) group of soybean growers.

4 Results

[Table 5 About here]

[Table 6 About here]

MNL estimates were satisfactorily robust to the definition of the dependent variable. Discordance between MNL and fallow/fertilizer probits was relevant for only four of eighteen covariates (applied for credit, money limits new practices, time in the Amazon and crop area), in the case of the vegetation-based vs hybrid choice. For vegetation-based vs fertilizer choice discordance was observed for only two covariates (soil limits future plans and time on farm; details on appendix D). Covariates belonging to all the main classes of Table 1, namely market proximity, liquidity, and soil, were all jointly significant (Table 6). Rural extension was assessed only individually and proved significant in explaining the relative probabilities to opt for vegetation-based and hybrid technologies (Table 5). Results are thus in accordance with the previous studies reviewed.

Market proximity, rural extension, education and time on farm favoured the option for hybrid instead of vegetation-based incumbent. Land tenure disfavoured. Now comparing the probabilities of choosing fertilizer-based and vegetation-based, the former was favoured by market proximity and education. It was disfavoured by limited cash.

Consequently, smallholders closer to markets had higher probability of using fertilizers. This is in line with previous fertilizer adoption studies reviewed (e.g., Kormawa et al. (2013), for Bénin, Lambrecht et al. (2014) for Congo and Ricker-Gilbert et al. (2011), for Malawi). The positive relationship between access to rural extension and fertilizer adoption makes sense considering the historical emphasis of such services on the input (Druilhe and Barreiro-Hurlé, 2012; Viebrantz, 2008).

In parallel with Shuck et al. (2002), there was a negative and significant relationship between education level and the probability of burning vegetation for nutrients. This is also in accordance with the claim by Asfaw and Admassie (2004) that a significant influence of education is commonplace in studies on the adoption of new agricultural practices, especially fertilizers. Experience on farm increased the likelihood of opting for the hybrid.

Figure 1 below presents predicted probabilities of opting for each of the two alternatives to the vegetation-based technology in choices involving the three options (equation 1, section 3.2 above), under three different constraint levels – details on appendix C. The probability of opting for the hybrid nutrient source was clearly larger than the probability of choosing exclusively fertilizers at all combinations of values for the market proximity and constraint levels considered.

5 Discussion

5.1 Correlates of nutrient source options

The evidenced relevance of market proximity further attests the critical role of the factor for fertilizer adoption in the rural regions of developing countries. High transport costs due to limited access to quality roads and to the need to import fertilizers were found to constrain adoption of fertilizer inputs by smallholders in Ethiopia (Croppensted et al. 2003, Zerfu and Lawson, 2002). Lambrecht et al. (2014) also found market distance to constraint fertilizer tryout by smallholders in DR Congo and Kormawa et al. (2013) argue that concentration of fertilizer supply in urban areas imposed a barrier to adoption by many smallholders in Bénin (sub-saharan Africa).

It is a common claim that fertilizer adoption in the Brazilian Amazon is limited by the large freight cost due to importation from countries and regions thousands of kilometers away (Mercado, 2015, Wadt et al. 2010). In consonance, the average smallholder sampled were 113 minutes away from the nearest urban centre and 33% of sample were more than 7 kilometers from the nearest road.

It must be noted that market distance is only one of many determinants of market access. However, the fact that it was a significant explanatory variable in our results suggests that other factors that could counteract the effect of distance are limited in their influence. Examples of other factors include opportunities to share freight costs via smallholders' associations, quality and weather-proofing of roads and the design of government settlements especially in what regards to the distances among settled smallholders (see Pacheco 2009; and Guedes et al. 2014).

The relevance of liquidity (i.e., purchasing power) echoes multiple studies which recognize capital accumulation and credit access as necessary conditions for technology adoption by Amazonian smallholders (Sorrensen, 2009, Caviglia-Harris and Kahn, 2001, Perz, 2003). This is also true for African smallholders. Zerfu and Lawson (2002) and Croppenstedt et al. (2003) found strong evidence of credit constraints disfavouring fertilizer adoption in Ethiopia. The probability of Malawian smallholders to buy fertilizers at the market price was increased by credit access, according to Ricker-Gilbert et al. (2011). In DR Congo, credit constraints prevented the continued adoption of fertilizer (Lambrecht et al., 2014). However, even with special credit lines for smallholders being supplied in the Amazon, only 35% of the sample had ever borrowed money from banks and 42% had attempted to. This apparently low demand may result from the lack of required documents, especially land titles, which were owned by only half of sample (a finding that corresponds to that of Sorrensen, 2009, Wood et al., 2001, Pokorny et al., 2013 and Coady et al., 1995). As such, the potential of rural credit to expand fertilizer adoption by smallholders is being probably underutilized in practice.

The significance of rural extension, education and experience attests the relevance of the cost of learning how to efficiently manage fertilizers. This is in line with previous studies of African countries that point to the cost of learning as one of the main barriers blocking fertilizer adoption (Duflo et al., 2011, Druilhe and Barreiro-Hurlé, 2012). Education enables farmers to read instructions on fertilizer bags, to learn about the amount to be applied to particular soil types, and to obtain and process information for improving fertilizer use. Its favouring influence in fertilizer adoption by smallholders was confirmed, for instance, in Ethiopia (Asfaw and Admassie, 2004, Zerfu and Lawson, 2002, Croppenstedt et al. 2003) and in DR Congo particularly regarding awareness about fertilizer (Lambrecht et al., 2014). In Northern China, the overuse of fertilizers was less likely among highly educated farmers (Zhou et al. 2010).

The influence of experience as measured by time on farm related to the ability to adapt new techniques to specific farming conditions and also to combine new and already well-known techniques. This result is consistent with Brondizio and Moran (2008)´s study on climate change adaptability, where they argue that experience with farms' biophysical features is crucial for smallholders to build an ability to adapt to transformations.

It is intriguing that the two groups that differed most strongly in the three factors related to the cost of learning (rural extension, education and experience) were not those occupying the extremes of the fertilizer use spectrum in our sample. In fact, differences were considerably larger between vegetation-based and hybrid groups than between hybrid and fertilizer adopters - considering MNL estimates. As differences should be reduced by group turnover, the flow of farmers shifting groups may be considerable between the groups of hybrid and fertilizer adopters and negligible between vegetation-based and hybrid. This suggests that the hybridization model is not simply a tryout phase of fertilizer adoption, but rather a first step into continued adoption and, additionally, integral nutrient sourcing from fertilizers may be reversed to partial sourcing.

Regarding the relevance of rural extension, Schuck et al. (2002) found a similar result in Cameroon when also measuring access to rural extension with a binary variable for received visits from technicians. Lambrecht et al. (2011) also observed a positive and significant partial effect of rural extension on the probability of a Congolese farmer to tryout fertilizers. In addition Kormawa et al. (2013) found a positive and significant influence of the number of extension visits received annually and the demand of fertilizer in Bénin, Africa. However, it must be clarified that in practice few smallholders benefit from rural extension. Only 35% of the sampled smallholders received an extension visit and 50% of them were visited for the last time at least two years before the interview. This supports the recent assessment by Paula Filho et al. (2016) which reveals that less than 10% of the demand is met in Pará state, another parallel with the African context (Schuk et al., 2002). Consequently, even with significant partial correlation in the sample, rural extension probably shifts, in reality, a small number of smallholders from vegetation nutrients to the hybrid model. Also, as already pointed out, rural extension made no difference in the choice between hybrid and full fertilizer use, echoing the limited influence the service had in fostering continued adoption in DR Congo (Lambrecht et al., 2014).

5.2 Interpreting the hybrid technology option

The relevance of the hybrid (Table 3 and Figure 1) finds support in the work of Byerlee and Polanco for the Mexican Altiplano (1992). In the historical adoption paths estimated by the authors, improved and traditional inputs coexisted for 8 to 20 years. The mixing was probably more salient among smallholders (<20 hectares) whose adoption rate increased more slowly.

Stringency of liquidity constraint, high discount rates and risk seem to be the main factors driving the high adoption rate of the hybrid. Regarding the first, of the 213 staple crop growers surveyed, 97 (46%) reported to be interested in introducing new practices with 82 (84%) of them mentioning fertilizers or tractors. A minority of 23 farmers was able to carry this plan and most of those that were not able stated they were constrained by lack of money in their ability to change practices. The stringency of smallholders' budget constraint is enlightened by a simple estimate. The Brazilian institution of agronomic research, EMBRAPA, recommends that maize be planted in the state of Pará with an input of nutrients whose estimated cost is of R$543/ha[3]. Rural households of the three studied municipalities had a median monthly income of R$574 in 2010 (IBGE 2012). Farmers would need, thus, to save around 8% of their annual incomes in order to be able to purchase fertilizers for the next year. Even this apparently small saving rate may be unfeasible for poor smallholders, whose discount rates are generally high (Duflo et al., 2011).

Only those who expect a considerable return from fertilizer will forego 8% of their consumption to invest in fertilizers. Although it is valid to expect higher returns with yield gains from fertilizer adoption in Pará (Hölscher et al., 1997, Kato et al., 1999), higher average returns tend to come with higher return volatility (Dercon and Christiaensen, 2011). Additionally, the probability distribution of the returns of the fertilizer-based technology is less known by early adopters than that of the traditional vegetation-based technology.

Summing up, technological hybridization is a way to adapt to the liquidity constraint faced. It may also be a risk mitigation strategy since it allows for experimenting new

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[3] This number was estimated considering two fertilizers, (i) NPK 4-28-20, applied in a quantity 215kg/ha to meet the required rates of 60kg P_2O_5/ha and 40kg K_2O/ha, recommended by Cravo et al.(2007), with a cost of R$1.6/kg (SINDIFERPA, 2009) and; (ii) Urea, which needs to be applied in 153.2 kg/ha to meet the (minimum) recommendation of 80 kg of Nitrogen per hectare (Cravo et al.,2007). A price of R$1.3/ha is considered for Urea (Maneschy, 2008). It is assumed that one hectare is cultivated per year.

practices without eliminating traditional practices that play the role of safety net (Byerlee and Polanco 1992).

[figure 1: about here]

6 Concluding remarks

Our results demonstrate that, even under constraints of limited liquidity, insecure land tenure and costly learning, smallholders may adopt new methods such as fertilizer-use, depending on the degree of access to markets and rural extension and also on their education and experience level. This also means that fertilizer may, thus, not be adopted even when it is more profitable than the traditional reliance on ashes from burning vegetation (Dercon and Christiaensen 2011).

It was found that, even with expanding supply of transport infrastructure, distance still determined the degree of fertilizer adoption, suggesting many smallholders are not being benefited by a reduction in transport cost. The potential of credit and rural extension to favour fertilizer adoption were probably being under-explored in practice mainly due to supply constraints. In compensation, the cost of learning how to use fertilizers was substantially lowered by education and experience on farm.

Importantly, the willingness to adopt the ash-fertilizer hybrid suggests that fertilizer adoption should be seen as a process and not a one-shot decision. Indeed, the average hybrid adopter was more experienced than those that went ‘all the way’ using only fertilizers. Through gradual adoption and keeping traditional practices, smallholders minimize risk and cost of learning and take time to accumulate capital, progressively overcoming the factors that hinder fertilizer use. Additionally, hybrid nutrient use is not necessarily a short temporary phase and full use of fertilizers is not necessarily perennial.

An important limit of the analysis must be highlighted. Results are necessary but far from sufficient to understand the costs and benefits of a transition away from the vegetation nutrients of traditional slash-and-burn, as, besides nutrient sources, alternatives for land preparation, weeding and pest control must also be accounted for (Nepstad et al., 1999). Moreover, the social and environmental risks of a transition away from slash and burn should also be considered. Fire-dependent smallholders are among the poorest and providing them fertilizers and tractors may have undesired side-effects such as threatening food security (due to increased profitability of non-staple crops such as soybeans and perennials, Börner et al., 2007, Pereira et al., 2016), reducing biodiversity by supressing fallow from farming (Padoch and Pinedo-Vasquez, 2010) and encouraging deforestation (due to increased profitability of agriculture).

Another limitation is that, due to the snap-shot and non-experimental nature of our sample, we were unable to identify which explanatory variables are causally linked to the type of nutrient source chosen by farmers. This implies that the fact that the nutrient options groups differ regarding a given characteristic, e.g. market proximity, does not necessarily mean that a change in such characteristic (e.g. increase in proximity to markets) would necessarily lead to a change in the choice of nutrient source. Instead, we focussed on the identification of socioeconomic variables correlated with technological choices, which provides important insights and hypotheses that could be tested in future work on the causes of fertilizer adoption.

Overall, results suggest that a rural extension program aimed at supporting a rapid and complete replacement of ashes from vegetation by fertilizers could prove unsuccessful for smallholders. Rural extension should be planned to manage a process of adoption that may be slow and also likely to be reverted. It should support smallholders in improving farming practices under the dynamic constraints faced, act within a feasible term and recognize the multi-faceted nature of Amazonian agricultural systems, not all of which will be amenable to mechanization or fertilizers.

Appendix A

A.1 Liquidity

Credit dummies were obtained as follows. The survey has asked farmers (i) whether they had ever been granted with credit and (ii) whether they ever had a credit application rejected, providing two dummy variables. One takes a unitary value for farmers that had ever obtained credit and zero for farmers that had never obtained credit. The other takes a unitary value for farmers who had ever applied for credit and zero for those that had not applied.

Data on income sources, on farm and off-farm, were also available. From it, the total annual income was calculated as the sum of the net revenue of the farm in 2009 (revenue less costs and a 10% depreciation on investment) and of other sources of income, comprising off-farm labor, income transfers from the government and from family members residing out of the farm and net revenue from other farms.

The survey asked farmers about the limiting factors (i) for future plans and (ii) for investing in new practices for growing annual crops. Financial resources (cash, capital, credit, government subsidies) were revealed to be the most important factor, mentioned by a total of 23% of 213 smallholders. Dummies with unitary values for farmers who declared lack of financial resources for the two finalities mentioned are incorporated as measures for the perceived stringency of the liquidity constraint faced.

A.2 Soil quality

The survey asked farmers about limiting factors (i) for future plans and (ii) for the introduction of new practices for growing annual crops. From the answers of the two questions, two dummies were built. They indicate with unitary value farmers that recognize soil quality as a limiting factor. Slope was calculated from a Digital Elevation Model with 30m resolution, resampled to 100m resolution to speed up computation.

A.3 Land tenure

Land tenure was classified into three main types: (i) Landowners have official documents emitted by government agencies, (ii), a range of situations from complete lack of documentation to the holding of a “receipt (of purchase)” or a “land occupation certificate”, but where land ownership is not recognised in all cases, and (iii) Missing or insufficient information to determine land-tenure status. Farmers in the first category are assigned a unitary value, those in the second a zero, and those in the third treated as missing data.

A.4 Experience

Time on farm was estimated from household migration history data. For some observations, data were not available for the person that answered the questions on farm management, who was supposedly the decision maker (referred in this paper as “the farmer”). For these cases, the migration history of the interviewee’s (living) parents, who also live in the farm (and probably take part on decision making), was used. Therefore, time on farm (and also time in the Amazon) refers to farmer’s family (named “core family”).

Time in the Amazon was calculated by subtracting the year when the interview was conducted (2010/2011) by the year where the core family arrived in a state that belongs to the legal Amazon. Therefore, experience with Amazon is grossly defined as the uninterrupted permanence in at least one of the nine states of the region known as Legal Brazilian Amazon (Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Tocantins, Rondônia, Roraima).

Appendix B

[Table B: about here]

Appendix C

This appendix explains how figure 1 was built. The level of constraint captured by each plot corresponds to a particular set of values for covariates except market proximity, as follows:

1. “Totally constrained”: farmers with low levels of liquidity, declared soil quality, education and crop area, no access to rural extension and no land title.
2. “Liquidity-constrained”: low level of liquidity, high levels of declared soil quality, education and crop area and access to rural extension and land title.
3. “Not constrained”: high levels of liquidity, declared soil quality, education and crop area and access to rural extension and land title.

The values of the covariates in basis of which the three categories differ are detailed in Table C below. All other covariates take their sample values, except for market access metrics. To be consistent with the strong correlation of distance and travel time to nearest towns, the former was taken as a function of the latter and the plots were traced for different values of travel time. The functional form came from the estimation, with sample data, of a simple linear regression with distance explained by travel time.

[Table C about here]

Appendix D

Results of robustness assessment is presented in the two following tables with “nsig” standing for non-statistically significant, “sig+” for significant and positive and “sig-” for significant and negative. The last row informs the significance/sign of the estimate after accounting for discordances between MNL and probits. Details on probits estimation are found in table D.3.

[Table D.1 about here]

[Table D.2 about here]

[Table D.3 about here]

Table 1 Main factors favouring (+) and disfavouring (-) fertilizer adoption by smallholders according with the literature review and factors considered in this paper

Class	**Factors in the literature**	**Papers** [a]	**Factors in this paper** [b]	**Channel through which factors affect fertilizer adoption**
Market	proximity to market/roads(+), market orientation(+), output price(-) , complementary input prices(+), price stability(+), fertilizer price(-) importance of fertilizer price on adoption decision(-)	8 of 10	Time to towns, distance to roads [market proximity]	Transport cost channel
Liquidity and wealth	credit(+), wealth(+), lifestock(+), off-farm income(+)	8 of 10	income, credit (applied for? obtained?), financial resources as limiting factors (to new practices/future plans)	Budget constraint channel
Soil	soil depth(+), pH level(+),soil fertility(-)	3 of 10	slope [c], perceived soil quality	Soil quality channel
Learning cost	rural extension(+)	4 of 10	rural extension	Learning cost channel
Education and experience	education(+), household average age(+), age of HHH (-)	Education: 3 of 10; experience (age): 2 of 10	education, age, time in the Amazon, time on farm	Learning cost channel
Other	farm size(+), social capital(+), land entitlement(+), level of socioeconomic development(+), household labor supply(+), household size (+), deforested area upon acquisition of land (-), rainfall level (+), subsidized fertilizer acquired (-), favorable climate (+), use of organic fertilizer (+), adoption of high-yield variety (+), share of non-working persons (+), irrigation(+), use of manure(-), proximity to fertilizer distribution center (+)	farm size: 6 of 10, social capital: 3 of 10; other factors: 1 of 10 (mostly)	total size of plots with annual crops, land tenure, region [d]	Not relevant (other factors function exclusively as controls)

[a] Number of papers that attested the influence of at least one of the factors. Papers considered are: Vera-Diaz et al (2008), Perz (2003), Wood et al. (2001), Ricker-Gilbert et al. (2011), Asfaw and Admassie (2004), Kormawa et al. (2012), Lambrecht et al. (2014), Zerfu and Lawson (2002), Shakya and Flinn (1985) and Zhou et al. (2010).

b Detailed definition of variables in table 4.

[c] Slope is included for being a topographic feature potentially related with the erodibility of farm’s soil (Blanco and Lal: 2008, table 1.3, p.9), making it a relevant indicator of the effectiveness of fallow management to provide nutrients for annual crops. It is also negatively related with returns from mechanized land preparation and use of machinery in general (Müller et al., 2011).Further details on appendix A.

[d] A dummy variable is included in order to capture peculiarities of the two regions not controlled by other covariates.

Table 2 Main agricultural features of the study region

Region	% of total value of staple crop production [a]		% of total value of soybean production [a]		Rate of fertilizer use (2006) [b]	Increase on soybean planted area from 2002 to 2012 [c]
	2009	2009-2011	2009	2009-2011		
PGM	67%	47%	26%	41%	0.264	30.57
STM- BTA	59%	64%	31%	28%	0.08	83.57
Brazilian Amazon	DA				0.079	0.95
Brazil	DA				0.328	0.53

[a] total value includes all annual and perennial crops grown in the regions. Source: Municipal Agricultural Output Survey (*Produção Agrícola Municipal*), editions of 2009 to 2011 (IBGE, 2014).

[b] Source: IBGE(2010)

[c] Source: IBGE (2014)

Table 3 Cross tabulation of nutrient sources and land preparation practice

Nutrient source / land preparation	Fire only	Fire and tractors	Tractors only	No fire, no tractors	Total
Only fallow	135	20	5	4	**164**
Fallow and fertilizers	10	5	2	1	**18**
Fertilizers only	0	1	16	2	**19**
No fallow, no fertilizers	7	3	0	0	**10**
Total	**152**	**29**	**23**	**7**	**211**

*Note: only fire use between 2007 and 2010 considered. Two farmers with missing values for tractor use were excluded, what explains the difference with the size of the estimation sample (N = 213).

Source: RASDB.

Table 4 Variables' definition and descriptive statistics (average (standard deviation)) by group of technology adopted

Description [a]	Short name [b]	Full sample	Veg.-based [c]	Hybrid	Fert.-based [d]
Time to arrive at the nearest urban center	Time to towns (min.)	112.63 (66.04)	121.36 (64.75)	88.06 (49.32)	55.00 (58.67)
Distance to the nearest road	Distance to roads (km)	6.64 (7.23)	7.23 (7.71)	2.83 (2.92)	4.75 (2.81)
Annual income in 2009	Income (10^3 Reais)	24.67 (33.94)	20.72 (27.03)	25.59 (17.00)	60.40 (68.48)
Have ever obtained credit?	Obtained credit	0.35	0.32	0.44	0.58
Have ever applied for credit?	Applied for credit	0.42	0.38	0.56	0.63
Financial resources constrain adoption of new cropping techniques?	Money limits new practices	0.28	0.30	0.22	0.21
Financial resources constrain future plans?	Money limits future plans	0.37	0.38	0.22	0.47
Slope of the terrain	Slope (%)	4.39 (2.69)	4.46 (2.77)	4.26 (2.02)	3.87 (2.61)
Does soil quality constrain adoption of cropping techniques?	Soil limits new practices	0.13	0.14	0.11	0.11
Soil quality constrains future plans?	Soil limits future plans	0.05	0.05	0.11	0 (0)
Rural extension dummy	Rural extension	0.35	0.30	0.67	0.53
Has land ownership document?	Land title	0.50	0.51	0.50	0.47
Education > lower secondary level	Education	0.06	0.03	0.11	0.32
Duration of permanence in Amazon	Time in the Amazon (yr)	43.82 (16.37)	44.46 (15.79)	46.67 (16.58)	35.16 (19.53)
Time on farm	Time on farm (yr)	21.05 (13.47)	20.28 (13.17)	30.94 (14.37)	18.79 (12.13)
Age of farmer	Age (yr)	53.15 (13.69)	52.92 (13.86)	58.44 (12.33)	50.32 (12.62)
Paragominas dummy	Region	0.31	0.31	0.11	0.47
Annual crop area	Crop area (ha.)	3.01 (9.69)	1.70 (2.13)	3.14 (7.49)	15.00 (28.98)
Poverty [e]	DA	0.43	0.46	0.31	0.32
Market [f]	DA	0.70	0.68	0.69	0.94
N	DA	213	176	18	19

[a] Details on variables are found in appendix A; [b] min. ≡ minutes, Reais ≡ Brazilian currency, yr ≡ years (all variables with measurement unit in parentheses are binary); [c] Vegetation-based technology; [d] Fertilizer-based technology, [e] binary variable for the receipt of income transfers from Bolsa Família, [f] "market" ≡ binary indicating whether annual crop output was sold.

Table 5 Estimation results, explained variable: nutrient source

Variables	**Hybrid vs forest (base)**	**Fertilizers vs forest (base)**
Time to towns	-0.014*	-0.025*
	(0.006)	(0.012)
Distance to roads	-0.176*	-0.130+
	(0.075)	(0.069)
Income	0.001	0.006
	(0.008)	(0.007)
Obtained credit	-0.859	1.118
	(0.915)	(1.063)
Applied for credit	Uncertain	-0.033
		(0.976)
Money limits new practices	Uncertain	-2.238*
		(1.032)
Money limits future plans	-0.438	0.857
	(0.976)	(0.757)
Slope	0.058	0.242
	(0.132)	(0.148)
Soil limits new practices	0.188	0.362
	(1.220)	(0.863)
Soil limits future plans	1.564	Uncertain
	(1.132)	
Rural extension	2.827***	0.694
	(0.782)	(1.237)
Land title	-1.426*	-1.624
	(0.712)	(1.004)
Education	1.907+	2.033+
	(1.135)	(1.139)
Time in the Amazon	Uncertain	-0.008
		(0.027)
Time on farm	0.076**	Uncertain
	(0.028)	
Age	0.020	-0.020
	(0.027)	(0.038)
Region	-1.238	1.490
	(0.997)	(1.124)
Crop area	Uncertain	0.194**
		(0.064)
_cons	-2.650	-1.374
	(2.166)	(1.670)
Observations	213	
Pseudo-R^2	0.445	
Log-likelihood	-68.853	
Chi-square	1233.725	

Standard errors in parentheses, p-values are indicated as + $p<0.10$, * $p<0.05$, ** $p<0.01$, *** $p<0.001$, “log-likelihood” and “chi-squared” are statistics of global significance tests.

Table 6 Joint significance tests for covariate categories (N = 213)

Covariate category	Test statistic (LR ratio test)	p-value
Market proximity [a]	15.12	0.0045
Liquidity [b]	24.75	0.0059
Soil [c]	224.41	<0.01%
Education and experience [d]	11.73	0.0683

a Comprises the covariates "time to towns" and "distance to roads";

b Covariates: "Income", "Obtained credit", "Applied for credit", "Money limits new practices", "Money limits future plans";

c Covariates: "Slope", "Soil limits new practices", "Soil limits future plans";

d "Education", "Time in the Amazon", "Time on farm".

Note: results here shown passed the robustness test.

Table B Pairwise correlation matrix for covariates (with fallow and fertilizer dummies included)*

	fallow?	fertilizer?	towns	roads	income	obtained?	applied?	money new?	money future?	slope	soil new?	soil future?	rural	title?	educ?	amazon	farm	age	region	annual
fallow?	1 *	-0.5 *	0.29 *	0.07	-0.41 *	-0.14 *	-0.11	0.13	0.02	0.04	-0.05	0.02	-0.11	-0.01	-0.24 *	0.12	0.15 *	-0.01	-0.18 *	-0.31 *
fertilizer?	-0.5 *	1 *	-0.29 *	-0.18 *	0.25 *	0.15 *	0.16 *	-0.07	-0.02	-0.06	-0.03	0.02	0.23 *	-0.01	0.3 *	-0.09	0.12	0.04	-0.01	0.3 *
towns	0.29 *	-0.29 *	1 *	0.3 *	-0.26 *	0.12	0.17 *	0	0.08	0.32 *	0.12	0.07	0.05	-0.06	-0.09	-0.02	-0.05	-0.23 *	0.12	-0.14 *
roads	0.07	-0.18 *	0.3 *	1 *	-0.1	-0.01	0.02	-0.05	-0.03	0.21 *	0.05	-0.01	0.22 *	-0.1	-0.13	-0.13	-0.27 *	-0.41 *	0.54 *	-0.05
income	-0.41 *	0.25 *	-0.26 *	-0.1	1 *	0.2 *	0.19 *	-0.09	-0.06	-0.15 *	-0.04	-0.05	0.05	0.13	0.21 *	-0.1	0	0.12	0.05	0.35 *
obtained?	-0.14 *	0.15 *	0.12	-0.01	0.2 *	1 *	0.87 *	0.06	0.11	0.17 *	0	-0.07	0.3 *	0.12	0.06	-0.07	-0.02	0.03	0.13	0.15 *
applied?	-0.11	0.16 *	0.17 *	0.02	0.19 *	0.87 *	1 *	0.06	0.12	0.15 *	-0.02	-0.05	0.25 *	0.12	0.06	-0.08	-0.04	-0.02	0.14 *	0.13
money new?	0.13	-0.07	0	-0.05	-0.09	0.06	0.06	1 *	0.28 *	0.01	-0.24 *	0.06	-0.05	-0.04	0.06	-0.13 *	-0.07	-0.12	-0.1	0.13
money future?	0.02	-0.02	0.08	-0.03	-0.06	0.11	0.12	0.28 *	1 *	-0.03	-0.15 *	-0.17 *	0.13	-0.01	-0.07	-0.05	-0.07	-0.08	0.12	-0.02
slope	0.04	-0.06	0.32 *	0.21 *	-0.15 *	0.17 *	0.15 *	0.01	-0.03	1 *	0.03	-0.05	0.02	-0.04	0.08	-0.01	-0.01	-0.2 *	-0.17 *	-0.04
soil new?	-0.05	-0.03	0.12	0.05	-0.04	0	-0.02	-0.24 *	-0.15 *	0.03	1 *	0.31 *	0.09	0.11	0.02	0.02	-0.09	-0.1	0.16 *	-0.02
soil future?	0.02	0.02	0.07	-0.01	-0.05	-0.07	-0.05	0.06	-0.17 *	-0.05	0.31 *	1 *	0.02	0.09	-0.06	0.04	0.02	-0.03	0.05	-0.03
rural	-0.11	0.23 *	0.05	0.22 *	0.05	0.3 *	0.25 *	-0.05	0.13	0.02	0.09	0.02	1 *	0.16 *	0.06	-0.02	-0.06	-0.13	0.43 *	0.17 *
title?	-0.01	-0.01	-0.06	-0.1	0.13	0.12	0.12	-0.04	-0.01	-0.04	0.11	0.09	0.16 *	1 *	0.02	0.2 *	0.25 *	0.14 *	0.11	-0.02
educ?	-0.24 *	0.3 *	-0.09	-0.13	0.21 *	0.06	0.06	0.06	-0.07	0.08	0.02	-0.06	0.06	0.02	1 *	-0.19 *	-0.08	-0.18 *	-0.13	0.43 *
amazon	0.12	-0.09	-0.02	-0.13	-0.1	-0.07	-0.08	-0.13 *	-0.05	-0.01	0.02	0.04	-0.02	0.2 *	-0.19 *	1 *	0.51 *	0.5 *	-0.2 *	-0.24 *
farm	0.15 *	0.12	-0.05	-0.27 *	0	-0.02	-0.04	-0.07	-0.07	-0.01	-0.09	0.02	-0.06	0.25 *	-0.08	0.51 *	1 *	0.51 *	-0.33 *	-0.1
age	-0.01	0.04	-0.23 *	-0.41 *	0.12	0.03	-0.02	-0.12	-0.08	-0.2 *	-0.1	-0.03	-0.13	0.14 *	-0.18 *	0.5 *	0.51 *	1 *	-0.28 *	-0.11
region	-0.18 *	-0.01	0.12	0.54 *	0.05	0.13	0.14 *	-0.1	0.12	-0.17 *	0.16 *	0.05	0.43 *	0.11	-0.13	-0.2 *	-0.33 *	-0.28 *	1 *	-0.01
annual	-0.31 *	0.3 *	-0.14 *	-0.05	0.35 *	0.15 *	0.13	0.13	-0.02	-0.04	-0.02	-0.03	0.17 *	-0.02	0.43 *	-0.24 *	-0.1	-0.11	-0.01	1 *

Asterisks (*) denote correlations significant at 5% level. Definitions of variables: "fallow?" ≡ Fallow dummy,"fertilizer?" ≡ Fertilizer dummy,"towns" ≡ Time to towns,"roads" ≡ Distance to roads,"income" ≡ Income,"obtained?" ≡ Obtained credit?,"applied?" ≡ Applied for credit?,"money new?" ≡ Money limits new practices,"money future?" ≡ Money limits future plans,"slope" ≡ Slope,"soil new?" ≡ Soil limits new practices,"soil future?" ≡ Soil limits future plans,"rural" ≡ Rural extension,"title?" ≡ Land title,"educ" ≡ Education,"amazon" ≡ Time in the Amazon,"farm" ≡ Time on farm,"age" ≡ Age,"region" ≡ Region,"annual" ≡ Annual crop area

Table C Values of covariates of the three constraint levels*

Covariate value / group	Totally constrained	Liquidity-constrained	Not constrained
Annual income (10^3 Reais)	Low: p25("income") = 7.47	Low: p25("income") = 7.47	Average: mean("income") = 24.67
Credit	Not obtained, not applied		Obtained (and applied)
Money	Limits new practices and future plans		Does not limit
Soil	Limits new practices and future plans	Does not limit	
Rural extension	No access	Has access	Has access
Land title	No title	Has title	Has title
Education	Below lower secondary	Lower secondary of above	Lower secondary of above
Crop area	Low: 1 hectare	Average: mean("crop area") = 3.01	

* “p25” stands for the 25th percentile, and “mean” for the average

Table D.1 Vegetation-based (base choice) vs hybrid MNL compared with probits

Variables	MNL	fallow probit	fertilizer probit	sign
Time to towns	sig-	sig+	sig-	sig-
Distance to roads	sig-	sig+	sig-	sig-
Income	nsig	sig-	nsig	nsig
Obtained credit	nsig	sig-	nsig	nsig
Applied for credit	sig+	nsig	nsig	uncertain
Money limits new practices	nsig	sig+	sig-	uncertain
Money limits future plans	nsig	nsig	nsig	nsig
Slope	nsig	sig-	nsig	nsig
Soil limits new practices	nsig	nsig	nsig	nsig
Soil limits future plans	nsig	nsig	nsig	nsig
Rural extension	sig+	nsig	sig+	sig+
Land title	sig-	nsig	sig-	sig-
Education	sig+	nsig	sig+	sig+
Time in the Amazon	sig-	nsig	nsig	uncertain
Time on farm	sig+	sig+	sig+	sig+
Age	nsig	nsig	nsig	nsig
Region	nsig	sig-	nsig	nsig
Crop area	nsig	sig-	sig+	uncertain
_cons	nsig	sig+	nsig	nsig

Table D.2 Vegetation-based (base choice) vs fertilizer MNL compared with probits

Variables	MNL	no fallow probit	fertilizer probit	sign
Time to towns	sig-	sig-	sig-	sig-
Distance to roads	sig-	sig-	sig-	sig-
Income	nsig	sig+	nsig	nsig
Obtained credit	nsig	sig+	nsig	nsig
Applied for credit	nsig	nsig	nsig	nsig
Money limits new practices	sig-	sig-	sig-	sig-
Money limits future plans	nsig	nsig	nsig	nsig
Slope	nsig	sig+	nsig	nsig
Soil limits new practices	nsig	nsig	nsig	nsig
Soil limits future plans	sig-	nsig	nsig	uncertain
Rural extension	nsig	nsig	sig+	nsig
Land title	nsig	nsig	sig-	nsig
Education	sig+	nsig	sig+	sig+
Time in the Amazon	nsig	nsig	nsig	nsig

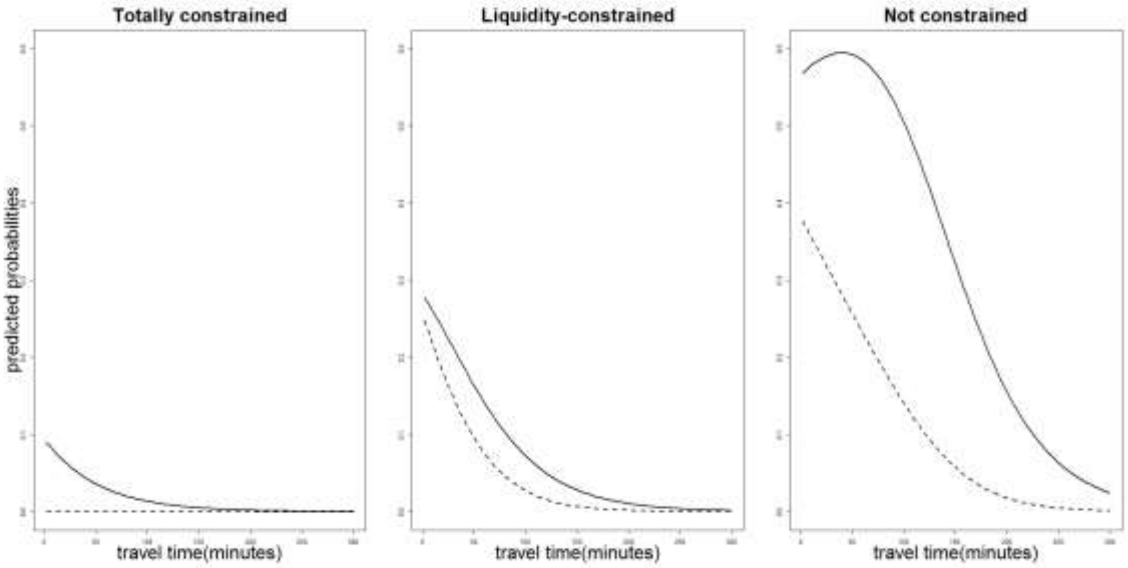
Time on farm	nsig	sig-	sig+	uncertain
Age	nsig	nsig	nsig	nsig
Region	nsig	sig+	nsig	nsig
Crop area	sig+	sig+	sig+	sig+
_cons	nsig	sig-	nsig	nsig

Table D.3 Detailed results of probits estimation

	Y: fallow dummy	Y: fertilizer dummy	Y: no fallow dummy
Time to towns	0.009*	-0.010**	-0.009*
	[0.004]	[0.003]	[0.004]
Distance to roads	0.057*	-0.067**	-0.057*
	[0.025]	[0.026]	[0.025]
Income	-0.009**	0.003	0.009**
	[0.003]	[0.003]	[0.003]
Obtained credit?	-0.908*	-0.191	0.908*
	[0.432]	[0.507]	[0.432]
Applied for credit?	0.634	0.742	-0.634
	[0.418]	[0.466]	[0.418]
Money limits new practices	1.314**	-1.030**	-1.314**
	[0.462]	[0.359]	[0.462]
Money limits future plans	-0.244	0.183	0.244
	[0.299]	[0.324]	[0.299]
Slope	-0.143**	0.056	0.143**
	[0.051]	[0.051]	[0.051]
Soil limits new practices	0.027	0.017	-0.027
	[0.420]	[0.400]	[0.420]
Soil limits future plans	-0.69	0.873	0.69
	[0.712]	[0.539]	[0.712]
Rural extension	0.061	1.031**	-0.061
	[0.390]	[0.397]	[0.390]
Land title	0.252	-0.845**	-0.252
	[0.330]	[0.302]	[0.330]
Education	-0.751	1.082*	0.751
	[0.565]	[0.528]	[0.565]
Time on Amazon	-0.002	-0.012	0.002
	[0.010]	[0.009]	[0.010]
Time on farm	0.025*	0.032**	-0.025*
	[0.013]	[0.011]	[0.013]
Age	-0.013	0.002	0.013
	[0.014]	[0.012]	[0.014]
Region	-1.256**	-0.018	1.256**
	[0.399]	[0.442]	[0.399]
Crop area	-0.066*	0.104*	0.066*

	[0.032]	[0.042]	[0.032]
_cons	1.700*	-0.826	-1.700*
	[0.770]	[0.792]	[0.770]
N	213	213	213
r2_p	0.432	0.414	0.432
ll	-48.136	-57.641	-48.136
chi2	69.944	45.009	69.944

Figure 1 Predicted probabilities of adoption for the hybrid (solid line) and fertilizer-based (dashed line) technologies, for three constraint levels and across the range of travel time to urban centers



Note: details on appendix C

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