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Abstract

We estimate the effect of malaria on settlement and land use patterns in the Brazilian Amazon, where potential settlers were randomly assigned to plots in a newly opened settlement area. The random assignment allows us to estimate the risk of malaria on each plot based only on its characteristics. Using survey data, we find that a high malaria risk significantly reduces the probability that a plot is inhabited. Using satellite images, we find that a high malaria risk does not reduce forest clearance or crop coverage on a plot. Non-resident farming substitutes for physical inhabitation when malaria risk is high.

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1. Introduction

Malaria is widespread in the tropics and it has been suggested that it may have a substantial economic impact. Gallup and Sachs (2001) argue that countries with a high prevalence of malaria have lower economic growth. There are several mechanisms through which malaria can affect the economy. There are the direct costs of malaria prevention and treatment (Ettling and Shepard (1991), Leighton and Foster (1993)). There are also indirect costs due to the effect of malaria on labor productivity through working days lost to illness and low productivity when ill (Nur (1993), Sauerborn et al. (1995)). Malaria in young children can have more severe effects than in adults, sometimes leading to death. Recent work finds that early childhood exposure to malaria can have long term consequences on physical and cognitive development (Jukes et al. (2006)) that manifests itself as low educational attainment and low productivity as an adult (Bleakley (2010), Cutler et al. (2010), Lucas (2010)). Ashraf et al. (2007) and Gollin and Zimmermann (2007) construct general equilibrium models of the effects of malaria attempting to capture these mechanisms.

Chima et al. (2003) discuss the mechanisms through which malaria can affect the economy and highlight the fact that the usual calculations of economic cost based on direct and indirect costs may miss the effect of important avoidance strategies. People can avoid malaria by avoiding malarial areas. They may also avoid malaria in endemic areas by undertaking production in such a way as to avoid exposure to mosquitoes, though this requires knowledge of how their activities affect exposure to malaria. Malaria can impact the pattern of settlement and land use, which can have long term consequences for an economy. When malaria is avoided by land use patterns very few cases of malaria may actually occur in equilibrium, making the apparent direct and indirect costs low, though they may be a large hidden cost in terms of opportunities for land use that are forgone.

There have been a number of studies on malaria, settlement and land use. Wang'ombe and Mwabu (1993) find no effect of malaria on choice of crop in Kenya. Conly (1975), however, found an effect of malaria on the choice of crop in Paraguay. Laxminarayan (2004) finds an effect of malaria control in Vietnam on the crop choice and income levels of households in endemic areas. In this paper, we investigate the effect of malaria on settlement (or physical habitation of the plot) and land use patterns in a settlement program in the western Brazilian

Amazon, named Machadinho, in the 1980s. Malaria has been found to be an influential factor in this settlement program. Martine (1990) finds that malaria can lead to abandoning a plot. Sawyer (1984) argues that the common pattern of living in town and working on plots in the settlement area, without settling on them, is in order to avoid malaria and to obtain better job opportunities. Castro and Singer (2005) argue that high levels of malaria and low soil quality in the settlement area can result in failure of small farmers and, over time, to the emergence of large cattle farms that amalgamate several plots.

We focus on the early years of the settlement, the period 1985-1987, immediately after the allocation of plots to settlers in late 1984. Malaria rates in this period were very high, a result of dramatic environmental changes that created breeding grounds for mosquitoes, an influx of settlers who lacked both natural immunity to malaria and basic knowledge of malaria prevention and treatment, and of failures in planning and governance (Castro et al. (2006)). The initial allocation of potential settlers to plots was random among eligible applicants; eligibility depended on socioeconomic characteristics, in particular not owning any other land. The aim of the project was to encourage settlement on the plots and sale of plots was initially illegal, although in practice some plot turnover did occur over time. We exploit this random allocation process to argue that potential settler attributes are uncorrelated with plot characteristics in the early stage of settlement. This means that although malaria outcomes depend on the socioeconomic status and knowledge of the settlers (Castilla and Sawyer (1993)) we can model malaria as depending only on plot characteristics; the omitted settler characteristics will be uncorrelated with the plot characterizes and can be regarded as random variation.

While a settler was allocated to each one of the 1,742 plots in Machadinho, less than half of the plots were actually occupied in 1986-1987. We can use malaria rates experienced on plots that were settled to obtain expected malaria rates on unsettled plots, and then estimate the effect of expected malaria on settlement patterns. A difficulty with this approach is that our estimates of expected malaria rates are biased by a selection effect; people avoid plots with the highest levels of malaria. We therefore estimate a simultaneous equation system that both finds the effect of expected malaria on settlement and estimates expected malaria on each plot correcting for the fact that we observe malaria only on settled plots.

We find that a high level of expected malaria significantly reduces the probability a plot is physically inhabited based on a survey in which each plot was visited. However, we also have data on how much of each plot is cleared of forest and how much is planted with crops, obtained from satellite images. Settlers typically cleared part of the plot using slash and burn techniques. The major crops in the area are coffee, cocoa, and rubber trees. We find no effect of expected malaria on the percentage of area cleared in a plot and that plots with high expected malaria have higher percentage of their area planted with crops. Expected malaria deters physical settlement and inhabitation, but does not appear to deter land use. This is consistent with the finding by Sawyer (1993) that living in town and commuting to work on plots in the settlement area was widespread. By farming the land during the day, and avoiding being present during the dusk and nighttime periods when mosquitoes are most active, settlers may reduce their exposure to malaria.

The next section of the paper describes the background of the Machadinho Settlement Project. Section 3 provides the model of expected malaria rates, settlement and land use, and addresses issues of identification and estimation. Section 4 describes the data, and section 5 presents results. The final section concludes the paper.

2. The Machadinho Settlement Project

The Machadinho Settlement Project, located in Rondônia state, Western Brazilian Amazon, was approved in 1982, and occupation started by late 1984. Prior to occupation, the project area was mostly forest, sparsely inhabited by rubber tappers (Castro, Monte-Mór, Sawyer and Singer (2006)). Technicians and engineers first entered the region from a southwest anchor (called the south entry in the latter part of the paper) to conduct planning activities. Machadinho has a unique design that took into account the local topography and hydrography. As a result, the project does not have the common fish-bone plot design. Each plot was designed to have a source of water at the back, with front to a road. The road network is comprised of three types of roads: collector roads (the best quality among the three, gravel-surfaced with a width of 6 meters), access roads (gravel-surfaced with a width of 4 meters), and penetration roads (non-gravel surfaced with an approximate width of 4 meters). An urban center was located in the northeast of the settlement area, and secondary urban areas distributed across the project to provide basic services to settlers. Patches of forest inside the project were assigned as forest reserves (Sawyer and Sawyer (1987)).

At first, settlers were not legally allowed to sell their plots, they acquired ownership rights to the plot over time conditional on using it (Fearnside (1985)). However, turnover has become common over time for various reasons (e.g., diseases, soil quality, pressure from cattle ranchers). We limit our analysis to the period 1985-87, immediately after the initial distribution of plots in 1984, to try to limit the effect of land sale on our results.

Malaria became a problem in the area soon after occupation. Both *Plasmodium falciparum* and *P. vivax* are observed, and the main malaria vector is the mosquito *Anopheles darlingi*, which prefers breeding habitats with stagnant water and partial shade. In 1985, the Annual Parasite Index (API - number of positive blood slides per 1000 population per year) reached 3,400 , 65.7% of the population had malaria at least once, and this number jumped to 90.1% in the next year. Also in 1986, 55.9% of people had malaria episodes in more than five months of the year (Castro, Monte-Mór, Sawyer and Singer (2006), Sawyer (1986), Sawyer (1988b), Sydenstricker (1992)). Malaria in settlements projects in the Amazon is characterized as frontier malaria Sawyer (1988a). A majority of the settlers in the project came from malaria free areas in Brazil. They lacked any natural immunity to malaria, and knew little about malaria prevention and treatment (Castro, Monte-Mór, Sawyer and Singer (2006)).

3. The Model and Identification

To construct the model of how malaria affects settlement and land use, we need to have the expected malaria burden for each plot, and then estimate how this expected burden affects settlement. One issue is that the expected malaria burden on each plot depends on both the characteristics of the plot and those of the potential settler. Since settlers were randomly allocated to plots, we can estimate a model where settlement depends only on the characteristics of the plot, on the grounds that the omitted household characteristics of the potential settler can be considered as random.

A second issue is that we only have information for malaria cases experienced on plots that were settled, but we need expected malaria on all plots to estimate the effect of the disease on settlement. To overcome this problem, we can use the data on these settled plots to impute expected malaria rates on the plots that were not settled, based on the characteristics of the plots. While doing this, we need to correct for the selection bias introduced by the fact that settled plots are not randomly chosen.

Our model is therefore a two equation simultaneous system. The first equation estimates the expected malaria burden on a plot based on the plot characteristics. The second equation estimates the probability of settlement based on expected malaria and other plot characteristics. We can estimate the model using a reduced form, based on two identifying assumptions. The first is that we have a variable, the distance of the plot to the southern entry to the settlement area, which affects settlement decisions but does not affect malaria. The southern entry point was the only entry point into the settlement area in the early years of occupation. It was the original site of the settlement administration and settlers were brought here before being taken to their plots. We postulate that plots near the southern entry were more desirable at this early stage of the settlement process as they demanded lower travel distances. We also assume that distance to the southern entry does not directly affect the burden of malaria. This assumption is not absolutely required for identification of the selection equation, but without some force that affects settlement but not malaria the selection equation estimates may be very unstable (Puhani 2000).

In order to identify the effect of malaria on settlement, we need a variable that affects malaria but does not directly affect settlement. The river that runs through the area provides a suitable habitat for mosquito breeding. It provides stagnant water, especially when its level falls, and along the forested banks there are areas of partial shade. We take the distance from the center of the plot to the river, bounded at a distance of 7 kilometers, as our instrument for the risk of malaria. We choose 7 kilometers as the upper bound for risk from being near the river as this was the maximum range that was found for mosquito travel in a capture-recapture experiment in Rondônia (Charlwood and Alecrim 1989). In this experiment, 160 *An. darlingi* mosquitoes were captured, marked, and released. These mosquitoes were then recaptured at various locations at different distances from the test site and the number of marked mosquitoes at each distance noted (about 15% of the released mosquitoes were recaptured over nine days). The maximum range attained by any mosquito was 7.2 kilometers. We postulate mosquito density and malaria intensity vary linearly[1] with distance to the river, up to a maximum of 7 km. While being close to the river is correlated with a high risk of malaria (Castro et al. (2007)), distance to the river could affect settlement though other mechanisms. To control for these possible mechanisms we add covariates. We add a dummy variable for plots that are adjacent to the river since direct access to the riverside may allow river use, for example fishing. We also control for soil quality, area of the plot covered by water, and the ruggedness of the land (percentage of the plat that is hilly and percentage that is steep or mountainous) which could in principle be may be correlated with distance to the river. We control for distance to the nearest stream that gives access to water; the area has high rainfall and there are numerous streams and plots are designed to back onto a stream where possible. Streams may also give suitable breeding sites for mosquitoes in terms of having water but can be overgrown with trees and lack partial shade.

Regarding the formal modeling of the system, we assume that the level of malaria m_{it} experienced on an occupied plot i in year t depends on the time invariant characteristics and geography of the plot, x_i, the characteristics of the household that lives on the plot, h_{it}, a time dummy, d_t, and two random error terms v_{it} and ε_{it}. We distinguish two error terms in the model to account for the fact that settlers may have better information on plot characteristics and the likelihood of malaria than we, the researchers, do. The first error term, v_{it}, represents characteristics of plot and household at time t that are not known to the researchers but may be known or observed by the potential settler. The second error term, ε_{it}, is the random noise in the malaria burden that is unknown prior to settlement and is revealed to the settlers, and the researchers, only if settlers live on the plot. In terms of the characteristics of the plot we single out one variable, the distance between the plot and the river, r_i, which will be central in identification, as described above. Therefore, the malaria model is defined as:

$$m_{it} = \beta_x x_i + \beta_r r_i + \beta_h h_{it} + \beta_t d_t + v_{it} + \varepsilon_{it}, \qquad (1)$$

where β represent the parameters to be estimated.

[1] We tried other functional forms such as log, or quadratic, and different cutoffs distances for the effect, but these did not significantly improve the fit of the model.

Plot occupancy is a variable Y_{it} taking the value one if the plot is occupied and the value zero if it is not occupied. We assume that plot occupancy is determined by a continuous latent variable y_{it} that depends on the characteristics and geography of the plot, x_i, the characteristics of the household that decides whether to live on the plot, h_i, and the malaria that would be expected if the settler decides to live on the plot $E_i(m_{it} \mid x_i, r_i, h_{it}, d_t, v_{it})$, a time dummy, d_t, and a random error term, u_{it}. We focus on expected malaria, rather than experienced malaria, because the decision to live on a plot is forward looking. After being allocated to a plot people will decide whether to settle and live on the plot based on their expectations, over time they decide to stay or not, again depending on their expectations, which may be informed by their acquired private information about the plot. At each time the decision to remain on the plot depends on the expected future malaria burden. Note that in forming the expected malaria burden the settler may have private information, v_{it}, as discussed above, but expected malaria is not conditional on ε_{it} which is not observed by the potential settler.. We also single out one plot characteristic, the distance to the southern entry of Machadinho, s_i, as an identifying variable. Therefore, the model for the latent variable y_{it} that determines settlement is defined as:

$$y_{it} = \phi_x x_i + \phi_s s_i + \phi_m E_i(m_{it} \mid x_i, r_i, h_{it}, d_t, v_{it}) + \phi_h h_i + \phi_t d_t + u_{it}, \tag{2}$$

where actual settlement is given by $Y_{it} = 1 \; if \;\; y_{it} \geq 0, \quad Y_{it} = 0 \; if \;\; y_{it} < 0$, and the vector ϕ represents the parameters to be estimated.

If we assume that the distribution of the error term u_{it} is normal we have a standard probit model of occupancy. We are interested in the impact of ϕ_m of expected malaria on y_{it} and the probability of plot occupancy. A fundamental problem with estimating equations (1) and (2) is that the household characteristics, h_{it}, and malaria on the plot, m_{it} are only observed for occupied plots. We could estimate equation (1) giving a model of malaria on occupied plots but this would be subject to a selection bias, since the expected malaria burden affects the occupancy decision. Equation (2) cannot be estimated as it is stands since we have no malaria information for unoccupied plots. To address these issues, we construct a reduced form of the model. Firstly, we remove the expected malaria burden from equation (2) by substituting in the determinants of malaria from equation (1) and conditioning on the private information. This assumes rational expectations. Secondly, we replace the household characteristics with terms involving their mean and their deviation from mean using the relationship $h_{it} = \bar{h} + (h_{it} - \bar{h})$, and then collect the $(h_{it} - \bar{h})$ terms into a composite error term in square brackets at the end of each equation. This reduced form is given in equations (3) and (4) below.

$$m_{it} = \beta_h \bar{h} + \beta_x x_i + \beta_r r_i + \beta_t d_t + \left[\beta_h (h_i - \bar{h}) + v_{it} + \varepsilon_{it} \right] \quad (3)$$

$$\begin{aligned} y_{it} = {} & (\phi_h + \phi_m \beta_h)\bar{h} + (\phi_x + \phi_m \beta_x) x_i + (\phi_m \beta_r) r_i + \phi_s s_i + (\phi_t + \phi_m \beta_t) d_t \\ & + \left[(\phi_h + \phi_m \beta_h)(h_i - \bar{h}) + \phi_m v_{it} + u_{it} \right] \end{aligned} \quad (4)$$

The terms of average household characteristics, $\bar{h}$, are common across all observations and merely affect the intercept. The error terms in equations (3) and (4), shown in square brackets, now include the expression $(h_i - \bar{h})$. However, since settlers were randomly allocated to the plots, this term is uncorrelated with plot characteristics. Therefore, putting $(h_i - \bar{h})$ into the error term, and ignoring it in the estimation, will not affect the consistency of our estimates. Randomization of settlers to plots is crucial for our modeling; without randomization we could not treat household characteristics as part of the residual, and, instead, would have to model how they affect the settlement decision, information that we do not observe (there are no data on the characteristics of settlers that were allocated to a plot but did not settle on it and were not surveyed).

If we assume that the error terms have mean zero and are jointly normally distributed equations (3) and (4) form a standard Heckman selection model (Heckman (1979)). We can estimate the selection equation given by (4) for all plots since it now depends only on the characteristics of the plot. We can also estimate the malaria equation given in (3) for plots that are settled, correcting for the selection effect. The selection effect will bias results in naive estimation of the malaria equation when the error terms in equations (3) and (4) are correlated. This correlation occurs for two reasons. The first is that both the selection equation and the malaria equation error terms now depend on the characteristics of the settlers. The second is that the error term in the malaria equation may have a component that is unobserved by the researchers but is private information to the potential settlers, which may also affect their settlement decision.

We estimate the reduced form system given by equations (3) and (4) as a Heckman selection model using the maximum likelihood estimator. This does not give us a direct estimate of the parameter of interest, ϕ_m, the effect of expected malaria on the decision to settle a plot. However, this parameter is identified, and we can estimate it from the reduced form as in indirect least squares. We can take the coefficient on the distance from the plot to the river, r_i, in equation (4), which estimates $\phi_m\beta_r$, and divide it by the coefficient on distance to the river in equation (3), which estimates its effect on malaria, given by β_r, to derive an estimate of the effect of expected malaria on settlement $\hat{\phi}_m = \frac{(\widehat{\phi_m\beta_r})}{\hat{\beta}_r}$. This is the effect of malaria on the latent variable y_{it}. In order to find the effect of malaria on the probability of settlement we need to take the effect of the change in the latent variable on the probability of settlement at the margin.

We can use a similar approach to estimate the effect or malaria on land use. We measure how much of the plot is cleared of forest and how much is plated with crops using satellite images. Our estimates of the reduced form Heckman selection model give us the effect of distance to the river on malaria. Reduced form land use equations find the effect of distance to the river on land use. Assuming the identifying condition that distance to the river affects expected malaria, but does not directly affect land use, we can derive an indirect least squares estimate of the effect of expected malaria on land use, z_{it}, measured as a continuous variable indicating the percentage of the plot that is cleared of forest or planted with crops.

The structural equation for land use is defined as:

$$z_{it} = \pi_x x_i + \pi_s s_i + \pi_m E(m_{it} \mid x_i, r_i, h_{it}, d_t, v_{it}) + \pi_h h_i + \pi_t d_t + w_{it} \tag{5}$$

where π represent the parameters to be estimated.

We assume that land use depends on expected malaria, but not directly on distance to the river. Substituting out for expected malaria we can derive the reduced form of equation (5):

$$\begin{aligned} z_{it} = {} & (\pi_h + \phi_m\beta_h)\overline{h} + (\pi_x + \phi_m\beta_x)x_i + (\pi_m\beta_r)r_i + \pi_s s_i + (\pi_t + \phi_m\beta_t)d_t \\ & + \left[(\pi_h + \phi_m\beta_h)(h_i - \overline{h}) + \phi_m v_{it} + w_{it} \right] \end{aligned} \tag{6}$$

We can estimate (6) directly from the data giving us an estimate of $\left(\pi_m \hat{\beta}_r\right)$ the coefficient on distance to the river, e can then in principle identify the effect of malaria on land use using the formula $\hat{\pi}_m = \frac{\left(\pi_m \hat{\beta}_r\right)}{\hat{\beta}_r}$ where $\hat{\beta}_r$ is estimated from equation (3) as before. A fairly large number of plots have no visible forest clearance or crop coverage. We therefore estimate equation (6) as a Tobit model where the outcome is censored to be at least zero clearance or crop coverage.

Given that our key identifying variables, plot distance to the river and distance to the south entry, are fixed over time we cannot use plot fixed effects in our estimation. However, it is likely that there are unobserved plot characteristics that are correlated over time. In addition, the household characteristics in the error terms in equations (3) and (4) are likely to be correlated over time. We therefore cluster our standard errors at the plot level, which allows for correlation between the error terms for a plot over time.

All data analyses were done using Stata (Stata Corp.; College Station, TX, USA).

4. Data

The allocation of settlers to plots took place in late 1984. This study uses data extracted from four different sources. Information of plot location and distances to features such as the river were undertaken using a map of the area. Second, we used data on plot soil quality and elevation acquired through a soil reconnaissance survey (Wittern and Conceição (1982)). Third we use information collected in household surveys of the Machadinho Settlement Project conducted in 1986 and 1987 (Sawyer (1992)). The surveys included data for all households who lived either full time or part time on their plots (Sawyer (1985)), and asked about the household experience of malaria over the previous year. A survey was also conducted in 1985, but it is estimated that only 76% of household living on plots were contacted (Castro (2002)); therefore, we chose not to use data from that year.. Finally, we used information on land cleared of forest and planted with crops generated through interpretation of Landsat 5-Thematic Mapper (TM) satellite images acquired in 1985 and 1986. Unfortunately, due to cloud coverage, no images were available for 1987 (Castro and Singer (2011)). For our modeling purposes, we used 1986 and 1987 household survey data for the settlement model – equation (2), and 1985 and 1986 satellite derived information for the land use model - equation (5).

Figure 1 shows a map of the Machadinho Settlement area. The map shows plot boundaries, road network, the Machadinho river, urban and secondary urban areas, forest reserves, and the location of the south entry. Using this map as a reference, we constructed several variables characterizing geographical features of each plot. The first was distance to the Machadinho river (measured as the nearest distance from the centroid of the plot to the river bank). This distance was created as a continuous variable kilometers, which assumed the value of .2 for distances equal to or lower than 200 meters, and 7 for distances equal to or larger than 7 kilometers. A dummy variable was generated for plots adjacent to the Machadinho river, and another dummy for being adjacent to the forest reserve. We measured the distance from the centroid of the plot to the nearest urban center or secondary urban areas. All plots have a road on a least one side. We created a dummy indicating if this was a collector road (highest quality) and another dummy variable that indicates if it was an access road (medium quality) - the residual category is a penetration road (lowest quality). We also measured distance from the plot centroid to the nearest stream. Finally, we measure the distance from the plot centroid to the south entry. All mapping was done in ArcGIS 3.0 (ESRI, Redlands, CA, USA).

For soil quality, we used the soil quality index, which is a continuous measure of the agricultural suitability of the plot. It was calculated as a weighted average of the percentages of each type of agricultural suitability, with weights equal to 0.5 for good, 0.25 for medium, 0.15 for restricted, and 0.05 for soils inappropriate for agriculture or not recommended at the management level (Castro and Singer (2011)). The soil quality of the plot potentially ranges from 0.05 (worst soils) to 0.5 (best soils). Based on the satellite images, we observed that in 1985 and 1986 about 10% of the plot area was cleared of forest and about 1% were being utilized for crops. The maximum clearance on a plot was 69% of the plot area.

The first part of Table 1 shows data for the physical characteristics of the plots. The second part of Table 1 shows summary information from the household surveys in 1986 and 1987. In 1986 and 1987, on average, about 37% of plots were actually occupied. Exposure weighted malaria illness rates (referred to simply as malaria rate) were calculated as the sum of the number of months each person in a household had malaria during one year as the numerator, and the exposure time - number of person-months exposed to the disease as the denominator (Sawyer (1988b)). The rate is based on self-reported information, and a rationale for this kind of assessment is given in Sawyer and Sawyer (1987) and Singer and Sawyer (1992). The reported malaria rate was 32% and 26% in 1986 and 1987, respectively. Settlers typically had a low level of education with an average of about one and a half years of schooling. From the household roster we construct variables for the total size and age structure of the household. There were substantial numbers of children living on plots, but very few older people. Many families in the survey lack basic farming tools, chainsaws and planters, which are useful for clearing the plot and working the land.

Table 2 shows a correlation matrix of the plot characteristics, while Table 3 shows the correlation between plot characteristics and household characteristics. The critical values for the significance levels of the tests for correlation are Bonferroni-adjusted to account for the fact that we are undertaking multiple tests. Table 2 shows that plot physical characteristics are highly correlated. If all the plots were occupied, the random assignment would lead us to expect no correlation between plot characteristics and the settlers' characteristics. Given that there is a selection effect, and not all plots are occupied, a correlation may occur. We find only two significant correlations in Table 3. Plots adjacent to the Machadinho river tend to have higher than expected proportion of people over 65, while plots near an access road (medium quality) tend to have larger than average household size. We would emphasize that this correlation may be due to selection rather than non-random assignment.

Figure 2 shows a histogram of the reported malaria rate on each occupied plot. There is a wide spread of outcomes with some households reporting no malaria and some reporting malaria in every month of exposure for every family member – a malaria rate of 1. Figure 3 shows the distribution of the percentage of the plot that is cleared. Figure 4 shows the distribution of the percentage of the plot that has crops planted. Many plots have no crops planted, which could be related to soil quality, to missing the time window of the planting season, or to lack of resources to work the land.

5. Results

Column 1 of Table 4 reports the estimates of the selection equation, eqaution (4) above. The coefficients of the probit model have been transformed to report marginal effects of the variable on the probability of occupancy at the mean of the explanatory variables. Results indicate that settlement was more likely further from the river. The probability of settlement rises by 0.015 for each kilometer further away from the river. This means that a plot 7 kilometers or more from the river had 0.11 higher probability of occupancy than a plot close to the river. Settlement was also more likely for plots adjacent to the collector road, the highest quality road. Being next to a collector road raises the probability of occupancy by about 0.16. Plots further from the south entry were less likely to be settled, each kilometer form the south entry lowers the probability of settlement by about 0.005. Settlement was higher in 1987 than in the base year 1986.

Column 2 of Table 4 reports the results of the malaria equation, equation (3). The outcome variable is the malaria rate which goes form zero to one. We found a significant effect of distance to the river on malaria. Each additional kilometer from the river lowers the malaria rate by 0.043. This means that at 7 kilometers, the limit of the malaria effect for the river, the malaria rate was about 0.30 lower than on plots close to the river. The malaria rate was significantly lower near the collector road than in other areas. This may be because the collector roads were laid out along ridge lines, to prevent flooding in the rainy season, and therefore may have a lower frequency of stagnant pools and mosquito breeding sites.

The malaria equation and occupancy selection equation in columns 1 and 2 of Table 4 were estimated simultaneously by maximum likelihood, with standard errors adjusted for clustering at the plot level. Rho gives an estimate of the correlation between the error terms in the selection and malaria equations. We found a negative estimate for rho, indicating that plots with malaria rates lower than expected were more likely to be settled. However, a Wald test of the null hypothesis that the two equations are independent (and that rho is zero) was significant only at the 10% level.

We used the estimates in Table 4 to generate predicted malaria rates for each plot, shown in Figure 5. Note that the predictions are much more concentrated that the observed data shown in Figure 2. Table 5 compares summary statistics for the reported and predicted malaria rate. If we limit prediction to occupied plots, and condition on the fact that the plot is occupied, we get an average predicted malaria rate very close to the average of the reported malaria rate. However, if we predict the malaria rate for every plot, and do not condition on the plot being occupied, the average predicted malaria rate is higher. The negative correlation between the error terms in the occupancy and malaria equations reported in Table 4 means that occupied plots have lower expected malaria than average and our estimate of the malaria rate over the whole site is higher than that observed on the occupied plots.

The effect of malaria on settlement can be derived by taking the ratio of the coefficients of distance to the river in the malaria and selection equations as shown above. We take the marginal effect of distance to the river on the probability of settlement and divide it by the marginal effect of the river on malaria. This marginal effect of expected malaria E(m) on the probability of settlement, and its t –statistic is

$$\frac{dP(Y)}{dE(m)} = \frac{0.0156}{-0.0431} = -0.36 \quad , \qquad t = 2.98$$

This implies that going from a malaria rate of zero to a malaria rate of one, lowers the probability a plot is settled by 0.36. The average of the predicted malaria rate in the settlement area was 0.33. This gives us an estimate of the effect of eliminating malaria from the site. Multiplying the average malaria rate by the marginal effect of malaria on the probability of settlement gives a figure of 0.12. This implies that we estimate that without malaria the average level of physical occupancy on the plots in the settlement area over the period 1986-1987 would have been 49% rather than the 37% actually observed.

Columns 3 and 4 of Table 4 report the estimates of the marginal effects on land use, measured by the percentage of plot cleared (column 3) and percentage of plot planted with crops (column 4). The fraction of a plot that can be cleared, or cropped, is bounded below by zero and above by one. While no plots are near the upper bound many are at or very close to the lower bound. This suggests that a standard ordinary least squares model is inappropriate since it will predict negative fractions cleared or cropped in some cases. We therefore estimate Tobit models for the fraction cleared and cropped, where any predictions outside the feasible range (zero to one) are censored to lie at the boundary. Again we cluster standard errors at the plot level to account for correlated error terms for a plot over time.

In column 3 of Table 4 we see that plot clearance is lower on plots adjacent to the river and forest reserve. It is substantially higher on plots adjacent to the collector road and higher on plots adjacent to an access road (the omitted category is the lowest quality, penetration roads). Percentage cleared area was higher the closer the plot was to a stream and lower the larger the plot. Clearance was lower further from the south entry, and higher in 1986 than in the baseline, 1985. Distance to the river is not a significant predictor of forest clearance.

Results for percent of the plot area cropped, shown in column 4, are similar. Cropped area was much smaller than cleared area, but the direction of the effects was the same as for area cleared. The one exception was distance to the river. Plots further from the river were less likely to be cropped. The effect of distance the river on cropping was statistically significant but very small in magnitude. However, it had the opposite sign from what we would expect if malaria reduced cropping. Table 6 shows the pattern of land use by plot occupancy in 1986. Percentage of plot cleared was almost identical on occupied and non-occupied plots. On the other hand, plots that were unoccupied had higher percentage of area cropped than plots that were occupied. Living on a plot was not required for the land to be used. The fact that forest clearance does not decease as we move closer to the river and a high level of malaria risk, means we have no evidence that malaria reduces land usage in the form of forest clearance. Families could live in the urban area, and travel to the plot to clear the land.

We find that being close to the river, and at high risk of malaria, has a positive effect on the percentage of the plot planted with crops. One explanation may be the low level of farming equipment owned by families who live on their plot (see Table 1). Families that do not live on their plot, but move to the urban area, may be more likely to find non farm work which allows them to purchase both planting equipment and seeds. Another issue is that the malaria burden on families that live on their plots may mean that they are unable to work during the crucial planting and harvesting periods. However, the key point is that we find no evidence that malaria reduces land use, either clearance of land or cropping.

6. Conclusion and Discussion

Higher malaria risk, due to being near a river, is found to lower the probability of a plot being physically occupied by a settler. However, even if a plot is not occupied it may still be used by owners who reside elsewhere. The possibility of non resident farming, traveling to the plot to clear the land and plant crops, mitigates the effect of malaria on land use.

The results in this paper refer to a particular site in Brazil and a particular settlement project. The random allocation of settlers to plots helps us with identification, but may lead to an overestimate of the effects of malaria on settlement. In equilibrium, when trade of land is allowed, we would expect sorting to take place, with high malaria plots settled by people who are less susceptible to malaria. On the other hand our finding of increased non resident farming on plots with a high risk of malaria may depend on the road system that was put in place for this project, with each plot being adjacent to a road.

While other sites may have different outcomes, in general our results imply that the costs of malaria can be diminished by avoidance strategies though which people reduce their exposure to malaria. These avoidance strategies, such as not living in areas with a high risk of malaria, themselves impose an opportunity cost. However our result suggest that the cost may not always be the areas at a high risk of malaria are completely unused, rather then are be used in ways that reduce exposure to malaria.

Table 1: Summary Statistics

Plot Characteristics	Obs	Mean	Std. Dev.	Min	Max
Distance to the Machadinho river (=7km if over 7km)	1734	4.75	2.36	0.2	7
Plot adjacent to the Machadinho river	1734	0.08	0.27	0	1
Plot adjacent to the forest reserve	1734	0.25	0.44	0	1
Distance to the nearest stream (km)	1734	0.46	0.26	0	1.58
Nearest road is major road (1=yes; 0=no)	1734	0.13	0.34	0	1
Nearest road is sub-major road (1=yes; 0=no)	1734	0.35	0.48	0	1
Distance to the nearest urban or suburban centers (km)	1734	4.38	2.04	0.3	11.56
Distance to the south entry (km)	1734	15.2	7.8	0.44	29.48
Soil quality index	1670	0.16	0.03	0.07	0.44
Plot size (hectares)	1734	45.41	10.36	16.13	124.08
Percentage of the plot area that is covered by water	1734	0.05	0.05	0	0.33
Percentage of the plot area is flat or slightly hilly	1672	0.66	0.37	0	1
Percentage of the plot area that is hilly	1672	0.33	0.37	0	1
Percent of the plot area that is steep or mountainous	1672	0.01	0.05	0	1
Household Characteristics by Plot (1986 and 1987 combined)					
Plot is occupied (1=yes; 0=no)	3468	0.37	0.48	0	1
Reported malaria rate	1286	0.28	0.26	0	1
Household head's education	1281	1.66	1.91	0	7
Household head spouse’s education	1083	1.59	1.79	0	7
Proportion of people on the plot younger than 5	1279	0.13	0.17	0	1
Proportion of people on the plot between 5 and 15	1279	0.26	0.23	0	1
Proportion of people on the plot over 65 on a plot	1279	0.01	0.09	0	1
Total number of people living on the plot	1299	5.17	3.01	1	18
Number of chainsaws household on the plot owns	1299	0.53	0.55	0	3
Number of planters household on the plot owns	1299	0.5	0.54	0	2
Land Use by Plot (1985 and 1986 combined)					
Proportion of land deforested	3468	0.1	0.09	0	0.69
Proportion of land cropped	3468	0.01	0.02	0	0.27

Table 2: Correlation Matrix of Plot Characteristics

	Distance to river	Adjacent to river	Adjacent to the forest reserve	Distance to the nearest stream	Nearest road is collector road	Nearest road is access road	Distance to nearest urban/ suburban center	Distance to the south entry	Soil quality index	Plot size	Percent water area	Percent flat or slightly hilly	Percent hilly	Percent of steep or mountain-ous
Distance to river	1													
Adjacent to the river	-0.5283*	1												
Adjacent to the forest reserve	-0.0701	0.0351	1											
Distance to the nearest stream	-0.0738	0.0209	-0.0821	1										
Nearest road is collector (best) road	-0.0454	-0.0693	0.0089	0.0614	1									
Nearest road is access (2nd best) road	0.1071*	-0.0821	-0.1847*	0.043	-0.2866*	1								
Distance to nearest urban/suburban center	0.071	0.0549	0.0356	-0.0818	-0.1388*	-0.1000*	1							
Distance to the south entry	-0.0036	-0.0467	-0.0141	0.0256	-0.1070*	0.0812	-0.0705	1						
Soil quality index	0.1238*	-0.0458	0.1416*	-0.0286	-0.0556	-0.0897*	0.0463	-0.0522	1					
Plot size	0.1493*	0.0028	0.0641	-0.1119*	-0.0747	-0.024	0.1804*	0.0166	0.0196	1				
Percent water area	0.1034*	-0.0864*	0.0747	-0.5595*	-0.0431	0.0023	0.0726	-0.0549	0.0263	0.1354*	1			
Percent flat or slightly hilly	-0.1305*	-0.0011	-0.1976*	0.0987*	0.0409	0.0301	-0.1057*	0.1784*	-0.2211*	0.0078	-0.0302	1		
Percent hilly	0.1321*	0.0042	0.1743*	-0.1030*	-0.0389	-0.0309	0.1017*	-0.1731*	0.2394*	-0.0149	0.0228	-0.9892*	1	
Percent steep or mountainous	0.002	-0.021	0.1759*	0.0193	-0.0175	0.0022	0.0372	-0.0533	-0.1006*	0.047	0.0529	-0.1726*	0.0264	1

Note: * denote correlation significant at 5% level, Bonferroni-adjusted for multiple tests.

Table 3: Correlation between Plot Characteristics and Household Characteristics

	Distance to river	Adjacent to river	Adjacent to the forest reserve	Distance to the nearest stream	Nearest road is collector road	Nearest road is access road	Distance to nearest urban/ suburban center	Distance to the south entry	Soil quality index	Plot size	Percent water area	Percent flat or slightly hilly	Percent hilly	Percent of steep or mountain-ous
Household head's education	-0.0311	0.0522	0.0108	-0.0235	-0.0308	0.0052	0.0473	-0.0026	0.0057	0.0655	-0.0229	0.0392	-0.0417	0.0132
Household head spouse's education	-0.0438	0.0442	-0.0052	-0.062	-0.0355	-0.0034	0.0064	0.0321	0.0082	0.0234	-0.0188	0.0256	-0.0188	-0.0498
Proportion of people on the plot younger than 5	0.0651	-0.0362	0.002	-0.0024	0.0101	0.0029	0.0285	0.0033	-0.0312	0.0122	0.0199	-0.0389	0.0336	0.0408
Proportion of people on the plot between 5 and 15	0.0272	0.0086	0.0367	0.0345	0.0384	-0.004	0.002	-0.0078	-0.0401	-0.0283	-0.0106	-0.0232	0.0219	0.0113
Proportion of people on the plot over 65 on a plot	-0.0324	0.0423	0.0224	0.0019	0.0075	-0.0111	-0.0136	0.0358	-0.0293	-0.0227	0.0046	0.0154	-0.0132	-0.0167
Total number of people living on the plot	0.0583	-0.0141	0.0315	0.0728	0.0956*	-0.021	-0.028	-0.0284	-0.0394	-0.0157	-0.0383	-0.001	-0.002	0.021
Number of chainsaws household on the plot owns	0.0171	0.0074	-0.0075	0.0196	0.0349	0.0059	-0.0021	0.0107	-0.0051	0.0208	-0.0201	0.0321	-0.0314	-0.0083
Number of planters household on the plot owns	-0.0023	0.0098	0.0305	0.0156	0.0245	0.0228	-0.015	-0.0309	0.0163	-0.016	-0.0218	-0.0194	0.0214	-0.0116

Note: * denote correlation significant at 5% level, Bonferroni-adjusted for multiple tests.

Table 4: The Impact of Malaria on Land Occupancy and Land Use

	Heckman Selection Model		Tobit Model	Tobit Model
	Plot Occupancy	**Malaria Rate**	**Percentage Deforested**	**Percentage Cropped**
Independent variables	(1)	(2)	(3)	(4)
Distance to Machadinho river (km)	0.0157**	-0.0438***	-0.00129	-0.000555***
	(0.00508)	(0.00434)	(0.000713)	(0.000168)
Adjacent to the river	-0.0364	-0.0430	-0.0125*	-0.00327**
	(0.0443)	(0.0416)	(0.00572)	(0.00121)
Adjacent to the forest reserve	-0.0149	0.0218	-0.0110**	-0.00314***
	(0.0236)	(0.0197)	(0.00363)	(0.000735)
Distance to the nearest stream (km)	0.0545	0.0178	0.0136*	0.00358**
	(0.0459)	(0.0338)	(0.00666)	(0.00133)
Nearest road is collector (best) road	0.157***	-0.0955***	0.0523***	0.00694***
	(0.0337)	(0.0212)	(0.00582)	(0.00118)
Nearest road is access (2nd best) road	0.0267	-0.0109	0.00895**	0.00127+
	(0.0224)	(0.0169)	(0.00341)	(0.000712)
Distance to nearest urban/ suburban center (km)	0.00717	-0.00359	-0.0000676	0.0000312
	(0.00510)	(0.00385)	(0.000700)	(0.000137)
Soil quality index	-0.502	0.139	0.0600	-0.00113
	(0.346)	(0.328)	(0.0632)	(0.0152)
Plot size (hectare)	0.000939	-0.000348	-0.000656***	-0.0000867**
	(0.000967)	(0.000778)	(0.000144)	(0.0000304)
Percent covered by water	-0.476	0.209	0.0465	0.0113
	(0.256)	(0.215)	(0.0381)	(0.00728)
	-0.00297	0.0206	-0.00413	0.00146
Percent flat or slightly hilly	(0.0291)	(0.0208)	(0.00441)	(0.000961)
Percent severely hilly or mountainous	0.0443	-0.0401	0.00243	0.00546
	(0.174)	(0.197)	(0.0225)	(0.00624)
Distance to the south entry (km)	-0.00461***		-0.000726***	-0.000299***
	(0.00130)		(0.000198)	(0.0000405)
year 1987	0.114***	-0.0596***		
	(0.0134)	(0.0133)		
year 1986			0.0659***	0.0187***
			(0.00153)	(0.000554)
Rho	-0.098			
	(.067)			
Wald test of independent equations of chi2 (1) under the null	2.11			
Observations	3333		3340	3340

Standard Errors clustered at the plot level. The table presents the marginal effects, with standard errors shown in parentheses. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 5: Self-reported vs Predicted Malaria Rate 1986 and 1987

	No. of Observations	mean	S.D	Min	Max
Self-reported malaria rate for occupied plots	1286	0.282	0.261	0	1
Predicted malaria conditional on occupancy for occupied plots	1239	0.281	0.099	0.079	0.52
Predicted malaria unconditional on occupancy for all plots	3340	0.326	0.107	0.091	0.577

Table 6: Land Use by Occupancy (1985 and 1986)

		No. of Observations	mean	S.D	Min	Max
Proportion plot cleared	Plot occupied	825	0.135	0.093	0	0.620
	Plot not occupied	1190	0.124	0.092	0.001	0.092
Proportion plot cropped	Plot occupied	825	0.017	0.023	0	0.235
	Plot not occupied	1190	0.025	0.029	0	0.269

Figure 1: Machadiho Settlement Project Area Map

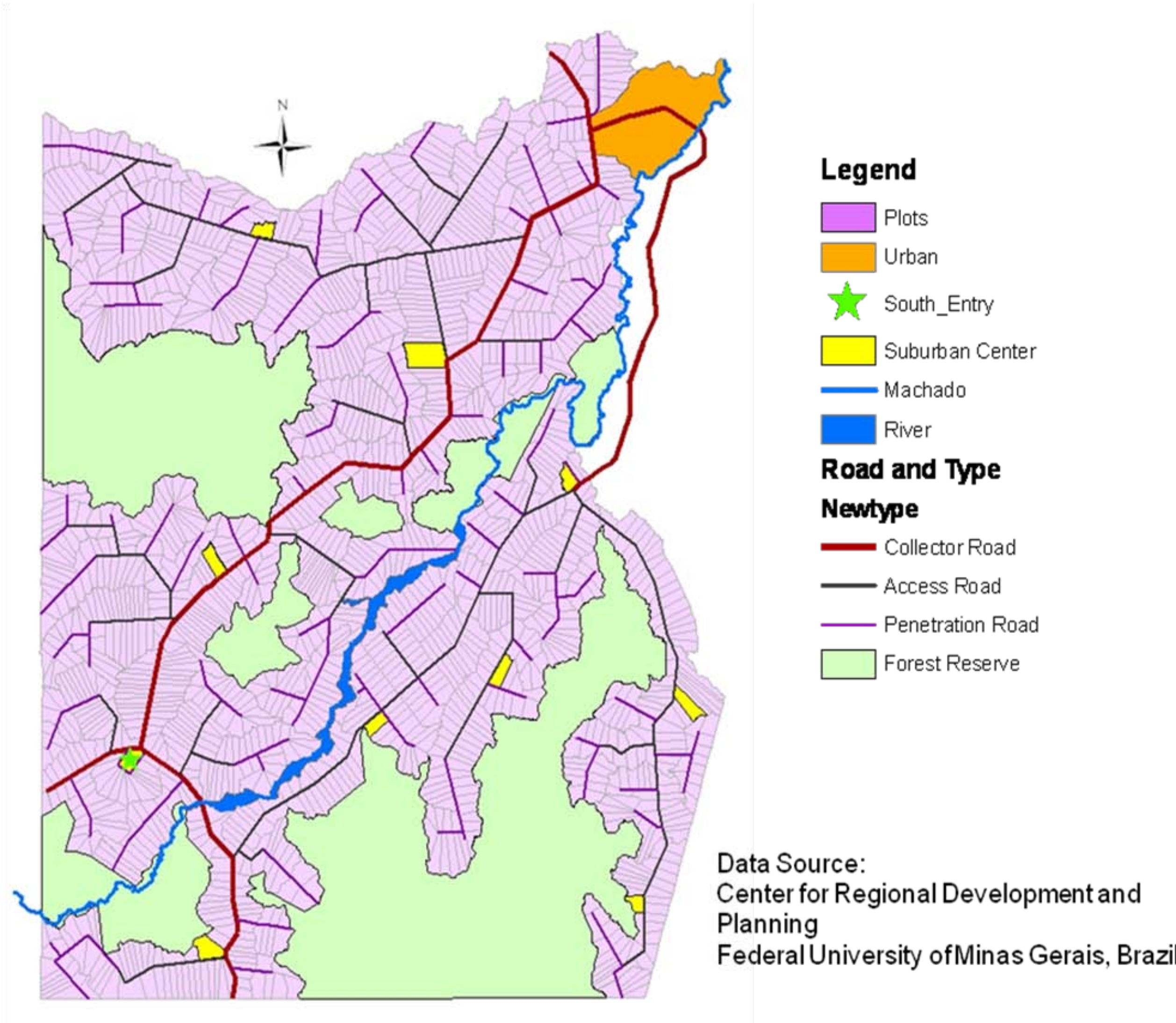


Figure 2: Distribution of Reported Malaria Rate (1986 and 1987)

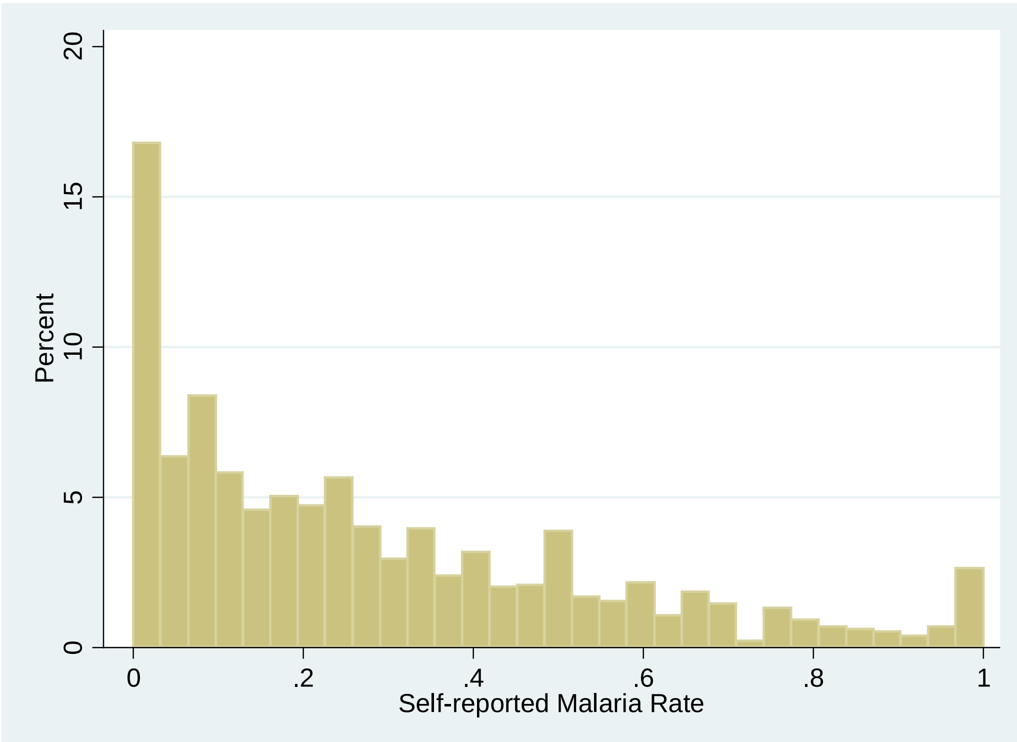
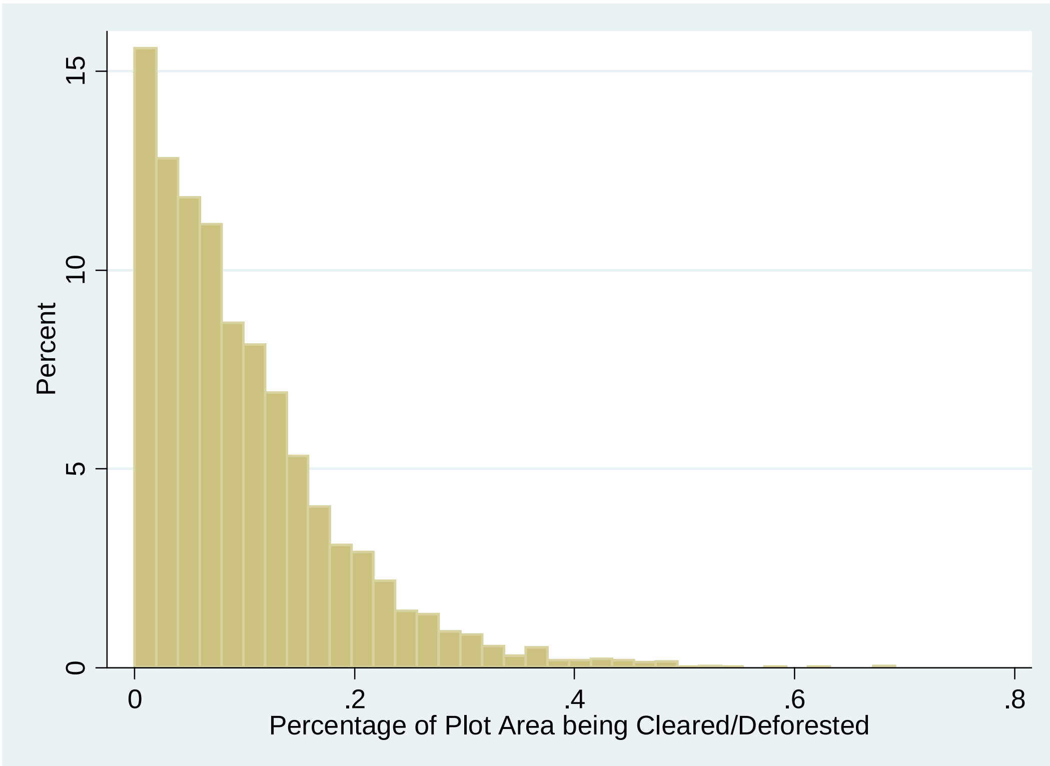
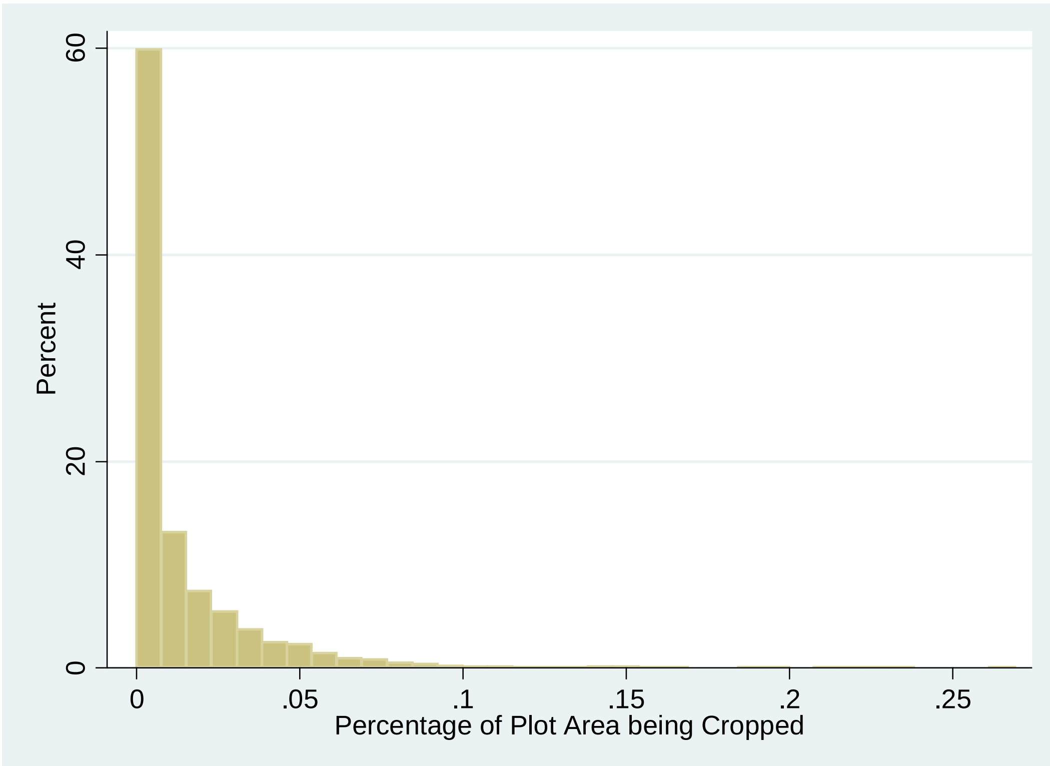


Figure 3: Distribution of Percentage of the Cleared/Deforested Area of a Plot (1985 and 1986)



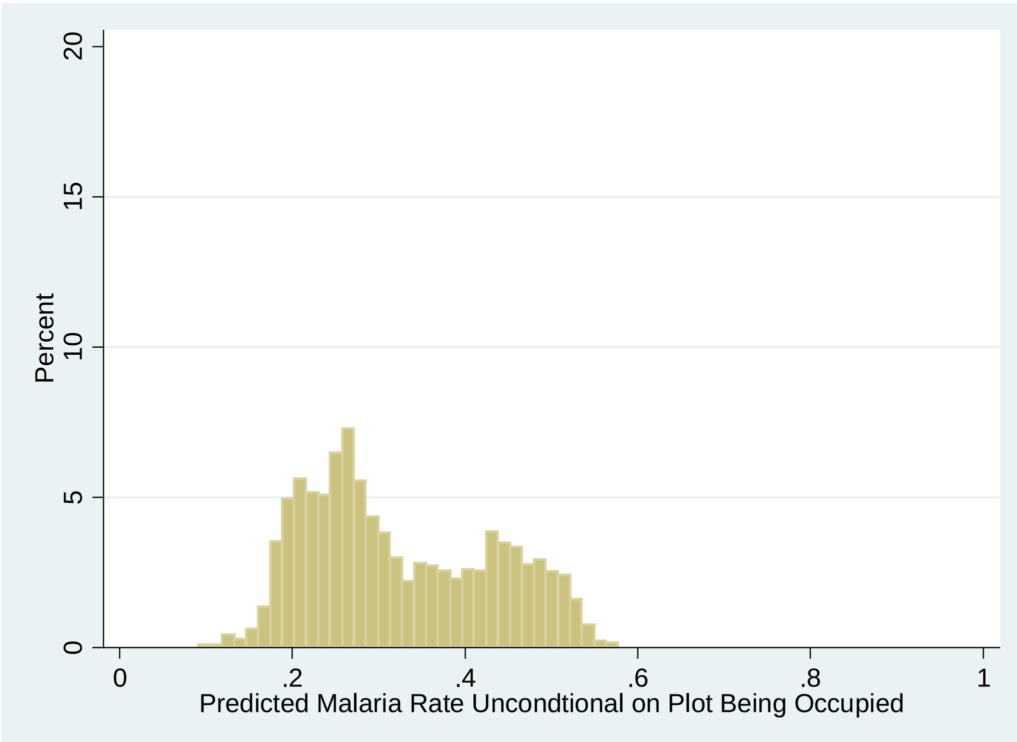
Note: Plot area covered by water is not included in the calculation

Figure 4: Distribution of the Percentage of the Plot Cropped (1985 and 1986)



Note: Plot area covered by water is not included in the calculation

Figure 5: Distribution of Predicted Malaria Rate (1986 and 1987)



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