SOIL QUALITY, AGRICULTURE SETTLEMENT, AND DEFORESTATION IN THE BRAZILIAN AMAZON

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1. Introduction

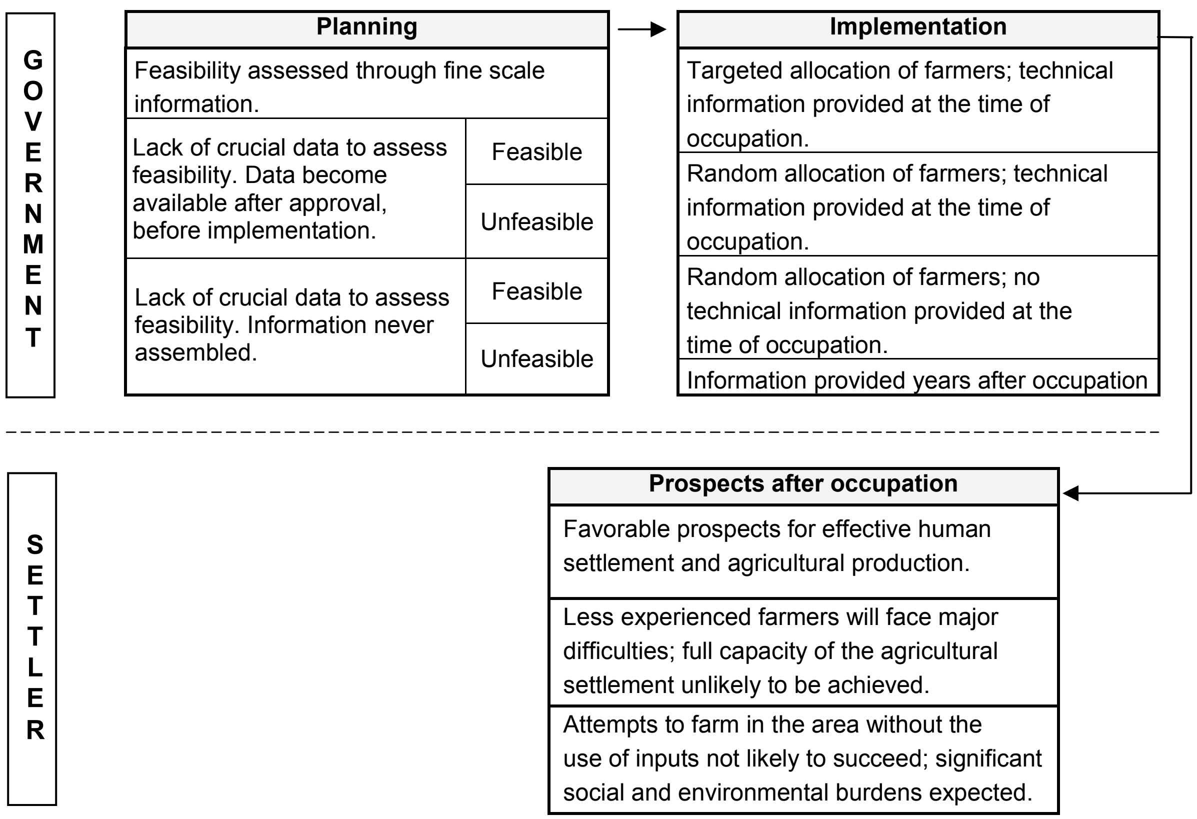
In the past four decades, different development plans have been devised and implemented in the Brazilian Amazon (Becker, 2001; Mahar, 1979; Schmink & Wood, 1984). The extent to which they have been successful depends on what one defines as development and as success. An important initiative integrated in those development plans was the distribution of land at very low prices for colonization by migrant peasants and small farmers from other regions. Criteria for selection of potential settlers were established in 1964 by a federal law (Brasil 1964), favoring landless people with larger families, lower income, ages lower than 45, and more than five years working in agricultural activities (Brasil 1988).

Until 2007, almost 2,500 agricultural settlements have been opened in the Brazilian Amazon, reaching approximately 378 thousand families, 77% of the total estimated capacity (MDA/INCRA/DTI, 2007). The settlements varied in terms of available resources, average size of land, and soil quality. Impacts were equally varied, such as rate of turnover, health outcomes, and patterns of deforestation and land use driven by a multitude of factors operating at varied temporal and spatial scales (Brondízio, McCracken, Moran, Siqueira, Nelson, & Rodriguez-Pedraza, 2002; Browder, 2002; Wood, 2002). The planning and implementation of agricultural settlements are crucial steps towards successful colonization efforts since they impact farmers' decisions. Ideally, planning should be made based on detailed information that allows decision making at the plot level, indicating the feasibility of the project and facilitating the assessment of carrying capacity (Fearnside, 1986a). That information should be used during the implementation of the project in the form of technical support provided to new settlers. Although accurate local knowledge (e.g. soil quality perception) plays a role in successful agriculture production among older communities, migrant farmers often lack this knowledge (Moran, Brondízio, & McCracken, 2002), and therefore depend on technical support to implement adequate practices.

The worst scenario, when poor planning and inadequate implementation results in opening a settlement area with substandard soil quality for occupation, imposes major social and environmental burdens. On the one hand, farmers face a blind-process: they do not know the potential of the land, the ideal crops to be planted, and the practices to be used, but, most importantly, they do not know that the land has restricted potential for a long-term sustainable agricultural production. On the other hand, failure to make the land productive results in deforestation levels beyond initial expectations, and eventual use of the land for pasture.

This discussion becomes even more critical given that most Amazonian soils are weathered and lack good fertility (Hecht & Cockburn, 1989; Jordan, 1985). More than 75% need chemical inputs and technological management in order to promote sustainable annual cropping, and some fertilizers largely used in temperate climates would not be appropriate for use in the Amazon since they could lead to soil degradation, nutrition imbalance and loss of organic matter (Goodland, 1980). It has been estimated that only 7% of the soils in the Amazon have no major limitations (Cochrane & Sanchez, 1982). Nevertheless, comprehensive assessments of soil quality at a fine scale that could inform planning activities – ideally 1:20,000 or 1:10,000 (Moran, 1990) – were rarely available prior to approval of new agricultural settlements (Fearnside, 1989). Soil quality information at a regional scale (1:1,000,000) for the Amazon was assembled by the RADAMBRASIL project during the 1970s, and potential land utilization maps produced by RADAMBRASIL based on a concept of "ideal land". This was defined as land that had soils with high natural fertility, no deficiency of water and oxygen, no susceptibility to erosion processes, and that did not present any impediments to mechanization (RADAMBRASIL, 1978). Any deviation from this concept would imply limitations for agricultural production. The millionth scale, however, does not allow decision-making at a farm level. It provides a rough indication of general resources in particular areas, but cannot support specific policies regarding occupation and promotion of sustainable agriculture. Nevertheless, findings from the RADAMBRASIL project were largely used for that purpose (Moran, 1990), exaggerating the quality of soils.

This paper discusses the implications that the lack of fine scale information on soil quality during the planning and implementation phases of new agricultural settlements can have on farmers. We assume that those phases shape future potential of the settlement area and future decisions that settlers may make, as represented by a two-tiered decision-making process shown in Figure 1. Outcomes of the planning phase determine if a new area soon to be opened for settlement has feasible conditions for agriculture production, while the implementation phase seeks to provide the means to maximize the chances that future occupants will succeed in their endeavor. Both set the initial conditions (and challenges) that future settlers are likely to experience. When no information is provided during implementation, the occupation becomes a blind process from the settler's perspective. When accurate information was not available during planning either, then a double-blind process occurs; both government and settlers are unaware of the real agricultural potential of the land. Yet, ideal planning and intervention does not guarantee that sustainable agricultural production will happen. Many factors can augment or nullify soil quality - a conceptual framework of environmental change and land use is provided by Wood (2002).



Figures 1 – New settlement project decision-making flow

As a result, instead of trying to represent all possible connections between the planning and the implementation phases, and between implementation and occupation, we draw arrows that simply indicate the direction of the flow. Different outcomes during planning and implementation result in different occupation scenarios. In this paper we focus on instances when planning and final approval of a new agricultural settlement are made without proper information for decision-making at the plot level, and when implementation is deficient. We illustrate the discussion using the Machadinho settlement project, located in the western Amazon, as a case study.

2. Study area: Machadinho, RO

Machadinho is located in the western part of the Brazilian Amazon[1], in the northeast portion of Rondônia State (Figure 2). It was one of the settlement areas promoted by the Northwest Region Integrated Development Program – POLONOROESTE, co-sponsored by the Brazilian government and the World Bank (World Bank, 1981). The area was primarily jungle before the settlement started, sparsely populated by rubber tappers. Although six tracts were initially planned, only 4 were included in the final plans, given the poor quality of soils evaluated at a millionth scale (INCRA, 1991).

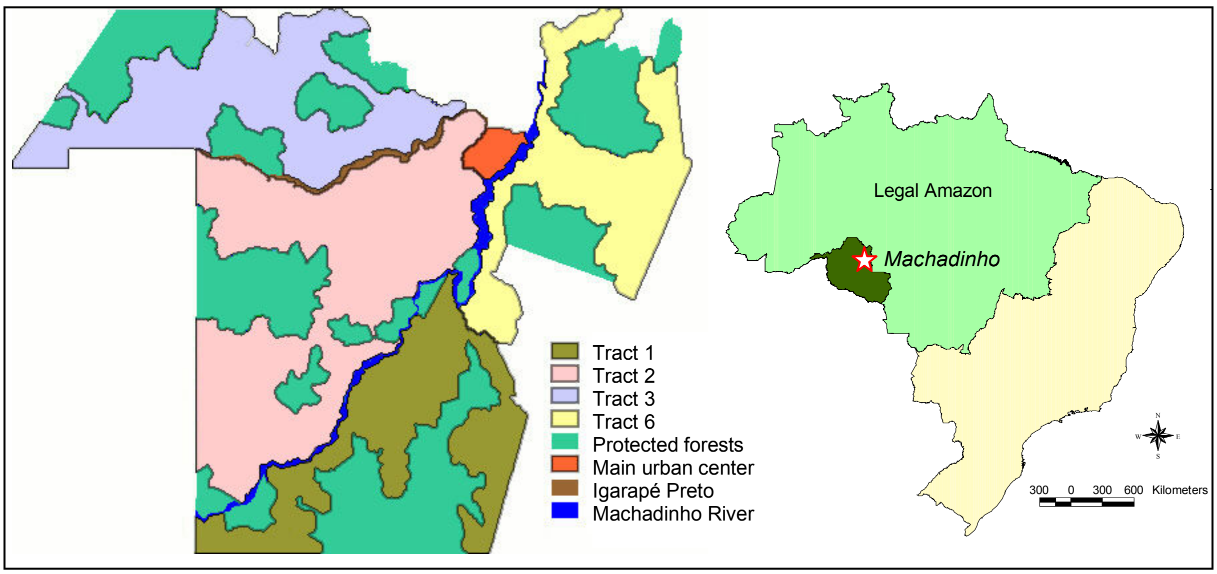


Figure 2 - Spatial location of Machadinho settlement project

Machadinho was the first colonization project that incorporated a plan of action to prevent the most harmful consequences of frontier expansion previously observed (Sawyer & Sawyer, 1987). That included an original and carefully planned plot design, accounting for the local topography and hydrology, which avoided the usual and often inefficient fishbone

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[1] The Brazilian Legal Amazon includes all States of the North region - Acre, Amazonas, Rondônia, Roraima, Pará, Amapá, and Tocantins, and the States of Maranhão - west of 44°W, and Mato Grosso (Brasil 1953; Brasil 1966).

pattern[2] (Castro, 2002). However, a combination of poor soil quality, lack of technical and financial support, and economic and fiscal crisis in Brazil contributed to a major social, environmental, and health problem (Monte-Mór, 1997; World Bank, 1992).

Multiple household surveys were carried out in Tracts1 and 2 of Machadinho, covering 76% of what were regarded as occupied plots in 1985 and 100% of such plots in 1986, 1987, and 1995 (Castro, 2002). An occupied plot is one in which settlers cleared some of their land and lived at least part-time in Machadinho (Sawyer, 1985). The survey instrument included questions assessing health, demographic, economic, social, ecological, and agricultural characteristics (Sawyer, 1985; Sawyer & Sawyer, 1987). We will use these data to evaluate patterns of occupation and land use contrasted with soil quality information.

2.1. Soil assessments

Prior to its approval in 1982, the only available information on soil quality for Machadinho was based on the RADAMBRASIL project, which revealed that the majority of the area had restricted agricultural capability (assuming no use of inputs and mechanization), and small patches of land were not appropriate for farming (RADAMBRASIL, 1978). A thorough evaluation based on soil quality and socio-economic variables (population, migration, agricultural production, etc) identified areas where detailed studies should be done in order to determine the potential for future occupation (SUPLAN/CEDEPLAR, 1979); the area of the Machadinho settlement project was not included.

Detailed reconnaissance soil surveys were conducted in Machadinho between 1982 and 1984, but did not play a role in decision making during the planning phase (occupation of the area started in late 1984). They were made in a 1:50,000 scale; although not an optimum scale for planning at the farm level it is the most detailed information available for the area[3], and we use these data as reference for the present study. The surveys generated soil taxonomy, with detailed physical and chemical composition, and a qualitative description. In addition, they provided an assessment of land suitability for agriculture considering types of

[2] Such design is only possible in forested areas, where no occupation, construction, and agricultural use are in place. Therefore, areas of illegal occupation, for example, cannot benefit from an effective design.

[3] In 2003, reconnaissance soil surveys for all Tracts of Machadinho were released at a 1:100,000 scale (Valladares, Bognola, & Gouvêa, 2003).

soil limitation, strategies for improving soil conditions for agriculture, elevation, and level of management. The assessment did not consider the use of irrigation, and did not assume pasture as one of the suitable types of land use[4]. Table 1 summarizes the criteria used in the surveys (Wittern & Conceição, 1982).

Table 1 – Major components considered in the assessment of land suitability for agricultural purposes in Machadinho

Component/level	Description
Agricultural Management:	
Primitive (A)	Based on manual work, with very little use of financial and technical resources.
Pre-development (B)	Use of animal traction and modest use of financial and technical resources.
Developed (C)	Mechanization is present in all agricultural phases; there is intensive investment to improve the land, and intensive use of available technical information.
Soil limitation: (all limitations were classified as absent, low, medium, high, and very high)	
Lack of soil fertility	If lack of fertility is very high, there are extremely remote changes that the land can be used for agriculture purposes.
Deficiency of water	Each class indicates the period of time when the soil would not provide enough water for plants: low=1-3 months, medium=3-6 months, high=6-8 months, and very high=8-10 months. The longer the period, the lower the changes that year-long crops will succeed.
Excess of water or lack of oxygen	Refer to the natural draining capacity of the soil. Each class indicates the propensity for flooding.
Susceptibility to erosion	Intrinsically related to elevation. Each class indicates the need to use inputs: medium susceptibility demands intensive inputs since the commencement of land use, high susceptibility requires costly inputs (which often are not cost-effective), and very high is not suitable for agricultural use.
Restrictions to mechanization	This limitation only applies to the developed level of management, since the other two do not imply the use of mechanization. Intrinsically related to elevation – areas with intense terrain oscillations restrict the use of mechanization.
Improvements: (only possible at pre-development and developed levels of management; at primitive levels it was considered that lack of fertility could be improved for up to three years as a result of the slash-and-burn)	
Type 1	Simple techniques with small financial investments.
Type 2	Intensive and sophisticated methods requiring significant financial investments.
Type 3	Demands large scale projects, often beyond the financial capabilities of farmers.
Elevation:	
Flat	Absence of minimum terrain oscillations.
Slightly hilly	Terrain oscillations range from 3-8%.
Hilly	Terrain oscillations range from 8-20%.
Severely hilly	Terrain oscillations range from 20-45%.
Mountainous	Terrain oscillations range from 45-75%.
Roughed	Terrain oscillations above 75%.

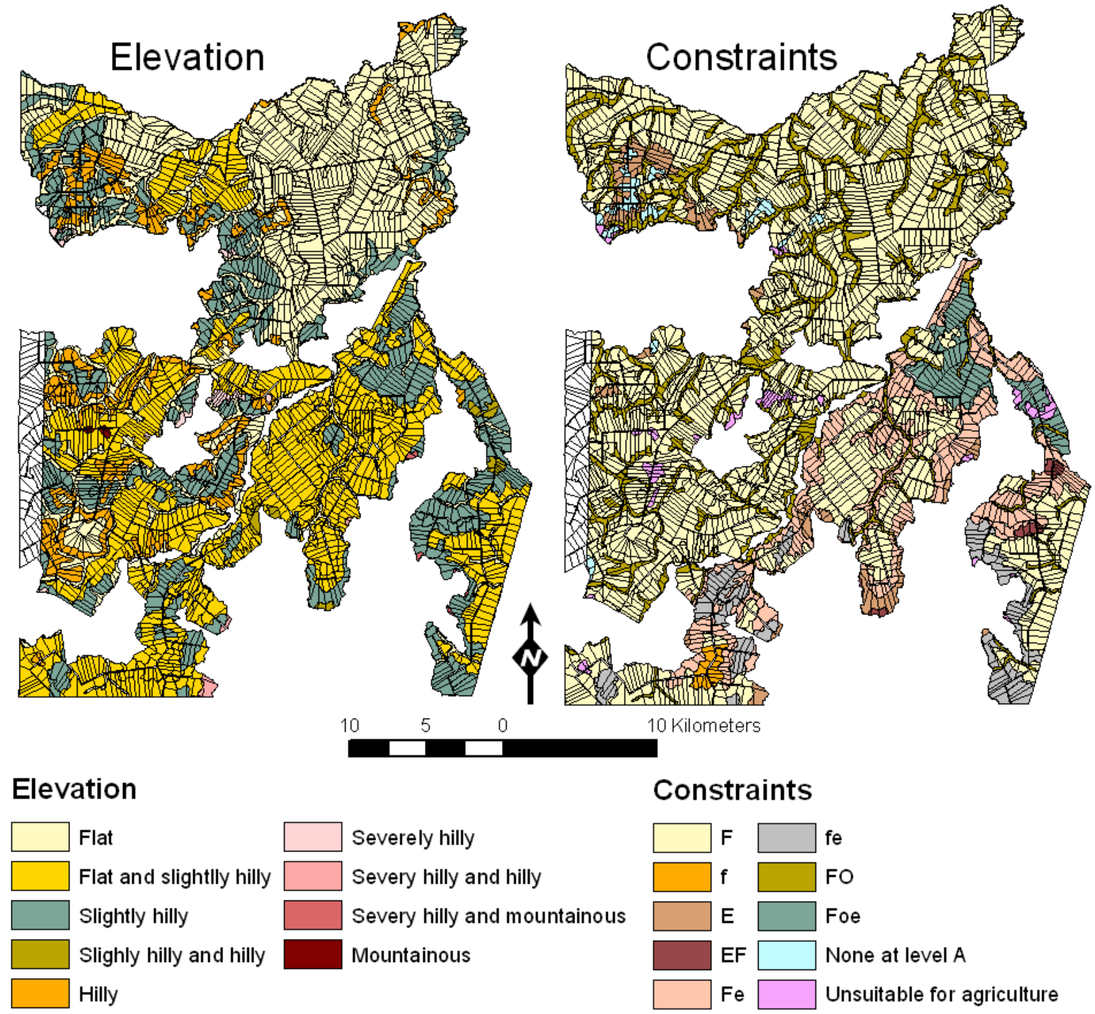
Source: Wittern & Conceição (1982).

[4] Replacing the forest with pasture was considered as an irrational choice, given the fact that the forest provide varied ways for sustainable economic use (Wittern & Conceição, 1982: 221).

Final agricultural suitability classification included four classes: good, medium, restricted, and inappropriate (areas that should be assigned for preservation). Each suitability class was evaluated for different levels of management. Therefore, some areas could present good quality at a developed management level, but only restricted at a primitive one. In addition, some soils could be unsuitable at a particular type of management level. Overall, a large diversity of soils was observed in the Machadinho area. In some plots, agricultural suitability ranged from good to inappropriate, which can compromise the success of the settlement project if farmers are not aware of this diversity. For example, settlers often start forest clearing near the road. If the best soils were located in the rear of the plot, chances were they would not be used for farming in the initial years of occupation (if ever). This highlights an intrinsic scale problem, crucial for planning: while at the millionth scale the whole area was dominated by one single type of soil, at a more refined scale large diversity was revealed.

All maps produced and published by the detailed soil surveys were scanned at a high resolution, digitized in ArcMap (ESRI, Redlands, CA, USA), and projected to match available spatial data for Machadinho. Using the plot boundaries for Tracts 1 and 2, we generated information on the area of each type of agricultural suitability, elevation, and soil limitation observed at the plot level. All maps shown in this study refer to Tracts 1 and 2 of Machadinho, since we have detailed household data for those areas.

Figure 3 shows maps of elevation and soil limitation (as defined in Table 1). The vast majority (95%) of plots lack adequate soil fertility at some level, which contributes to the reduced number of areas with good agriculture suitability at a primitive level of management. This average low fertility of soils in Machadinho was also highlighted in a comparative assessment of agriculture projects implemented in Rondônia between 1970 and 1985, using a 1:500,000 scale (Fearnside, 1986b). While seven projects implemented between 1970 and 1978 had 42.1% of the area comprised of good soils for agriculture at a primitive level of management, only 7.2% of the Machadinho area had the same soil capability. The majority of soils in Machadinho, 57.8%, were found to be good only if a developed level of management was used; in the remaining projects they amounted to only 13.8%.



Source: Wittern & Conceição 1982; INCRA 1984b, 1984c.

Notes:
1. Based on published maps the information on soil quality could be determined for 95.6% of the plots on Tract 2.
2. The letters F, E, and O used in legend of the soil constraints refer to lack of fertility, susceptibility to erosion, and excess of water/lack of oxygen, respectively. High caps indicate higher constraints levels, while low caps indicate lower levels.

Figure 3 – Elevation and soil limitations in Machadinho Project, Tracts 1 and 2

Machadinho also presented one of the highest percentages of soils unsuitable for agriculture purposes, 27.7% (Fearnside, 1986b). Most of those areas were assigned as protected forest reserves, based on aerial photographs taken in 1979 (Castro, 2002), but patches of varied size remained in 96 plots: in 29 of those the unsuitable soil was adjacent to the road. Areas close to streams are prone to flooding during the rainy season. They are represented by the “FO” category in Figure 3. Given the smart design of Machadinho, the majority of those areas is found in the rear of the plot.

2.2. Suggested crops

The detailed soil reconnaissance studies recommended that the pre-development level of management was ideal for Machadinho, but recognized that, at first, this would be impossible, given the likely low socioeconomic conditions of future settlers. Therefore, the study included suggestions to maximize output in the initial years of occupation, which would allow farmers to progressively accumulate capital that, in the future, could be used to improve the quality of the soil. A slash-and-burn process that takes advantage of timber with commercial value was recommended. It should only be done in areas where crops would be immediately planted, since exposure of the bare soil to the elements for a long period of time could promote erosion and loss of nutrients. Crop diversification and rotation were advised to control plant diseases. Rotation was also suggested in the specific case of cassava, which should not be cultivated in the same area for more than two years. Table 2 shows a list of selected crops recommended for each management level.

Table 2 – Recommended crops according to the level of agricultural management

Management level	Selected crops
A – Primitive	Cassava, rice, rubber tree, guarana, pineapple, banana, mango, guava, cupuacu, sapoti, bacuri, graviola, abiu, peach palm, abrico, biriba, mapati, Brazilian nut
B – Pre-development	Maize, beans, soy, sugar cane, sweet potato, coffee, pumpkin squash, melon, cucumber, chayote, watermelon
C – Developed	Cocoa, black pepper

Source: Wittern & Conceição (1982).

POLONOROESTE's recommendations included broad guidelines on crops to be produced in Machadinho. The plan suggested that perennial crops (economically and ecologically suited to the area) and fruit trees (able to avoid typical short-cycle crop disturbances) should be the basic elements of production (Millikan, 1996). Perennial crops could protect the surface from both the sun and run off, and maintain higher levels of organic matter (Leite & Furley, 1985). Also, governmental recommendations included guidelines regarding slash-and-burn practices, the use of legumes to protect the soil surface, and the cultivation of rice, beans, corn, rubber trees, and cocoa (INCRA, 1982). They also proposed two models of agriculture production. The first, recommended for fertile soils, consisted of the cultivation of cocoa, while the second, appropriate for soils with low fertility, suggested the cultivation of rubber trees; it was estimated that 95% of the plots would have rubber trees, and only 5% would produce cocoa (INCRA, 1982). Although rubber tree is native in the area, not all plots would have enough trees ready for production (and generation of capital) in the early years of occupation. In addition, it takes approximately 7 to 8 years for a rubber tree to start production after planting, which is a large investment for a poor farmer assigned to a plot with low quality soil.

3. Soil quality and the process of occupation

Our goal is to discuss the challenges faced by migrant farmers in Machadinho given the lack of detailed information during the planning phase, the overall poor quality of soils in the area, and the deficient technical support provided during the occupation phase. The diversity in agricultural suitability within and between management levels is shown in Figure 4. The most adverse conditions for agriculture are observed at the primitive level of management, which is the common practice among new settlers.

In order to facilitate comparisons at the plot level, we constructed an index of agricultural suitability. The index is a weighted average of the percentages of each of the five categories shown in Figure 5, 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. The calculated index ranges from 0.05 (worst soils) to 0.5 (best soils), and average values at each management level are significantly different, as shown in Table 3. A lower average index for a developed level, compared to a pre-developed, is justified by impediments to mechanization in areas with irregular elevation.

Table 3 – Index of Agricultural Suitability

Management level	Average	Standard Deviation	95% Confidence Interval
Primitive	0.1566	0.00067	0.1553 – 0.1579
Pre-development	0.2658	0.00128	0.2633 – 0.2683
Developed	0.2358	0.00156	0.2328 – 0.2389

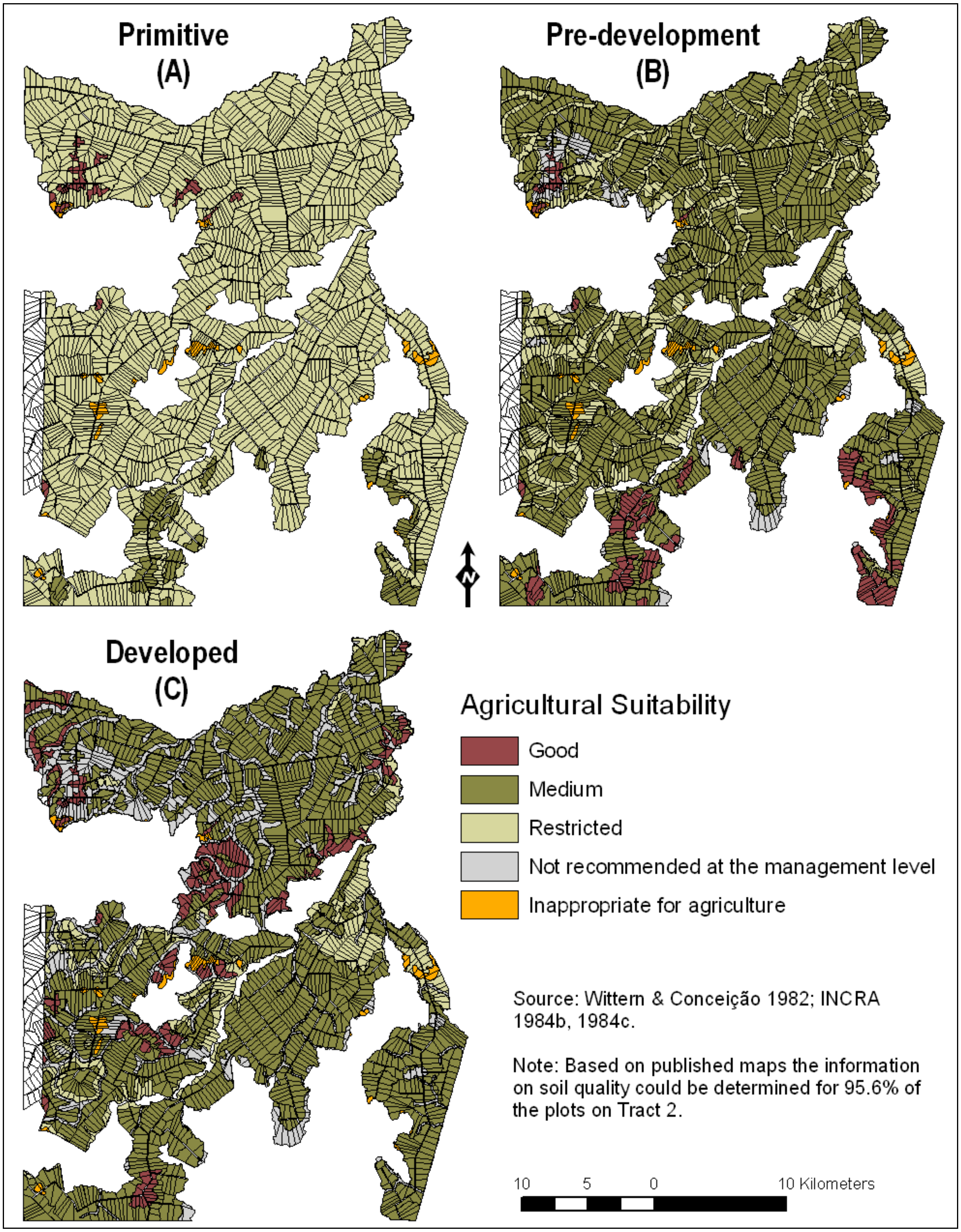


Figure 4 – Agricultural suitability in Machadinho, Tracts 1 and 2, according to different levels of management

Based on the index, 94% of the plots in Tracts 1 and 2 would have improved agricultural suitability if farmers could utilize a pre-developed management level. That could be achieved by access to information about soil quality and agricultural techniques recommended for the area, and by small financial support that would allow farmers to afford inputs to improve the quality of the land. Although that was part of the planned strategy in Machadinho, it was not effectively put in practice (World Bank, 1992). Also, according to the calculated index, only 3.6% of plots would have the same agricultural potential regardless of the amount of technical and financial inputs used by the farmer.

3.1. Settler allocation

Machadinho settlers were mostly migrants (mainly from the South region), some with previous agricultural experience, but most with no knowledge of agricultural potential or techniques necessary for farming in a tropical rain forest area; they were poor people attracted by cheap land and promised government support (Browder & Godfrey, 1997; Moran, 1981; Wood & Carvalho, 1988). Individual allocation of plots in Machadinho did not follow a rational procedure aimed at maximizing the potential for success in agricultural practices, despite attempts from the National Institute for Colonization and Agrarian Reform (INCRA) to schedule interviews with settlers before the assignment of plots. The purpose of these interviews was to investigate the crops they had produced in the past, in order to place the settlers in plots that would maximize their returns, based on the soil surveys. The initiative, however, was imperiled by the massive influx of migrants to the area, by the shortage of personnel to conduct the interviews, and by the fact that settlers preferred to be placed closed to friends' plots, regardless of the agricultural suitability (J.L. Oliveira, June 2001, personal communication).

In addition, there is no indication that settlers had good access to technical information: 43% of settlers did not receive technical assistance in 1986 from the Technical Assistance and Rural Extension Enterprise – EMATER (in 1989 this number increased to 72%), and that only 11% visited the local agency of the Brazilian Agricultural Research Corporation – EMBRAPA (Miranda, 1987; Miranda & Mattos, 1993). In 2002, 23% of farmers interviewed still listed the lack of adequate knowledge on soil characteristics and poor soil fertility as one of the main limiting factors for agriculture production (Mangabeira, Miranda, & Gomes, 2005).

Moreover, ethnographic assessments conducted in 1985-7 revealed that a “common-knowledge” soil map, shown in Figure 5, was used by local government officials to inform and advise settlers. We do not have information on which and how many farmers did have access do this information. However, compared to Figure 4, this classification has minimum overlap with the real soil information at any management level, even if the information in Figure 4 was smoothed in order to assign a single class to each plot. The map in Figure 5 neglects to portray the heterogeneity in soil quality, and does not indicate any unsuitable areas for agriculture.

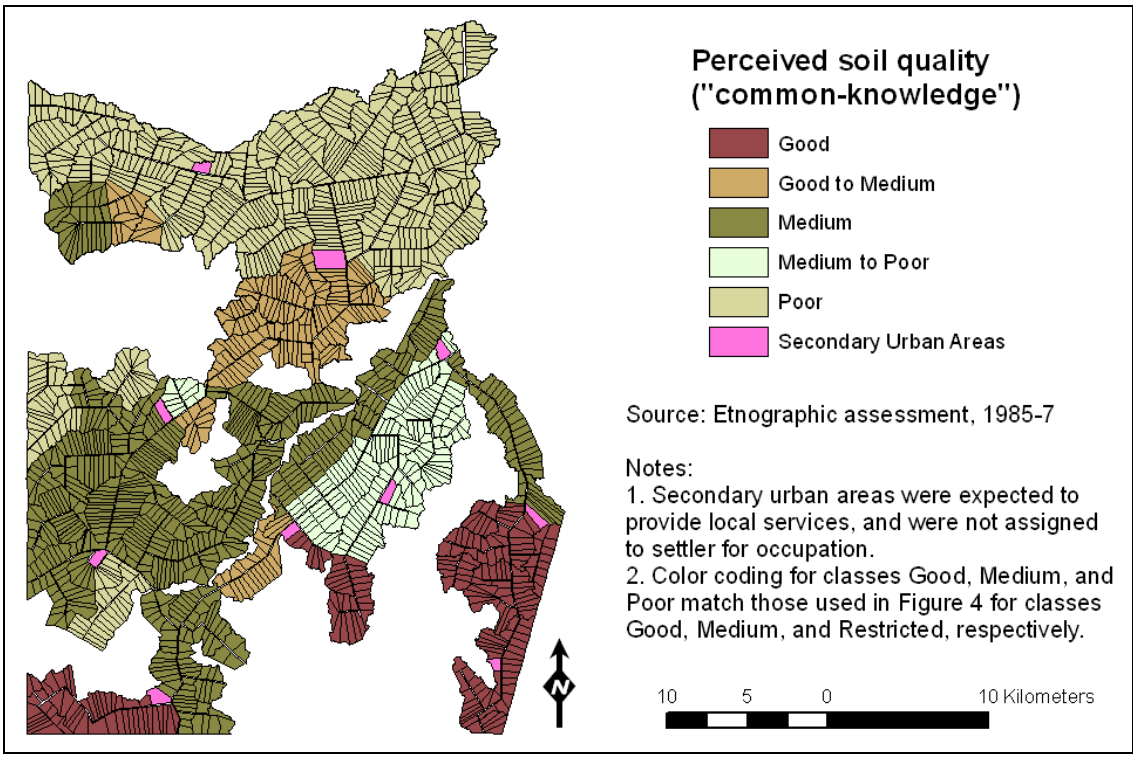


Figure 5 – Soil quality in Machadinho, Tracts 1 and 2, as perceived locally

Although INCRA has well defined rules on plot occupation and land tenure, some settlers did not physically live in the plot. Household surveys conducted in Machadinho at the onset of the project and 1, 2 and 10 years after its commencement revealed that approximately 16%, 31%, 43% and 55% of the plots were effectively occupied in 1985, 1986, 1987, and 1995, respectively. In addition, turnover of plots among settlers is very common (Campari, 2002;

Martine, 1990; Moran, 1993): 23.7% of settlers interviewed in 1985 were not living in the area in 1986 (Torres, 1987), and until 2001, only 29% of plots had only one owner, according to official records[5] (Castro, 2002).

The characteristics of those of who leave and those who stay are not straightforward. They include both very poor settlers, who end up with no other option but to sell their land and get some money to move on to another area, and settlers with more resources, who did not get used to farming in the Amazon. However, some poor settlers stayed in the area, no matter how sick and destitute they were, because the plot was, after all, their own land (Sawyer & Sawyer, 1987).

3.2. Clearing process: are better soils used first?

Considering the soil quality, the process of settler allocation, and the fact that farmers were not aware of the soil diversity in their own plots, we would expect that the clearing and preparation for planting would initially take place near the road. It is unlikely that this process will maximize settlers' changes of succeeding in the initial years after occupation, since the most productive soils may not necessarily be adjacent to the road. To evaluate this relationship between soil quality and the clearing process, we utilize information from Landsat 5-Thematic Mapper (TM) satellite images acquired in 08/07/1985 and 07/15/1994. The images were classified in order to extract information on the areas where the forest cover had been removed. The cleared area in each plot was matched with the information presented in Figures 3 and 4 (primitive management level), and the results are shown in Table 4.

Using the primitive level of management as a reference, less than 1% of the area in Machadinho presented good agricultural suitability, all located in Tract 2. Yet, only one tenth and slightly more than half of those areas had been cleared of the forest cover in 1985 and 1994, respectively. Soils with medium agriculture suitability were present in a small fraction of the area (4.47%), and less than half of them had been utilized until 1994. Approximately 30% and 40% of areas with restricted agriculture potential – the most frequent type of suitability at a primitive level, have been utilized in 1994 in Tracts 1 and 2, respectively.

[5] The percentage is likely to be even lower due to a lack of systematic surveillance of plot occupation, and the occurrence of illegal land transactions, both compromise the accuracy of official records.

Regarding soils not appropriate for agriculture, 8% and 40% of their area was cleared in 1985 and 1994, respectively. Of those plots that have unsuitable area, only 36% had the same owner between 1985 and 2001, and 20% had more than one fifth of the area used for pasture.

Table 4 – Distribution of soil attributes and cleared area in Machadinho, Tracts 1 and 2

Attributes of Soil at Primitive Management Level	% of area			% of area cleared in each soil attribute					
	Total	Tract 1	Tract 2	Total		Tract 1		Tract 2	
				1985	1994	1985	1994	1985	1994
Agriculture suitability									
Good	0.98	-	1.51	10.07	52.49	-	-	10.07	52.49
Medium	4.47	12.71	-	6.64	43.80	6.64	43.80	-	-
Restricted	93.34	86.10	97.27	5.47	37.24	3.71	30.64	6.31	40.41
Unsuitable	1.21	1.19	1.23	8.12	40.26	6.43	33.24	9.01	43.93

The panels shown in Figure 6 help to understand this dynamic of occupation and forest clearing. Panel 1 shows 6 plots that contain a mix of good, restricted, and unsuitable soils. No patch of the latter had been cleared until 1994, since they were located at the rear of the plots. Not all good soils had been used by farmers, although all used at least some patches closer to the road. Particularly, the plot in the farthest right corner reflects the lack of knowledge about soil quality, since good soils were left intact while restricted soils in the interior of the plot were cleared. In contrast, panel 2 shows a plot where good soils were located in the middle of the plot, and most of the clearing was close to the road, where restricted soils prevailed. All other variables held the same, farmers in the second panel would have lower chances to succeed compared to those in panel 1.

Panels 3 and 4 contrast plots with soils unsuitable for agriculture production. In the former, these soils were close to the road; all clearing done in 1985 was in that type of soil, and by 1994, most of the unsuitable area had been cleared Also, 36% of the area of the plots was covered with pasture in 1995, as reported by the settlers[6]. In contrast, unsuitable soils were located in the rear of the plots shown in panel 4, and until 1994 they had not been used by

[6] Farmers were asked to report the total area cleared, used as pasture, and used for different types of crops. It is unknown to what extent self-reported measures are accurate. The quality of the information may be related to farmers' experience and time lived in the area. That issue could be properly assessed by contrasting self-reported measures and remotely-sensed derived indicators.

farmers. Similarly to the previous example, a combination of chance and lack of information can make some farmers better off, assuming that all other variables are the same.

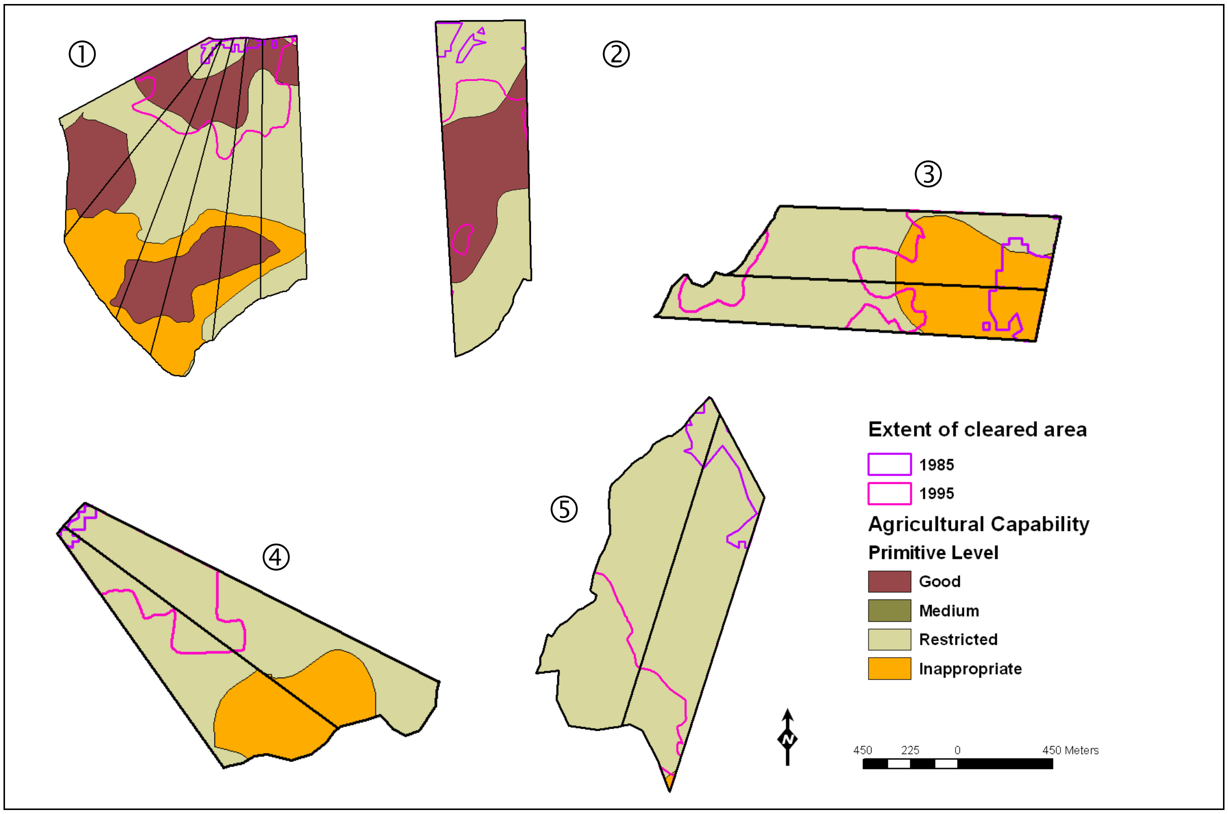


Figure 6 – Soil quality and land clearing in selected plots, Machadinho

Finally, panel 5 shows an example where plots have a unique type of soil: restricted. In this case, the lack of information does not impact decisions of where to clear/plant, but impact those related to what crops should be produced, considering low use of inputs. According to the 1995 household survey, 31% of the area of each plot shown in panel 5 was covered with pasture, as reported by the settler. In both cases, however, the current settler was not the first owner.

In summary, the average low agricultural suitability in Machadinho placed a burden on settlers, who had to manage poor soils with scarce financial and technical resources. Those who, by chance, received plots that had little or no variability in soil quality would be better off than those whose plot was highly heterogeneous in terms of soil attributes. In the latter case, the better off farmers were likely to be those who owned a plot that, despite having patches of soil of varied quality, had the best ones located near the road, where clearing initially starts. This heterogeneity, combined with the overall lack of detailed information about soil quality, results in an inefficient clearing process - best soils were not necessarily used first. Moreover, indirect consequences, such as conversion into pasture (McCracken, Siqueira, Moran, & Brondízio, 2002), undermine the main purpose of agricultural settlements.

3.3. Land use: management level and land suitability

In a simplified scenario, one could assume that farmers face 3 main questions upon arrival in a new agricultural settlement: Where to plant? Which crops to plant? How to plant? Based on the decision flow shown in Figure 1, the first two questions could be better addressed if adequate information was available and provided by the government during the implementation phase. The last question refers to the level of management farmers will be able to afford. Since the vast majority of settlers were poor, there was not much option other than a primitive type of management. As a result, part of the likelihood of successful agriculture production in the early years of occupation depended on how the planning and implementation phases were carried out.

Considering the recommendation of crops shown in Table 2, 1% of plots occupied in 1985 had rubber trees, and 13% were producing cocoa; in 1995 these numbers rose to 23% and 24%, respectively. The majority of plots were producing coffee in 1995, 86%, which became the most important crop in the area. The quality of coffee is below the national average, but cultivation progressively gained in importance, as a consequence of a municipal government incentive (Millikan, 1996). Both coffee and cocoa were not recommended crops at a primitive level of management: the former demands deep, well drained, and non sandy soils, while the latter needs soils with high nutrient levels (Wittern & Conceição, 1982).

Most plots had a combination of crops recommended for different levels. During the first year of the settlement (1985), 86% of the plots had at least one of the crops recommended for a primitive level of management, and 51% were cultivating crops recommended for a developed level. The latter decreased to 45% in 1995, although this number was not statistically significant from that observed in 1985. Plots with a combination of crops recommended for primitive and pre-development levels of management were the most common combination (92% of the plots in 1995).

On average, each plot had 6.8 ha were under cultivation in 1986, 8.9 ha in 1989, 6.8 ha in 2002, and 5.9 ha in 2005. This decline in cultivated areas was accompanied by an increase in areas utilized as pasture, although not an originally recommended use for the land (Wittern & Conceição, 1982): 1.1 ha in 1986, 2.8 ha in 1989, 21 ha in 2002, and 23.9 ha in 2005[7] (Grego, Miranda, Valladares, Custódio, Franzin, & Silva, 2007). Pasture is positively correlated with flat soils (Spearman correlation coefficient = 0.12 in 1995, p=0.0003), mostly located in the Northeastern corner of Machadinho (Figure 3). Although different mechanisms can result in use of land for pasture (Browder, 2002), some may contribute to concentration of land in the hands of large cattle ranchers (Amaral, 2007), which represents a step backwards towards the achievement of effective agrarian reform.

Regarding the inputs used by the farmers, only 28.6% and 33.5% of the settlers had a chainsaw in 1985 and 1986, respectively. In 1995, 9.4% of farmers in Tracts 1 and 2 requested a bank loan for agriculture, and only 1.2% requested a bank loan to buy agricultural equipments (Castro, 2002). Those numbers and the evidence that settlers did not have access to detailed technical information indicate that a primitive management level was largely used. This was corroborated by the results of the first Agrarian Reform Census conducted in 1996: in Rondônia, 49% of settlers had no access to technical assistance, only 3% used inputs to improve the soil, and only 7% used any type of mechanization (Incra/Crub/UnB, 1997b).

In summary, crop selection in the early years of occupation in Machadinho did not match recommendations presented in Table 2, and did not fulfill official plans. Over time, patterns of land use reflect local incentives (Millikan, 1996), market prices, individual opportunities and decisions, among a myriad of other factors (Wood & Porro, 2002).

4. Discussion

The Machadinho settlement project was designed to be a model of colonization in the Brazilian Amazon. Although some of its features indeed represented a step ahead compared to previous projects – e.g. the plot design, Machadinho came in short regarding the use of fine scale information for decision making. During the planning phase, two of the six tracts

[7] Plots in Machadinho have an average size of 40 ha.

of the project were excluded, but final approval was made before detailed soil surveys were available, and without comprehensive assessment of agricultural capability of the area; the average quality of the soil was low and agricultural suitability restricted.

The analysis presented in this paper show that most settlers in Machadinho had no knowledge about the agricultural capability of the area, did not receive technical information, had no means to afford the use of agricultural inputs, planted inadequate crops in the early years of occupation, and did not manage to stay in the plot for a long period of time. Approximately two thirds of farmers initially assigned to Machadinho had left 15 years after Machadinho was opened. The percentage of land dedicated to pasture has been increasing in Machadinho (Grego, Miranda, Valladares et al., 2007), and is often connected to ownership of multiple plots by one single rancher (Amaral, 2007). Land concentration in Machadinho was also reported by the first Agrarian Reform Census: an extreme case of 36 plots owned by the same person was recorded (Incra/Crub/Unb, 1997a).

Other settlement projects in Rondônia face similar problems: they were created in areas with poor soil that can only be produced for a limited number of years (Amaral, 2007; Moran, Brondízio, & McCracken, 2002). Land concentration have been reported in other areas in the Amazon (Campari, 2002; Incra/Crub/Unb, 1997a; Ludewigs & Brondízio, 2005). According to official numbers, 35,222 families have been settled in projects implemented in Rondônia until 2007, which is only 47% of the estimated number of families to be settled in the state (MDA/INCRA/DTI, 2007). However, the number of settled families is likely to be overestimated - during the first Agrarian Reform Census no families were found in six settlement projects in Rondônia, and a huge disparity between official records and census data was reported (Incra/Crub/Unb, 1997a). Although we cannot establish any causality between soil quality and low rates of family settlement in Rondônia, we argue that better planning and implementation of colonization projects could have improved effective occupation.

Following the turnover of a plot, new waves of settlers move in. They either share similar characteristics (and therefore challenges) of initial occupants, or have more resources and afford inputs to improve the quality of the soil. Nevertheless, those who left had few options (often limited by the availability of financial resources): return to their place of origin (if migrants), move to urban areas, or informally (and unlawfully) occupy other areas and start the clearing/planting process again. For example, the area of the two tracts not included in Machadinho due to poor soil quality, as previously mentioned, was progressively invaded. These areas had no infrastructure and, in response to the major social problems, INCRA started to legalize the occupations in 1995 through the creation of six new settlement projects (J.L. Oliveira, June 2001, personal communication). Five of these six projects were among those where no families were found during the first Agrarian Reform Census (Incra/Crub/Unb, 1997a). This process of invasion, and later legalization, highlights problems in the current Brazilian legislation regarding land ownership, which contribute to increased deforestation and land conflicts (Alston, Libecap, & Mueller, 2000; Fearnside, 2003; Hecht & Cockburn, 1989; Kirby, Laurance, Albernaz, Schroth, Fearnside, Bergen et al., 2006).

All those issues are critical if one considers that the agrarian reform program aims at improving land distribution, through changes in the patterns of land ownership and use, in order to fulfill social justice principles (Brasil, 1964). A qualitative study of settlement projects established in Brazil between 1985 and 2001 concluded that the agrarian reform program was a success from a national point of view. Regional differences, however, were significant. In the Northern region projects had soils with quality below the national average, there was a significant number of abandoned plots, land concentration was high, overall quality of life was lower, and environment-related indicators were not favorable compared to other regions (Sparovek, 2003).

In 2001, the National Environment Council (CONAMA) passed legislation demanding two licenses for the establishment of new settlement projects. The first, issued during the planning phase of the project, approves the location and design, and attests for its environmental feasibility based on detailed assessment reports. The second authorizes the opening of the area for occupation, given that any necessary mitigation measures are in place. All projects implemented before the approval of this legislation needed to have the second license issued, and those planned to be located in the Amazon need an evaluation of the susceptibility of the area for malaria transmission, prepared by the National Health Foundation. Although those recommendations had a clear concern with environmental issues[8] and overall suitability of the area for an agrarian reform project, their effective implementation has been far from ideal. A recent study revealed that less than 10% of all settlement projects implemented in the country (more than 7,000) have the required occupation license (Araújo, 2006). Moreover, it is unclear how invasion areas fit into those legal requirements. If future invasions will continue to become legal after a lagged period of time, the licensing process looses its purpose, since no planning is effectively made before an area starts to be used for agriculture.

The framework for conducting thorough evaluations during the planning phase of settlement projects is available. The Land Resource Information and Suitability System for Family Agriculture (LARISSA) is an expert system developed to assist evaluation and decision making, which combines qualitative and quantitative information on local physical attributes and socio-economic characteristics[9] (Sparovek, 2002). Such an expert system could dramatically improve the overall suitability of new agricultural settlements. Although the system was expected to be implemented by INCRA, it has not been incorporated to the decision making process regarding settlement projects. Also, the usefulness of the expert system in invasion areas is limited, since, as highlighted before, no effective planning is undertaken in such situations.

The problem with invasions is likely to continue given the current legislation on land ownership. Squatters who invade an area and prove that the land is being effectively developed may eventually secure land ownership. According to the legislation, conversion into pasture is one way to effectively use the land (Fearnside, 1985). Also, some of the squatters are former settlers selected for government sponsored agricultural settlements who abandoned or sold (unlawfully) their plots. Any financial aid they received at the time of occupation is linked to the plot, not to themselves, which provides an extra incentive to abandon the plot after the money is received (Fearnside, 2003). Legally, those farmers should not be assigned to any other settlement project. However, although in the recent years INCRA has improved the database of settlers benefited through the agrarian reform program,

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[8] Inspired on the National Environmental Act, which also requires approval licenses for any infrastructure project, based on an Environmental Impact Assessment - EIA (Brasil, 1988, 2005).

[9] A subsequent study compared two different decision support methodological approaches utilizing the indicators used by LARISSA (Costa, Ramos, Pereira, Bueno, Baca, Fidalgo et al., 2004).

a comprehensive and updated system that allows INCRA to track down farmers who abandoned or sold their plots, to remove them as candidates for future settlements, and to assure that initial loans are properly paid is yet to become operational.

Ideally, an effective planning process should make use of expert systems loaded with information at a scale suitable for plot level decision making, and should only approve projects with adequate agricultural suitability, based on expected socioeconomic characteristics of future occupants. Information on selected settlers needs to be stored and available in databases (routinely updated) that also contain data on any financial aid provided to the farmer. Such kind of planning would contribute to successful farmer outcomes in the early years of occupation, and to decrease the likelihood of plot turnover. In addition, it would impact on costs of the agrarian reform program. Currently, the government can expropriate areas for agrarian reform, which are paid with agrarian debt bonds. When areas with restricted agricultural capability are acquired (such as the case of Machadinho), the final cost surpasses initial estimations if one considers the social and environmental burdens likely to be observed. Proper planning would prevent the government from spending money in unsuitable lands, and in varied programs required to address social and environmental problems created due to occupation of those areas.

On a different matter, we also argue that soil quality can alter the risk of malaria transmission in different ways, a major problem in settlement projects in the Amazon (Sawyer & Sawyer, 1987). First, wet soils (appropriate for irrigation-based cultures), if not well managed, favor the proliferation of breeding sites for mosquitoes (Patz, 1998). Second, very poor soils that do not receive any kind of technical inputs will not generate significant profits in the early years of occupation. As a consequence, the settler does not have enough financial resources to improve his/her nutritional status, habitat conditions, and personal health (Lipton & De Kadt, 1988; Sachs & Malaney, 2002). Third, poor soils do not allow agricultural production for long periods of time, given that no inputs are used, which may result in plot turnover. The settler may decide to move on to another area, starting again the process of clearing the forest, and most likely carrying the parasite in his/her blood, which facilitates the spread of the disease to other locations (Coimbra Jr., 1988).

Although malaria transmission is often high in the early years of occupation of settlement projects, and it was particularly severe in Machadinho (Castro, Monte-Mór, Sawyer, & Singer, 2006; Sawyer & Sawyer, 1987), further studies are needed to evaluate if and how soil quality may impact levels of transmission. We did observe, however, a significant and negative correlation between malaria and flat soils, where most cattle production takes place; indeed clusters of low malaria rates were observed in areas with flat soils in Machadinho since the early years of occupation (Castro, Sawyer, & Singer, 2006). In addition, we observed a significant and positive correlation between malaria and plots that would have a better index of agricultural suitability (Table 3) if settlers were able to afford a pre-development or developed level of management; and a significant and negative correlation between malaria and plots whose index of agricultural suitability would remain unchanged regardless of the management level.

5. Conclusion

The issues here discussed exemplify how development strategies planned for the Amazon lack proper knowledge of the region's challenges, resources, and capabilities. Poorly planned and implemented agricultural settlements are likely to defy the main purpose of agrarian reform initiatives, resulting in significant environmental and socioeconomic burdens. The former is the burden of increased deforestation; it exposes soils with poor nutrient levels, which are unlikely to sustain farming in the long-run (eventually resulting in areas of secondary succession) and create the need to clear new areas. The latter is the burden on settlers, who move in with poor resources and are often forced to move out due to a combination of unfortunate events – e.g. debts, failed crops, and illness (that could have been mitigated), and end up occupying other areas without any infrastructure. The entire process generates a vicious cycle that penalizes the poor, favors the rich, and puts pressure on the environment. Without effective government willingness and commitment, adequate financial and human resources, and effective law enforcement, it is unlikely that this vicious cycle can be broken.

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