The London School of Economics and Political Science

Land use intensification in the Amazon

Revisiting theories of cattle, deforestation and development in frontier settlements

Petterson Molina Vale

A thesis submitted to the Department of International Development of the London School of Economics and Political Science for the Degree of Doctor of Philosophy

London, May 2015

Declaration

I certify that the thesis I have presented for examination for the MPhil/PhD degree of the London School of Economics and Political Science is solely my own work other than where I have clearly indicated that it is the work of others (in which case the extent of any work carried out jointly by me and any other person is clearly identified in it). The copyright of this thesis rests with the author. Quotation from it is permitted, provided that full acknowledgement is made. This thesis may not be reproduced without the prior written consent of the author. I warrant that this authorisation does not, to the best of my belief, infringe the rights of any third party.

I declare that my thesis consists of 91,166 words.

Statement of joint work

The data presented in Chapter 3 is based on fieldwork that I designed and led in partnership with Marcelo Stabile and Leonardo Ventura, and with the assistance of paid enumerators. An extended version of the chapter is being finalized in co-authorship with Marcelo Stabile for submission to a journal of methodology. The version presented here is totally the result of my work.

A different version of Chapter 6 has been co-authored with Diana Weinhold and Eustáquio José Reis and published as a Grantham Institute Working paper (Weinhold et al., 2012). More recently, a revised version of the joint work was submitted for publication (Weinhold et al., 2014). Many of the ideas in Chapter 6 have benefitted from discussions with the two co-authors and from the process of editing the mentioned papers. However, with the exception of table 6.3—which was elaborated by Diana Weinhold, to whom due credit is provided in the text—the analyses and text I present here are entirely the result of my work.

Statement of use of third party for editorial help

I confirm that parts of this thesis were copy edited for conventions of language, spelling and grammar by Gérard Klaus and the LSE Teaching and Learning Centre.

Abstract

More cattle, less deforestation? Land use intensification in the Amazon is an unexpected phenomenon. Theories of hollow frontier, speculative behaviour and boom-bust all share the prediction that livestock production will remain largely extensive. Yet between 1996 and 2006 productivity of cattle grew by an astounding 57.5% in the average Amazon municipality. How can this unlikely outcome be explained? What consequences for deforestation and human development? I provide a new framework for the analysis of the link between intensification, deforestation and development, focusing on four key elements: (i) frontier migration, (ii) land speculation, (iii) the rebound effect hypothesis, and (iv) the boom and bust hypothesis.

Does rising land productivity of cattle increase deforestation? If so, how? Based on a comparative case-study approach I assess the micro-level foundations of the proposition that intensification leads to frontier migration and deforestation. I employ an innovative procedure to collect georeferenced survey data that I then use to provide an initial test of the proposed model of land use intensification and frontier migration. I further use secondary data and spatial econometrics to look for evidence of a positive relation between cattle intensification and deforestation ('rebound effect'). The results suggest a substantial land-sparing effect, whereby intensification in consolidated areas is associated with lower deforestation in frontier municipalities.

Do booms in deforestation lead to busts in development? I use different sources of secondary data to scrutinize the theory that predicts welfare to bust as deforestation advances, and find consistent evidence against the supposition that deforestation impacts welfare in either direction. Land use intensification is the opposite of a bust in agricultural output, so the rejection of the boom-bust hypothesis is in agreement with the depiction of a rising land productivity. This does not preclude deforestation from affecting long-term welfare in the Amazon or in the rest of the world, neither does it imply that conservation should not be a policy objective. It suggests that policymakers facing explicit short term welfare targets at the local level may focus on other policy variables than deforestation.

Contents

Preface

> *There ain't no better business than cattle. Come rain or shine, the owner's gaze is just about enough to get the little beasts fattening*.
>
> — (Sergio, rural worker in an Amazon frontier).

The quote above epitomizes the ideas that are central to this thesis. When I picked up Sergio for a ride to the town at the end of a tiring day of fieldwork I did not expect that he would have summarized my work so well. After all, the chainsaw he carried and his robust, tough aspect suggested a logger, not a cattle rancher. "*My motorcycle broke down and I can't fix it. Can you give me a ride?*" It was a wet day and Sergio was covered in mud. I was looking forward to a silent ride back to the hotel where I would take a calm rest before continuing to a new frontier settlement the next day. But my passenger was eager for a conversation.

Sergio was about my age, and still today I can't fit him into any of the typical categories of Amazon peoples: settler, logger, cattle rancher, farmer, speculator, forest dweller; he was a bit of each. After placing his oily chainsaw on the dusty back seat of the car, he immediately started telling me that he was clearing his plot at the Galo Velho settlement when the rain came, so he thought it was time to head home. He rang his wife and told her he'd be home for supper. But next day he'd be back first thing. It was April and he expected to finish clearing on time so he could set fire before the 'winter', as they call the rainy season (the ideal period for fire setting is between June and September, depending on how dry it gets).

He gained my attention. It is unusual these days to find someone who speaks openly of the deforestation he is doing.—*What are you clearing the plot for?*, I asked. "*Cattle, of course*", he replied. He used to work for a logger for a daily wage, but he saw no future in it. He put away some money and in 2011 he heard that a man named Ronaldo had led an invasion of a huge farm in the border between Machadinho and Cujubim, and that there were still a few unoccupied plots. It was a bit far from the town, and the lot was forested, but he knew that once the pasture was planted and the fences raised the cattle would not need much besides a little gaze every week. He decided to get a piece of land in the new settlement so he would one day be able to fill it with stock and become a rancher.

Sergio had a family to feed and was investing a big part of his savings in the chainsaw, the fuel, and his own time. Yet he was not afraid of telling a stranger that he was part of a land invasion and that he was going to clear as much as he could before the start of the rainy season. As someone who used to work as a logger, he was fully aware of the dangers of being picked by environmental agents; but he was equally aware that distance and remoteness are effective deterrents of environmental enforcement.

The multifacetedness of frontier settlers challenges the rigid analytical categories of academics. Sergio is an enlightening example as he does not fully conform to the archetype of a cattle rancher to which I repeatedly refer in this thesis. Whereas his land use decisions seem to be determined by a straightforward economic logic (cattle is profitable due to low labour requirements), it is difficult to get to grips with his willingness to take risk, at least before some nuance is added to his story. How risky is his alternative job? Working as a daily wage logger in an Amazon frontier implies a substantial health risk and a risk to life, a non-negligible risk of violence and imprisonment, and a wage risk. From this perspective, it may well be that Sergio is being risk-averse by engaging in deforestation at a distant location where the probability of being caught on an environmental offense is close to zero.

Yet today's frontier settlers are no different from earlier ones. While the context was different in the 1980s—it sufficed to visit a government agency for a farmer to get an official 'agrarian reform' land allocation—the logic behind the land use decisions remains the same. Though they now possess a mobile phone and a motorcycle, initial settlers are typically poor and know that agriculture requires a lot more labour than beef cattle, so their ultimate goal is to become cattle ranchers. The initial step is clearing the land, which demands a considerable initial investment that often leaves settlers out of capital to build fences and buy stock. So they start from a combination of annual cash crops (rice, maize, beans) and subsistence crops (cassava) until they have the means to 'form' a pasture. If soils are good the settlers may stick to cash crops, or migrate to perennials such as coffee and cocoa, despite the high labour requirements. But in most cases they will switch to pasture as soon as they can buy their first stock.

The essential point in Sergio's narrative is that cattle is a good investment because it requires limited inputs, notably labour, to be profitable. This aspect of the enormous preference of farmers in the Amazon for pastures has been raised for a long time and is now well accepted. But it has a subtler corollary: that the transition to cattle ranching is a productive, not a speculative decision. This last point is one of the key themes that I discuss in this thesis, and I provide new insights into the criteria that demarcate speculative versus productive behaviour, as well as new data that allow for an empirical test of the land speculation theory.

Typically, farmers in the Amazon aim at beef cattle but start from dairy: milk production requires relatively lower capital input and provides a constant stream of income. In fact, cows are often dual-purpose, so they are also used for breeding with the aim of constituting a herd that will eventually allow farmers to convert to beef cattle. From learning about Sergio's experience it was noticeable that his skillset, as that of the average settler in a frontier area, includes logging, planting pastures and managing traditional forms of agriculture and cattle ranching, but not the management of more intensive land use systems. Traditional livestock systems in the Amazon relied on swiddening until recently, but due to the environmental legislation and to land scarcity, today's ranchers need to use other strategies to replenish soil fertility.

The actions of pioneers and the fate of frontier settlements in the Amazon are the ultimate topics of this thesis. Sergio's goal is to have a cattle ranch. Similar to most other pioneer settlers, he is not expecting that soil fertility will at some point pose him a challenge. But it is likely that to be sustainable in the long run he will have to adopt a set of techniques and technologies that include the proper management of soil fertility. If he is like most settlers, it will take him time to notice that the stocking capacity of his pastures declines after a few years of grazing, and the necessary investments in pasture recovery will possibly be delayed. This should trigger a set of processes that can eventually lead him to out-migrate.

Acknowledgements

This thesis is dedicated to the peoples of the Amazon. To their tenacity, but also to their enchanting lightness.

I start by thanking José Eli da Veiga, a teacher who became a Master and a friend. Zé Eli was not only largely responsible for guiding me through the difficult process of coming up with a proper research proposal, he also opened many professional doors that have been essential for this PhD.

My journey at LSE would not have been possible without the support of my supervisor, Diana Weinhold. Diana's decided critical spirit and profusely creative mind have kept me challenged all the way through. Tony Hall, my second supervisor, has devoted a lot of his time to discuss various aspects of this thesis with me, and has also given me crucial and timely advice on different occasions. The two examiners who evaluated this thesis, Ben Groom and Eugenio Arima, have further contributed to improving my work by providing thorough comments and an always positive approach to the last stage of my PhD. I am further indebted to Tim Forsyth, Robert Wade, James Putzel, Charles Palmer and Tim Laing.

I am thankful to a few other colleagues who in different ways have contributed to this thesis: Ademar Romeiro, José Eustáquio Reis, Daniel Caixeta, João Mangabeira, Marcelo Stabile, Henrique Neder, Andrei Cechin, Cláudio Townsend, Ricardo Gomes, Stephen Vosti, Jill Caviglia-Harris, Zander Navarro, Alberto Lourenço, and Geraldo Martha. Mélanie Fusaro and Gérard Klaus were incredibly patient and careful in reading the disorganized drafts of this thesis.

This research has been kindly funded by the Brazilian taxpayer. I am thankful to the staffs at the Ministry of Education (CAPES) who have so meticulously organized the implementation of my scholarship. The Amazon Environmental Research Institute (IPAM) and the Brazilian Enterprise for Agricultural Research (Embrapa) have extensively supported the data collection both technically and logistically.

The State Government in Rondônia provided continuous support to my work. I am especially thankful to Vilma Alves, who was time and again ready to intervene in my favour. The Secretary of Environment has provided great assistance, with the incessant support of Francisco Sales (who so generously hosted me in Porto Velho for many days), Arquimedes Longo and others. The Livestock Sanitation Control Agency (IDARON) kindly allowed me to interview farmers inside their dependencies, and provided large amounts of data. I am thankful to Marcelo Borges, Augusto Fernandes and Fabiano Alexandre, but also to the personnel in each agency where my team has worked.

I am indebted to many informants who out of good will dedicated long hours to this research: Amauri, Giocondo and Giovani Vale; Eanes Freire, Gleison GR, Inaldo Alves, and Jesualdo Melo. I am also thankful to Derquiane Sabaini, who led my team of surveyors and made herself available on the field wherever and whenever necessary.

My friends in London have made these four years lively and interesting. The Friday evenings at the White Horse will be much missed, as will be our beloved PhD room. There are so many of you that I will not take the risk of producing names: a huge thanks to each one.

My family has had the difficult task of standing an often stressed up husband, son, brother, in-law, and PhD candidate. Their support and understanding was critical, and the arrival of Tomas made everything easier, contrary to expectations. Mélanie's reassuring words in the difficult moments kept me looking forward to that future that both of us so much miss.

As I wrote this PhD I followed with great interest the evolution of a visionary cattle ranching intensification project in a little town in the Amazon. Curiously, four days before I submitted this thesis Don Aro was granted the first Embrapa Gold medal for excellence in cattle ranching in Rondônia. Their tenacity is the reason why I cannot but have a positive outlook of the future of the Amazon and its people.

Introduction

Traditional pastoralism is not very productive in the tropics without the aid of modem science and does a great deal of damage, for it does not conform to Nature's intentions.

— (Pierre Gourou, 1953, p. 64)

This thesis studies land use intensification in cattle ranching in the Brazilian Amazon. Contrary to Pierre Gourou's expectations, livestock production became a dominant activity in the South-American tropics. Contrary still to his predictions and in spite of problems of soil degradation—in fact, as I should argue, partly *due to* soil degradation—a substantial process of intensification has been observed in the last two decades. How can this unlikely outcome be explained? What consequences does it have for deforestation and human development? To start answering these questions I choose four topics in the *Environmental Social Sciences* literature to investigate in detail: (i) frontier migration, (ii) speculative behaviour, (iii) the rebound effect hypothesis, and (iv) the boom-bust hypothesis.

The first research question I address is: **does rising land productivity of cattle ranching increase deforestation**? **If so, how?** There is a on-going debate in the land use literature as to the effect of pasture intensification on the demand for cleared land, and so far it has been insufficiently answered at both the theoretical and empirical levels. The second question I address is: **do booms in deforestation lead to busts in development?** This research problem has an immediate connection with the previous question, but it also links forward to broader considerations about the fate of settlements in frontier locations. While I do not directly address the question on the success or failure of frontier settlements, I expect this thesis to add elements to its answer.

My original contributions are the following. At the level of theory, I put forth a set of hypotheses as to how cattle ranching evolves spatially and temporally in the Brazilian Amazon, why it eventually incorporates technologies to deal with pasture degradation, and how both processes relate to migration and deforestation. These hypotheses are then tested empirically using both primary and secondary data. At the empirical level, my contributions are threefold. First, I collect survey data to provide an initial test of the proposed model of land use intensification and frontier migration. Second, I use secondary data and spatial econometrics to look for evidence of an undesirable, positive relation between cattle intensification and deforestation ('rebound effect'). Third, I use alternative sources of secondary data to implement a test of the hypothesis that deforestation leads to a boom and bust pattern of development.

This is a thesis in *Environmental Social Sciences*, a research umbrella that studies the social dynamics of environmental issues and that has spatial analysis as a "lingua franca" (Moran, 2010). My focus is on land use change and my approach is anchored on an interdisciplinary tradition with theoretical foundations tracing back to the works Esther Boserup and Johann von Thünen. The literature and methods I use come from different disciplines in the social sciences, including geography, economics, and sociology. To deal with technical aspects of cattle ranching, I further resort to elementary concepts of zootecnics and agronomics. I make extensive use of GIS (Geographic Information Systems) tools for data generation, description and analysis. The research design is based on a comparative case study framework, and includes survey data collection, multivariate regression analysis, spatial econometrics, and to a lesser extent interview-based qualitative research and narrative analysis.

I start this introduction by presenting the broader policy and academic context that justifies my choice of research problem and methods. I explore important background questions about the success of frontier settlements in the Amazon that are the utmost motivation for this thesis. I then present the details of the research design, including a brief review of the key literature, a presentation of the mixed methods approach, and a short introduction to the data. Finally, in the last section I provide an outline to the thesis, which is divided into three parts containing two chapters each (besides this introduction and the conclusion), and pinpoint the six contributions to knowledge of the thesis.

The big picture

'Nutrient mining' was the term used by Robert Schneider (1995) to refer to the unsustainable extraction of soil nutrients that eventually unleashes a process of soil degradation. He implied that farmers would abandon degraded soils and move forward into the frontier in search of new areas to be mined. Schneider's World Bank Environmental Paper came out at the end of a full decade in which the World Bank was bombarded with criticism for the results of environmentally sensible projects it funded across the world, notably the 450 million-dollar *Polonoroeste*[1] project in the western Brazilian Amazon. His paper has an excellent coverage of many of the themes that are central to this thesis, including a comprehensive analysis of the fate of settlements in Amazonia, the role of land markets, and what he called the "sell-out effect".

This thesis provides a fresh look at a debate that was profuse in the late 1980s and early 1990s about the success or failure of frontier settlements in the Amazon, of which Schneider's article is a good synthesis[2]. The debate has been closed since then as issues of deforestation and later climate change and biodiversity became dominant. A revisit to the earlier conclusions of the frontier settlement discussion is much needed due to the emergence of two new phenomena that had not been properly considered. The first and most important is a process of land use intensification that is now evident not only in mechanized agriculture but also in cattle ranching. The drivers and consequences of this process, notably in terms of deforestation, are poorly understood. The second phenomenon is the consolidation of rural areas that were the objects of frontier settlements since the 1960s. Contrary to theories that predicted a bust in welfare or a stagnant 'hollow frontier' condition, consolidated areas are seeing a sustained process of development, with land use intensification and improvement in welfare.

[1] Wade (2011) provides an excellent discussion of the internal politics and management of the project at the World Bank. Polonoroeste became world-famous as the criticism it received for environmental issues and invasion of indigenous lands precipitated a process of 'greening' of the Bank.

[2] Other important references are Almeida (1992), Almeida and Campari (1995), Moran (1989) *apud* Schneider (1995), Coy (1983) and Clearly (1993).

A related topic that has been insufficiently covered is the role of pasture degradation in defining the fate of marginalized farmers in consolidated areas. While nutrient mining has been modelled by Schneider with a focus on frontier migration, his approach was restricted to a displacement effect where farmers *abandon* their land in older frontiers to start new soil mining activities in newer settlements. Today's reality of increasing land scarcity and a consequent land use intensification process were incipient at that time, so the crucial role of land markets was not integrated into his model. Even Barbier's (1997) excellent review of the role of land degradation on frontier migration—which is very similar to my own approach in many aspects—could not have considered the role of land use intensification and consolidated rural areas.

The motivation for this research is thus the need to incorporate livestock intensification, settlement consolidation, and pasture degradation into an enveloping analytical framework that relates agricultural development policies to deforestation outcomes in tropical regions.

Forest clearance in Brazil accounted for 16.3% of global gross forest cover loss from 2000 to 2005, while deforestation in the country's humid tropics amounted to 47.8% of global gross humid tropic forest cover loss in the same period (Hansen, Stehman and Potapov, 2010). Forests in the humid tropics enclose the highest stocks of biodiversity as well as very high stocks of carbon (Strassburg et al., 2010), so Brazil (i.e., its Amazon region) is a relevant case on its own. Moreover, even if the rate of deforestation in the Brazilian Amazon has seen a drastic decline since 2004, the opposite has happened in Bolivia (Chen et al., 2013), so understanding the dynamics of intensification vis-à-vis continued frontier settlement can be of potential use for neighbouring South-American countries.

Frontiers continue being born in Brazil, if at a lower speed than just one decade ago. Internal induced colonization projects such as the ones undertaken in the 1980s, for example under Polonoroeste, are nearly extinct, but autonomous frontier processes have emerged that guarantee the continued settlement of new areas (Perz et al., 2010). The environmental legislation is much tougher nowadays, and intensification of agriculture, and of cattle ranching, is a reality, as I show in this thesis. Deforestation is a fraction (approximately 1/5th) of what it was 10 years ago. The agricultural sector is gaining relevance in the national economy, and the extensive amount of land available in the Amazon is an important cause of that growth (Martinelli et al., 2010).

In the presence of the above conditions, it is easy to foresee that migration to frontier areas will disappear. First, without the government creating big colonization projects the migrants who first move to a frontier have to meet substantial settling costs. Second, with a tougher environmental legislation deforestation becomes more expensive, which adds up to the first point. Third, with agriculture modernizing rapidly in the more established areas (Van Wey et al., 2013), migrants' opportunity costs may increase, creating incentives to not migrate. That seems to be indeed taking place: the speed of creation of new frontiers is much lower today. In parallel, deforestation has also plummeted.

There is much debate about the causes of deforestation, and much debate about why deforestation has fallen so dramatically in the Brazilian Amazon (Hargrave and Kis-Katos, 2013). Was it a result of environmental policy? Was it an outcome of relative prices? A standard hypothesis is that policy has generated the kind of barrier to horizontal expansion which, in the presence of increasing population density, has triggered a Boserupian intensification process. This in turn would have had a land-sparing effect, so that less deforestation would follow from the intensification process, as higher output is produced with the use of equal or less inputs (particularly land) (Lapola et al., 2014). But is this so?

An ongoing discussion tries to establish whether yield increases that lead land to be used more intensively in the short term do end up saving forests in the long run or instead produce a sort of 'rebound effect'. In a recent paper Barretto et al. (2013) find some evidence that land use intensification generates pressure for further agricultural expansion and has been indeed correlated with more deforestation in frontier areas. Another study looks at cross-country data from South-America and also finds evidence of a rebound effect (Ceddia et al., 2013). Many papers have studied this apparent trade-off for the case of soya yield increases (e.g.: Brown et al., 2005; Macedo et al., 2012), but none has studied the potential effect that intensive cattle ranching can have on the expansion of cattle onto forest margins—a dynamic and spatially indirect effect.

It is possible that cattle ranching intensification leads to more rather than less demand for land, as argued by many authors (e.g.: Angelsen, 2010; Lambin and Meyfrodt, 2011). In this scenario, the displacement of low productivity cattle rearing[3] would be towards frontier areas. But if this is so, then counter-effects would need to have operated contemporaneously since deforestation has fallen dramatically in the Brazilian Amazon. One of these counter-effects may have been a tougher environmental legislation ('forest code') accompanied by higher enforcement inhibiting the opening up of new frontiers (Stickler et al., 2013). Another would be the attraction exerted by towns where part of rural emigrants head (Browder and Godfrey, 1990).

How successful has the frontier settlement enterprise been? The question of how cattle ranching dynamics impact deforestation is one component of a more general debate on patterns of development in forested areas. I close the loop between the fate of frontiers and development by assessing one prevalent theory on the dynamics of deforestation and welfare in forest-rich environments: that the economy follows a boom and bust development pattern as deforestation rises. This hypothesis can be linked back to theories of 'hollow frontier' as well as to the notion of 'resource curse'. I provide an extensive test of the boom-bust hypothesis in this thesis.

Research problem, data and methods

Are productivity gains in cattle ranching associated with higher deforestation? A process of land use intensification is evident in the last 20 years in the Amazon and there is a debate over its environmental consequences. While the drivers and outcomes of a rising productivity of croplands have been amply studied, the same is not true for cattle, which is still today a

[3] Productivity of cattle is henceforth defined as output per unit area per unit time. It can be measured in terms of quantity or value, the advantage of the latter being that it can synthesize beef and milk output in one measure. I use values most of the time.

largely extensive activity. I devote the most part of this thesis to scrutinize the hypothesis that livestock intensification increases deforestation in the long run.

The optimistic perspective regarding the link between land use intensification and deforestation tends to be accepted by a considerable establishment of governments, funding agencies and NGOs[4]. The pessimistic view, on the other hand, is often seen with suspicion by policymakers even if it remains a well-regarded hypothesis in the land use literature (e.g.: Angelsen, 2010; Lambin and Meyfrodt, 2011). Those sceptic of agricultural development in the Amazon, such as Phillip Fearnside (2004), lean towards embracing the rebound effect hypothesis for livestock intensification, even if the causal mechanisms remain poorly understood and the empirical evidence scarce or inexistent.

My concern when initially structuring the research was to avoid the mistake of incorrectly confirming what is already readily accepted: that intensification reduces deforestation. I therefore took the pragmatic approach of momentarily assuming the validity of the pessimistic hypothesis, making it my 'null hypothesis', so that, analogous to a statistical test, I minimize the risk of rejecting the null (rebound effect) when it is actually true. One contribution of this thesis is thus to depict the chain of causation that would lead to an undesirable rise in deforestation when land use is intensified, all else constant. I examine the micro-level foundations of the proposition that intensification can lead to increased migration of farmers to frontier areas and thus to more deforestation. I exploit the roles of the following fundamental drivers: institutional changes, biophysical constraints, technological dynamics, land markets, and economic behaviour.

I also look at the issue from a macro-level perspective, asking whether changes in land productivity in consolidated areas are associated with changes in deforestation in frontier settlements, allowing for a time lag. I find sufficient evidence to reject the hypothesis of a rebound effect; moreover, the econometric results suggest an important land-sparing

[4] Trivedi et al. (2012) and Strassburg et al. (2012) articulate the standard land sparing assumption from the point of view of funding parties. The UK is funding a programme that incentivizes farmers to invest in cattle ranching intensification technologies in various States in Brazil. The Dutch government has committed funds to a pilot project on sustainable livestock farming to be implemented in the Brazilian Amazon (GTPS, 2012). The Brazilian government provides subsidized credit for a "low carbon agriculture programme" that includes recovering degraded pastures. The official agricultural research and extension agencies have also created their own cattle intensification programmes: Embrapa *Boas Práticas Agropecuárias*, and Emater *Programa Balde Cheio*.

effect of intensification. This then leads to the logical question of *how* a rising productivity of cattle ranching may have caused deforestation in frontier locations to fall, and I do offer some initial theoretical elements to this discussion but in a mostly preliminary manner. The results I obtain therefore pave the way for future research on the micro-level (migration-related) mechanisms of a land-sparing effect.

I close the thesis by studying the links between land use and development and assessing the possible causal nexus between booms in deforestation and busts in development. I triangulate the results by combining different research methods, data sources and types.

Frontier settlements have been the object of a long history of scholarly debate in the social sciences, including their sociological role in the construction of the Nation (Turner, 1921 [1893]; Martins,1996), their economic role in allowing for agricultural expansion (James, 1938; Mueller, 1997), and the spatial pattern of colonization of new lands that they entail (Hudson, 1969). One paradigm that has prevailed in discussions in the recent past is that of the 'hollow' frontier, owing to the work of Preston James (1938). In studying agricultural expansion in the State of São Paulo, he advanced the theory that pioneer settlements were deemed to leave behind a scenario of low productivity cattle ranching, nutritionally depleted and badly eroded soils, and a declining population.

James's thesis proved popular as it seemed to be a good account of the unfolding dynamics of frontier settlement (Casetti and Gauthier, 1977). His ideas were subsequently linked to the theory that frontier dynamics are best described by a model of boom, bust and decline (Taylor, 1973), and to the view that speculative behaviour—economic decisions predominantly based on pecuniary rather than productive motivations—can explain land use decisions (for example, Almeida and Campari, 1995). The link between these three views on the process of land use change in frontier settlements is central to this thesis.

Do booms in deforestation lead to busts in development? A more encompassing discussion on deforestation and settlements in the Amazon frames the issue in terms of the resource curse theory (Wunder, 2005; Barbier, 2011). The idea is that resource-rich regions have a tendency to create conditions that prevent them from developing in a sustained manner.

The main mechanism would be the large amount of rents generated in the booming sectors (normally a mineral resource, but in this case the exploitation of forests), which would incentivize corruption, drain public resources thus reducing investments in public goods such as education, and prevent other economic sectors from flourishing. The economy would remain irresilient to crises and prone to a boom-and-bust-based development pattern that leads to long term stagnation (Rodrigues et al., 2009; Celentano et al., 2012).

While the hollow frontier paradigm has been challenged by a number of studies starting in the late 1990s, it remains an important foundation for theoretical and empirical analyses today (e.g.: Assunção, 2008; Bowman et al., 2012). Yet recent studies have challenged the validity of both the hypotheses of speculative behaviour (Sill and Caviglia-Harris, 2009) and resource curse (Hall and Caviglia-Harris, 2013). Moreover, recent evidence contradicts the key prediction of the hollow frontier theory that population collapses as frontiers evolve. I thus develop an alternative theoretical framework by resorting to a classical model of frontier colonization that predicts a phase of competition where the most able farmers stay and the less successful ones out migrate (Hudson, 1969). This allows me to at once explain the current land use intensification process and explore the idea of an indirect land-use effect, whereby increased productivity of land affects deforestation by causing unsuccessful farmers to migrate out of consolidated areas and into new frontiers.

A note on methods

There are three possible geographical delimitations of the Brazilian Amazon. The most inclusive and most used for statistical analysis is the 'Legal Amazon', a political construct that includes the States in the North Region (Acre, Amapá, Amazonas, Pará, Rondônia, Roraima and Tocantins) plus Mato Grosso and part of Maranhão. Being the most employed for region-wide policy and research purposes, this is the demarcation I adopt in this thesis. Two other popular definitions are of an ecological construct. The 'Amazon biome' refers to a set of animal and vegetal species that share a habitat with similar climatic conditions and a common environmental history, and embraces an area with closed boundaries that occupies 49.3% of the country's territory and contains mostly forests, but also savannahs. Lastly, the ‘Amazon rainforest’ refers to dense forests with heavy rainfall, and occupies 42% of the Brazilian territory. The latter two delimitations are very difficult to operationalize for statistical analysis as their boundaries do not follow the political boundaries.

Accounting for 61% of the Brazilian territory, the Legal Amazon is in many senses a challenging region to study. I started my research by conducting two waves of fieldwork in one representative State of the Amazon—Rondônia—and collecting qualitative data that allowed me to do a process tracing exercise. In this initial phase I interviewed 36 cattle ranchers in 6 locations of new settlement (frontiers), 17 cattle ranchers in 9 municipalities of older settlement (transition and consolidated areas), and a number of other informants in government agencies and farmers' cooperatives. The qualitative information I compiled was the basis for a paper[5] in which I lapidated the hypotheses that are the foundations for this thesis. In doing so I also put in practice a key method of inquiry consisting of "[unwrapping the] *cause-effect link that connects independent variable and outcome* [and dividing it] *into smaller parts; then* [looking] *for observable evidence of each step*" (Van Evera, 1997: 64), which I have extensively employed in studying the link between cattle ranching intensification, migration and deforestation.

At the most general methodological level, the research design follows a comparative case study framework, where the cases are municipalities in different stages of the settlement process: pre-frontier, comprised of deeply forested municipalities with economic and land use dynamics that are approximately exogenous to the settlement process going on elsewhere, and can thus be taken as counterfactuals to the causal mechanisms I study; frontier settlements, where a process of ‘rush to the gold’ causes high rates of immigration and leads to high deforestation activity; transition, where soils are degrading and the competition phase is setting in; and consolidated areas, where immigration rates and deforestation have converged to the State averages. I study each case by employing a combination of process tracing, descriptive statistical analysis, and econometrics. At the empirical level, I combine qualitative data from semi-structured interviews, survey data from primary fieldwork, and secondary data from conventional sources.

[5] Published in Portuguese as Vale and Andrade (2013).

An important contribution of this thesis is the generation of new cross-sectional evidence on cattle ranching. The third wave of my fieldwork consisted of a survey with 384 cattle ranchers in eight municipalities in the State of Rondônia, in which I used an innovative data collection strategy to generate a property grid containing the boundaries of 95.6% of the surveyed farms. The resulting dataset includes variables on land use decisions, economic and biophysical conditions, and zootechnical indicators that allow me to draw a precise and representative snapshot of cattle ranching in Rondônia as of May 2013. At the more aggregated scale, I assemble a municipality-level dataset that spans the period 1996-2012. The dataset includes standard variables from land use studies, such as deforestation, agricultural area, pasture area, and per capita GDP, as well as two newly constructed variables: a measure of the average legal reserve requirement (the amount of private lands that must remain forested according to the environmental legislation) that varies over space and time, and an estimate of farm gate beef prices for all Amazon municipalities.

Thesis outline and contributions

The thesis comprises three parts divided into six chapters, excluding this introduction and the conclusion.

Part One includes two lead-in chapters that are the radar of the thesis. Chapter 1 defines key terms and provide a literature review focused on the opposition between theories of hollow or collapsing frontier and an alternative approach based on the 3-phased model of rural settlement by John Hudson (1969). Chapter 2 advances the relevant theoretical insights on the intensification-migration-deforestation link that are then put to the test in Part Two.

Part Two contains two chapters that deal with the collection and analysis of primary data. My first contribution to knowledge is the data collection discussed above. In Chapter 3, I describe the population, the sampling framework and the procedures for data collection, and run a set of data quality tests. Rather than a methodological section for the full thesis, this chapter focuses on the design of the survey; other methodological discussions are within the relevant chapters.

Chapter 4 is the core of the thesis. It provides a comprehensive analysis of the survey data based on the theoretical propositions in Chapter 2. It starts from a contextualization of the four cases that I study. The context-setting section is more descriptive than analytical and includes a historical account of the settlement process as well as a discussion of the key counterfactual conditional. The second section includes the analysis of channels of causation relating land use intensification in consolidated areas to deforestation at the frontier—notably the role of frontier migration. Finally, the third section advances a framework to distinguish speculative from productive behaviour in land use decisions.

My second contribution is to document and analyse the cattle ranching intensification process. This is done in section 4.2, where I show that productivity is rising and that the process is concentrated in areas of older settlement—what I call consolidated areas. Intensification is a consequence of land scarcity—an argument dating back to Esther Boserup—and in the context of the Brazilian Amazon the evidence does support this claim. I argue that land scarcity has been rising due to the enforcement of environmental legislation such as the forest code, but also due to biophysical constraints leading to soil degradation in older settlements. These factors have generated the key push for intensification.

The phenomenon of rising land productivity in the cattle sector has until recently remained obscure, so it is no surprise that its drivers and outcomes have not been studied in an integrated way. My third contribution to knowledge is to develop the specific theoretical mechanisms that connect a set of enabling conditions to the intensification process, and from thereon to out-migration of farmers and to the new frontier settlements. The theoretical propositions are presented in Chapter 2 as hypotheses to be tested, and the related empirical analysis is in section 4.2.

To the best of my knowledge, this contribution adds many new insights to the existing literature on livestock intensification and land use change. I find that when land markets work reasonably well and when there is a group of farmers that cannot incorporate technology to their production functions in order to intensify, a process of migration from areas where there is intensification to frontier areas is likely to occur. I illustrate the argument with cross-sectional evidence from Rondônia and state a set of necessary conditions for this process to have a positive impact on deforestation in frontier locations.

The Boserupian framework in which the proposed causation mechanisms are based rests on the assumptions that farmers behave according to productive, not speculative motivations. My fourth contribution is to improve the analytical framework that allows for the distinction between productive and speculative motivations leading to land use decisions, collect the necessary data, and apply the model. This is in section 4.3.

Part Three includes the use of secondary data to test two key hypotheses on intensification, deforestation and development. In Chapter 5, I implement a quantitative assessment of the rebound effects hypothesis. The reduced-form model I employ is based on a spatial econometric specification and uses panel data at the municipality-level. I show that mounting productivity in consolidated areas has been associated with lower deforestation both in frontier and consolidated municipalities. This is my fifth contribution, and it suggests that the process of out-migration enabled by the rising productivity is insufficient to have a positive impact on deforestation.

The reason why that is so, however, remains unclear. It may be that marginalized farmers are leaving consolidated areas to go to peri-urban and urban areas; it may be that they are still going to the frontier but clearing much less than before, possibly due to a new pattern of household segmentation where part of the family lives in urban areas; or it may be a combination of a relatively low level of out-migration, migration to urban instead of rural areas, and a transition to a mode of production that is less deforestation-intensive in frontier areas.

How does all the above relate to development? My sixth contribution, in Chapter 6, is to show that deforestation can hardly be seen as a determinant of welfare in the Brazilian Amazon. I demonstrate that a boom-bust hypothesis for the dynamics of deforestation and welfare in the Amazon is not supported by the evidence. I initially scan through the literature in search of the possible mechanisms that can relate deforestation to welfare, and offer a simple summary model. I then use three sources of variation to look for a boom-bust pattern of development caused by deforestation: cross-sectional, time-series and case study data. In all cases the boom-bust hypothesis is rejected.

Land use intensification is the opposite of a bust in agricultural output, so the rejection of the boom-bust hypothesis is in agreement with the depiction of a rising productivity both in agriculture and cattle. The survey data from Rondônia does not confirm the prediction of a hollow frontier outcome. To the contrary, the areas that were first colonized are exactly the ones that are the most prosperous today. This, however, does not preclude deforestation from affecting long-term welfare in the Amazon or in the rest of the world, neither does it imply that conservation should not be a policy objective. What it does suggest is that policymakers facing explicit short term welfare targets should not expect that by stimulating deforestation they will be maximizing local welfare outcomes, nor that they will be doing so by curbing deforestation.

I conclude this thesis by discussing the relevance of my results for theoretical perspectives on land use change and the environment, presenting caveats and limitations, exploring policy implications, and suggesting new avenues of research on intensification, deforestation and devopment.

Part One

Theory

This lead-in part of the thesis contains two short chapters. The first is a literature review focused on the confrontation between competing theories of settlement in agricultural frontiers and development. The goal is to set the theoretical ground for the propositions I advance in the second chapter, which in turn sets the ground for the data collection and analysis in Part Two of the thesis.

In Chapter 1 I present the evolution of the notion of frontier settlements since Frederic Turner, and discuss the hollow frontier strand of the literature. I then present an alternative theory based on a 3-phased process of development of rural settlements, and argue that the latter is a better depiction of recent developments in frontier settlements across Brazil. In Chapter 2 I advance two sets of theoretical propositions about the link between land use intensification in cattle ranching, frontier migration and deforestation. First, I spell out the conditions that should allow for a land use intensification process to take place. Second, I propose three necessary conditions for intensification in consolidated areas to lead to migration to frontier areas and to deforestation.

The focus of this thesis is on spatial and economic aspects of land use change. The literature review also covers demographic and sociological considerations, but to the extent strictly necessary to the understanding of migration patterns from and to frontier areas. Political Science considerations, on the other hand, are not covered. For example, while the analysis of institutional dynamics would be central to understanding the evolution of the environmental legislation in Brazil, I take the law and its enforcement as given and study their impact on deforestation and cattle ranching. Likewise, when discussing the behaviour of farmers I take local institutions as given and focus on the strict economic rationality of their actions.

Chapter 1

Theories of rural settlement in frontier locations

Making room for intensification

In this lead-in chapter I explore the key theoretical literature that underpins my analysis on cattle ranching, intensification and deforestation. The text is organized around the opposition between two contrasting views of frontier settlements: one that predicts a situation of 'hollow frontier' consisting of depopulation, soil degradation and economic stagnation, and another that leaves open the possibility of a phase of consolidation where land use systems are pushed to become more efficient due to increasing competition. While in reality any given municipality or settlement is likely to have elements of both situations, I depict the theories in a stylized fashion in order to single out the model best able to explain the reality in the Amazon.

Land use intensification is the single most important theme in this thesis. When assessing theories of frontier settlement I am thus particularly interested in whether they can explain the recently observed tendency of intensification and reduction in deforestation. After reviewing the classic theories of hollow or collapsing frontier, I find that the new intensification developments were not predicted by these theories. I then explore an alternative model based on Hudson (1969)'s location theory of rural settlement, and argue that this is a better framework to explain the dynamics of land use in areas of recent colonization.

Hudson proposed that the settlement of a frontier has three phases: colonization, when pioneers occupy mostly empty spaces; dispersion, when population growth and new arrivals increase population density; and competition, when "*owing to limitations of the environment, weak individuals are forced out by their strong neighbors, density tends to decrease,* *and pattern stabilizes*" (p. 367). This last phase has been regarded by part of the literature as confirmation of agricultural and welfare involution, but new evidence suggests it may be a transitional phase, where competition pushes weaker farmers to urban areas or to new agricultural frontiers and leaves a network of more productive, established rural dwellers.

I further explore theories that establish the link between the process of frontier settlement and land use decisions. I concentrate on two insights that turn out to be central theoretical foundations for this thesis. The first is the idea by Esther Boserup that it can be rational for farmers maximizing the marginal utility of labour to migrate to marginal lands where soil fertility is high and land is less scarce. This is the main logic behind the argument that farmers who move from settled to new frontiers are not necessarily behaving speculatively, but may be responding to simple productive motivations. The second important insight is the idea by Willard Cochrane that technological dynamics in agriculture follow a 'treadmill' pattern. This is the supposition that consumers benefit from lower food prices due to modernization, but most producers do not gain anything as they are trapped on an eternal process of competition that forces them to adopt new technologies in order to stay ahead of falling prices.

The conclusive notes at the end of this chapter are a new synthesis of ideas by Hudson, Boserup and Cochrane that provide a coherent explanation of recent land use developments in the Amazon. To reach that point, I start from a succinct presentation of the historical and intellectual contexts of the internal colonization effort that gave rise to the latest wave of Amazon peopling and to today's social and economic conjuncture, stressing the still vivid debate between optimists and pessimists of Amazon development. Once the necessary background is introduced, I portray the seminal theory of the hollow frontier and related ideas on speculative frontiers, arguing that recent evidence calls for the revision of those perspectives. In the last section I draw on established models of land use and frontier settlement to propose explanations that can better capture the recent tendencies in land use dynamics in the Amazon. The final section sums up the chapter.

1.1. Internal colonization, the context

In this section I briefly explore the historic and intellectual context of the government-led process of occupation of the Amazon in the 1960s. The text is structured around the confrontation between two polarized perspectives, that of the 'technocentric' optimists of the possibility of development in the Amazon, and that of their 'ecocentrist' detractors. The debate between optimists and pessimists of Amazon development has more recently been reframed to include ideas of sustainable development, pro-poor growth and others, and it pervades the different chapters of this thesis inasmuch as it informs policy on agriculture, rural development and the environment.

The premise that induced settlements in the Amazon cannot lead to sustained improvement of wellbeing is deep-rooted. Since the beginning of the military-led internal colonization programmes, in the 1960s, there have been voices warning that the fragile environment of humid tropical forests would not be adapted to sustain the type of economic activity that is seen in other regions. Ecological arguments as varied as the deleterious role played by heat, the excess of rain, soil fragility, amongst others, were used to sustain the same basic idea: that Amazonia is essentially, and crucially, different from everywhere else.

Pierre Gourou's (1953) thorough assessment of numerous challenges faced by tropical countries to develop became the centrepiece of those who see no place for conventional economic development in Amazonia. With the technical look of an agronomist and the analysis of a human geographer, he expressed a pondered and pragmatic view of the possibilities of development in the Amazon as well as in other tropical regions. Yet his views were far less eschatological than normally assumed. Later, when the internal colonization process was in full swing, the most distinctly Malthusian take was that of Philip Fearnside (1986), who used a stochastic simulation model to find that population can grow only up a certain (low) threshold level in the region, after which any development effort becomes unsustainable, the probability of failure approaching one. Fearnside's positions on Amazon development became highly influential. On the more balanced side was Bourne (1978), who saw costs as well as benefits in the internal colonization effort, and accepted the idea from the military government that the Amazon region needed to develop as much as other regions in Brazil.

The internal colonization project of the military government in the late 1960’s to 1980’s, and its corresponding land reform programmes, meant that hundreds of thousands of peasant families migrated from all regions in the country to the ‘green hell’ of the Amazon forest in the span of 30 years (Almeida, 1992, p.29). Settlements for agricultural development were the organizational basis of the colonization effort, and while highly heterogeneous between each other, all included the demarcation of rural and urban plots and distribution to peasants according to pre-established criteria (including a subjective assessment of agricultural skills), either completely free of charge or against the payment of relatively small sums (Oliveira, 2010). Settlements also included a minimum provision of social and economic infrastructure (roads, schools, hospitals, police stations, etc), as well as the basic facilities of the state bureaucracy.

The intellectual position that gave support to the induced occupation of the Amazon is best represented in *Amazônia* (1967), a masterpiece by the then Brazilian Ambassador Álvaro Teixeira Soares that exalted nationalist feelings in arguing that the entirety of the Brazilian territory had to be occupied. The language used in the book is a good example of the kind of fine prose that was used to set the tone of the Brazilian march to the west. But there were also objective calculations behind the symbolism and rhetoric. The government assessed that world demand for beef and dairy products would rise sharply in the following decades, so cattle raising was a sector that could potentially play a similar economic role to what rubber had played for nearly a century in Amazonia (Tocantins, 1982), as well as sugarcane and coffee elsewhere[6].

The government exempted companies from outside the Legal Amazon from paying income tax on the amount they invested in cattle ranching in the Amazon (Mahar, 1979).

[6] See Soares (1967) for the official government’s, and Neto (1970) for an academic’s views of the time on the role of Amazonian cattle in supplying future demand for beef. See Crotty (1980) and Buse (1989) for detailed technical analyses of global demand for beef and dairy products in the 1980s, and for confirmation that the government’s forecasts were realistic. See Faminow (1998) for a discussion of the role of internal beef demand during the first two decades of the colonization process. See D’Silva and Webster (2010) for a contemporaneous discussion.

Gigantic cattle operations where thenceforth established in selected colonization projects, mostly in the State of Pará, by capitalists from São Paulo and other industrial areas (Costa, 2000), bringing forward a whole new institutional and organizational set—laws, credit lines, cattle farm suppliers, sanitation control agencies, slaughterhouses—that would later allow for the rapid expansion of livestock in Amazonia.

Deforestation in the Brazilian Amazon has been historically related to cattle, as documented by Fearnside (2005). Cattle was first introduced in the Amazon by the Jesuits in 1644 (Tocantins, 1982), but it was not until the 1970's that it started to grow to become today's most important economic activity in terms of land use. Pasture areas, mostly used for cattle raising, accounted for two thirds of the total cleared area in the Legal Amazon in 2008, as recently measured by the National Institute for Space Research (INPE). The contribution of the region to the national cattle ranching sector has also become significant, as the increment in the region's herd amounted to three fourths of the country's increment since 2000 (IBGE, the national statistical agency).

Peasants who migrated to the Amazon normally brought along some capital, enough to clear their plots and start growing cash crops, but far from sufficient to start raising cattle, an operation that presumes higher fixed costs and longer investment horizons than conventional staple crops. Since food staples have the further advantages of higher demand in the beginning of settlements due to ease of storage and lower prices, and lower logistical costs (transportation and storage), they are the preferred investment for most rural households in the early phases of settlement. The most common route is thus to grow rice for two or three years, then raise cattle (most cases) or, when soils are good (fairly rare), grow perennials—mostly coffee or cocoa (Witcover et al., 2006).

Capital accumulation by colonizers runs parallel to the land degradation process. For a few years after clearance, seasonal crops (rice, maize) benefit from a very high supply of nutrients that comes from the burning of the organic material that was stored on the forest ground. But it takes only five or six harvests until output per hectare start to fall to the point the land needs to either be abandoned for a couple of years (the slash-and-burn cycle), fertilized, or used for something that demands much lower levels of nutrients than staple crops, such as forage production. Most farmers will choose a combination of the first and last options, with very few, if any, having the assets (knowledge and capital) to move from a traditional to an intensive production system.

The resulting pattern of settlement in the Amazon represents a drastic change to what was previously prevalent. Population density rose sharply in the areas that were subject to the colonization effort, and the economy became much less dependent on forest products and more reliant on commercial agriculture. In the next two sections I explore different approaches to explaining how this new pattern of settlement relates to land uses and development outcomes in the Amazon.

1.2. Frontiers, speculation and the consolidation process

> *In this advance, the frontier is the outer edge of the wave - the meeting point between savagery and civilization. Much has been written about the frontier from the point of view of border warfare and the chase, but as a field for the serious study of the economist and the historian it has been neglected.*
>
> — (Turner, 1921 [1893], p. 7)

I start this section by presenting theories that predict bust outcomes of settlement in the Amazon, and finish by summarizing evidence that falsify those theories. Most of the literature studying land use in the Amazon has focused on the first phase of the colonization process: the agricultural frontier per se, also labelled "speculative frontier" (Margulis, 2004) or "expansion front" in Brazilian sociology (Martins, 1996). This space-temporal category is meant as those locations where the colonization process is in its initial early period of net arrival of migrants, property consolidation, and transition from a mostly crop-based economy to an increasing participation of cattle. Its distant roots are in Frederick Turner's classical analysis of the role of the expansion towards the west in the formation of the American Nation.

Agricultural frontiers have been defined in a plethora of ways since Frederick Turner, but only a handful of authors have bothered to generate workable definitions that can clearly identify a frontier area and distinguish it from other types of settlement. In the present thesis I adopt an economic characterization that captures the essential idea in a somewhat abstract manner, but I also establish a demarcation criterion that allows me to concretely specify what is a frontier and what is not.

Turner's broad definition was that frontiers are dynamic spaces (whose boundaries dislocate over time) with cheap land and vast "wilderness freedom". They thus not only attract peasants, but also enable individuals to create new communities, with institutions that are a real synthesis of the aspirations of those pioneering peoples. His was a concept aimed at analysing the sociological implications of the American march to the west, but it also provided the foundations to the Brazilian branch of frontier studies. One of the best known theorists in this tradition is the sociologist José de Souza Martins (1996), who sees two parts to the concept of frontier. The first is the "expansion front", where civilization advances upon new lands and breaks into the "frontiers of humanity". This borderline of frontiers is driven by a mechanical movement of colonization, an almost self-sufficient force that bears no relation with economic determinants. The advancement of the expansion front over the wilderness produces a clash of worlds between civilization and indigenous populations.

The second part, which is also chronologically posterior, is the pioneer front, where new forms of socialization—new institutions—are created, and where economic gains are the driver of expansion. It is in this category that Martins's ideas align with those of Turner, as both see a role for frontiers in the process of Nation-building. For Martins as well as for Turner, frontiers are where the new is being constantly created and recreated, therefore where the Nation can be shaped and reshaped. The opposite of frontiers are those older settlements in the Atlantic coast (both in Brazil and in the U.S.) that are instead emptied of population, "routinely", "traditionalist", and even "dead". This is in sharp contrast with the pessimistic view of frontier settlements that is expressed by ideas of "hollow frontier".

Rich as they may be, the sociological concepts above are far from workable definitions. A somewhat concreter idea is provided by Mueller (1997), who describes the frontier as an "*area where the net present value of land use just covers the opportunity cost of the least cost claimant*" (p. 42). In simple words, frontiers are places that are only worth it for the poorest, most marginalized individuals. This recalls the notion of an expansion front but also somehow defines why, in economic terms, individuals are attracted to the frontier. The reason is made explicit by Barbier (2011): frontiers are where land is abundant relative to labour and capital, so migrants (labour) move to frontiers in search of cheap lands and few competitors. Seen through the lenses of political economy, frontiers would be "*the* fringe *of market-oriented agriculture and ranching, which advances on subsistence farming or uncultivated wilderness, as the case may be, as a function of power relations and profit seeking behaviour in the larger society*" (Walker et al., 2009, p. 734).

All definitions capture in one way or another the emptiness and the newness of frontiers. In the words of Martins (1996), "[t]*he frontier is the frontier of humanity. Beyond it is the non-human, the natural, the animal*" (p. 34, free translation). The unifying idea is thus close to that of Hudson (1969), who based on ecological models defines frontiers as empty spaces (in terms of population) that have some kind of attractiveness sufficient for a group of pioneer colonizers to immigrate and start a settlement.

Geographers try to explain locational patterns, economists focus on the incentives for inputs to move to the frontier, and sociologists concentrate on the social relations that emerge from that movement. In this thesis the goal is to study the concrete movement of the frontier from a given empty, unsettled place to a more dynamic area, where an economic fabric and institutions emerge endogenously: "*a place that moves elsewhere, as one set of social relations gives way to another*" (Walker et al., 2009: 733).

Mueller's demarcation criterion has the advantage of parsimony, as it captures the dynamic nature of frontiers while remaining simple. But to be workable it would require difficult-to-obtain measures of the net present value of land and of farmers' opportunity costs. An intermediary approach between abstraction and concreteness is that of Campari (2002), who characterizes agricultural frontiers as areas with: higher than average immigration and deforestation activity; and lower than average population density, land prices, land titling, and deforestation extent. This set of criteria provides a useful qualitative picture of frontiers, but is still unnecessarily complicated to implement. For operational purposes the best approach is that of Rodrigues et al. (2009), whose demarcation criteria are based on the most salient feature of frontiers: deforestation. They define frontiers as areas with high deforestation activity and low deforestation extent, and consolidated areas as the inverse—low deforestation activity and high deforestation extent. These criteria only require data on deforestation and the choice of 'high' and 'low' deforestation thresholds. This is the working definition I adopt.

Pecuniary gain

Turner's work on frontiers was half-transplanted to Brazil in 1938 by the geographer Preston James. Studying the case of Northwestern São Paulo, where coffee plantations were expanding, James established a notion of "hollow frontier" that would become enrooted in narratives of frontier dynamics in the social and environmental sciences. A hollow frontier would be an area where a pioneer settlement leaves behind (i) substitution of crops for pastures, (ii) nutritialy depleted and badly eroded soils, and (iii) a declining population. Moreover, under this framing frontier dynamics would be best described by a sequence of boom, bust and decline (Taylor, 1973).

> *Why is Brazil still a land with a hollow frontier? The system of fazendeiro and colono, or wealthy landowning aristocrat and poor landless peasant* (…) *is a well known and basic cause of the failure of agricultural settlement to achieve any sort of permanence.* (…) *But this is not the whole story* (…) *The answer lies to a certain degree in the changing spirit of the Western world. Most of the colonists who came to São Paulo came not to seek liberty, but for pecuniary gain*.
>
> — (James, 1938, pp. 361-362; emphasis added)

The idea of pecuniary gain is recurrent in this thesis. The quotation synthetizes the view by Preston James that a different process was taking place in Brazil than what had been theorized by Turner for the United States. The difference was that in Brazil pecuniary gain was subverting the original spirit of the march to the west: the search for freedom. This link between speculative behaviour and a failed frontier would persist in the theorization of new settlements until the present day, and I will show that there is a neat connection between James's ideas and more contemporary theories of idle farming and land speculation.

The hollow frontier theory seems to have been valid for the State of São Paulo during the first half of the 20th century, as shown by Casetti and Gauthier (1977) and Taylor (1973). In sharp contrast, the very same areas in São Paulo that had seen soil depletion and a declining population until the 1950s—Marília, Araçatuba and Presidente Prudente, as well as western Paraná and Santa Catarina—are the regions that later became the most prosperous rural areas in Brazil, both in cattle ranching and agriculture. Hence, the hollow frontier theory has badly failed to predict agricultural developments in 'post-frontier' situations.

During the first three decades of directed colonization in the Amazon, a number of scholars tried to update the hollow frontier theory adapting it to what was being observed in many colonization projects across the region[7]. For example, Almeida and Campari (1995) made an extensive study of farmers' land use decisions with a model of rational resource allocation based on opportunity costs. Farmers allocate labour, land and capital so as to cover opportunity costs—the best return they can get to their resources in an alternative investment. When a farmer decides to clear land because he expects to sell out his plot at a higher price in the future (a pecuniary motivation, as in James's quotation above), he is said to be a speculative agent. If he instead clears with the objective of producing agricultural goods to sell in the market, he is said to be productively oriented.

The authors developed an empirical model where land is kept if its profitability matches its opportunity cost, given by land prices, otherwise it is sold out. They then calculated the profitability of agricultural and livestock systems and concluded that not all farmers kept lands due to their productive potential. In fact, they estimated that for up to 50% of

[7] Ideas of hollow frontier and boom-bust are very popular in Latin America more broadly. For example, in a thorough study of the history of *Scarcity and frontiers*, Edward Barbieri (2011) expresses a neat endorsement of those ideas, particularly for the case Latin-America. Rudel et al. (2002) is another well-known article that explores such theses for the case of Ecuador.

their sample, productivity levels did not increase fast enough to match land appreciation, so farmers must have been keeping land as capital assets in order to benefit from land prices that grew faster than bond yields. The authors argued that where farmers were not able to keep up with land appreciation, productivity levels tended to either stagnate or decrease, and a process of "agricultural involution"[8] took place, whereby farmers that were originally productive became land speculators, and the area transitioned towards a hollow frontier.

Assunção (2008) takes this view further by establishing the conditions under which farmers choose to invest in land for productive versus unproductive, or store of value, motives. He argues that the opening up of land rental markets improves land allocation in allowing skilled farmers to lease lands from unskilled farms, thus reducing the amount of land that is allocated to "idle farming". Bowman et al. (2012) further elaborate on the land speculation approach by dividing the Amazon into 4 Km^2 cells and estimating a profit function for each resulting pixel. They assume that spatial units (pixels) that cannot generate a flow of profits that is high enough to pay for the land at current prices (opportunity cost) are effectively speculative land uses. They thus find that anywhere between 9% and 13% of the region is vulnerable to speculation, and that up to 25% of total land is only marginally profitable at current conditions.

The prediction of the land speculation branch of the literature is that, in the absence of policies that deal with market failures such as dysfunctional credit and land rental markets, part of the land in the Amazon will be devoted to idle farming and enter a process of agricultural involution. In particular, where land prices are already high and still see rapid rises, all else constant, agents will be stimulated to switch to idle farming as productivity levels often cannot grow as rapidly as booming land prices. That is, in essence, the idea of a hollow frontier, where productivity and welfare are either stagnant or collapsing.

Contrary to the perspective above, many scholars have found evidence of an agricultural sector that becomes increasingly productive and efficient in its use of land, especially in

---

[8] The authors use the term, somewhat misleadingly, in a completely different way from Clifford Geertz in the classic *Agricultural involution: the process of ecological change in Indonesia* (1963).

consolidated areas, where land prices are high and often still rising considerably. Andersen et al. (2002) were among the first authors to make this point clear by means of careful empirical analysis. They found that from 1970 to 1995 per capita rural GDP grew at 5.8% in real terms, while cleared area increased by 4.8% annually, implying a rising productivity of land. They also analysed different social indicators and concluded that "*the developments in the Amazon have benefitted large parts of the population, not only a few rich speculators*" (p. 202). Moreover, they found that older, consolidated settlements had become dynamic centres of growth for local rural economies, much in contrast with the prediction that frontiers would eventually bust.

On the issue of land speculation leading to idle farming, Sills and Caviglia-Harris (2009) find little evidence of speculative behaviour in land price formation in Rondônia. They instead find a strong positive relation between stocking ratios and land values, as well as a negative effect of neighbours' degraded soils, both implying that land markets are instead productively oriented. Sticker et al. (2013) find that land prices in Mato Grosso are fully consistent with Net Present Values of 30-year agricultural rents and a discount rate of 5%. If speculative behaviour were largely in place, then land prices would have to imply a much higher discount rate.

> [D]*espite predictions that these colonist farming systems would be ecologically and financially unsustainable, the majority of farms in the survey sample saw the real per capita net value of production grow during the 10-year study period. It may be convincingly argued that this growth in production, bringing with it enhanced economic welfare for most of Rondônia's rural inhabitants, has come at the expense of the natural capital stock (i.e., natural forests) that has been progressively converted to pasture during this 10-year study period.*
>
> — (Browder et al., 2008: 1488).

The same conclusions that Browder et al. (2008) arrived at for the State of Rondônia were reached by Van Wey et al. (2013) for Mato Grosso, and by Barretto et al. (2013) and Martha et al. (2012) for the whole of the Amazon. Despite some flaws in the interpretation of results, the two latter papers gather robust evidence on the important productivity gains that cattle ranching has had in the last few decades. Pacheco and Poccard-Chapuis (2012) do the same exercise and arrive at similar conclusions, corroborating what Chomitz and Thomaz (2001) had found a decade earlier. All these papers find strong evidence of sustained productivity gains in the agricultural sector, providing further evidence that falsify the hollow / speculative frontier theses.

Consolidated regions are increasingly relevant to the Amazonian economic landscape. Despite important regional variation, post-frontier locations are in many aspects converging to the standards of average to high-development localities in the country's interior. This can be said of infrastructure and connectivity (Poccard-Chapuis et al., 2005; VanWey et al., 2013), economic output and welfare (Costa, 2012; Margulis, 2004; VanWey et al., 2013), industry life-cycle (Hall and Caviglia-Harris, 2013; Merry et al., 2006), but also—and most importantly for this study—of agricultural productivity (cited above). Consolidated rural areas display features that very clearly differentiate them from areas of recent colonization: a more technified agriculture, more concentrated land distribution, and greater degree of land titling.

Hence, the recent evidence on the advancement of the frontier suggests that situations of failure are not the main outcome of settlements in the Amazon. In particular, the finding that agricultural productivity is in fact increasing in the region as a whole goes against the predictions of the land speculation literature. But if the hollow frontier theory is falsified, recent developments in the Amazon can be explained by an alternative body of literature. In the next section I show how a Boserupian framework of agricultural change can account for the recent evidence, and how ideas of land speculation can be reconciled with an intensification process.

1.3. Three phases of rural settlement

I now turn back to a classic geographical model to establish the basis of the analysis of recent agricultural frontiers in the Amazon. I then add a Boserupian insight and a well-known economic model of technological dynamics in agriculture to complete the fundamentals of the theoretical advancements proposed in this chapter.

Inspired by ecological models of ecosystem colonization and based upon reasonable assumptions of social and economic processes of rural settlement, Hudson (1969) proposed the following 3-phased theory of rural settlement location. By migrating to a new settlement pioneers reduce overall population density. They establish locational clusters based on a number of ecosystem variables that influence their choices. Then, in the second phase, population growth and new waves of immigration determine the dispersion of the original clusters into unoccupied areas, thus filling up the space and increasing population density. The third phase is a crucial one:

> [T]*here is a lower limit on the size of the farm that can be operated economically. Increase in prices may bring smaller farms into production (change in volume of the niche space), but even with such a condition, the biotope is of finite size and so are the farms, and the process is inevitably checked. The process of competition is a struggle between settlements to hold their domains intact and to increase their holdings. Larger settlements absorb smaller ones, just as larger trees get greater nourishment by blocking sunlight from smaller trees near them* (…) *Under low density there is no need for competition. It is only under high density conditions that the competition for space comes into being and the process will become important only when farmers try to expand their holdings. The recent agricultural history of the United States has been characterized by these conditions - a small decrease of land in farms, a marked increase in average size of farm, and a decline in the number of farms.*
>
> — (Hudson, 1969, p. 371).

Hudson's seminal theory gives way to the idea that economic consolidation in the context of competition is associated with productivity gains on the one hand, and exiting farmers on the other. Weaker farmers who end up being bought out will inevitably migrate either to towns or to new frontiers. Those who stay are better able to invest in land-saving technologies[9]. For the ones who stay and intensify, continuous competition reinforces itself by creating a "treadmill pattern" of technological change and land property, whereby early, skilled adopters of new technologies benefit from lower unit costs and end up either forcing other, less skilled (laggard) farmers to adopt the new technology or forcing them out by buying up their lands (Levins and Cochrane, 1996).

This kind of treadmill technological pattern has been shown to emerge in the presence of low technological contagion and high adoption costs, which generates low levels of early adoption (Berger, 2001; Deroïan, 2002). In the same vein, Börjeson (2007) suggests that land use intensification may have a self-reinforcing effect, whereby long term capital investment for preservation of soil fertility attracts immigrants to the region, which in turn spurs further intensification. More recently, Duflo et al. (2011) find evidence that behavioural constraints related to present-bias can have a role in preventing farmers from adopting new technologies at early stages.

In the agricultural treadmill's terms, laggards are farmers who are unable or unwilling to switch to a more intensive cropping system. These are seen by a traditional Boserupian model as being simply optimizing the use of labour, as the transition to a more intensive system is assumed to imply lower marginal productivity of labour. This is a crucial point that will permeate the analysis in the following chapters, so I will present it in detail. In studying the relation between population and agricultural development, Boserup (1965) formulated a theory of agricultural intensification, understood as the process that leads to the adoption of land use systems that increase output per unit of land. Her key argument was that population growth is the central factor to explain land use transitions, and that the adoption of technologies that affect land and labour productivity would be triggered by demographic pressure. Population growth raises demand for food, thus putting

[9] Hall and Caviglia-Harris (2013) provide panel data evidence of a 3-phased model of agricultural market advancement—"growth, development and consolidation"—in the State of Rondônia.

pressure on land, but it also increases labour supply. It is natural, then, that farmers respond by employing techniques that use more labour to spare land[10].

The oldest form of land use, shifting cultivation or slash-and-burn, relies on long fallow (20 years) to recover soil fertility, thus requiring large quantities of land and comparatively low labour inputs. One of the most provocative insights made by Boserup was that, in this most basic land use system, output per unit of labour is maximized. Such a view is in sharp contrast with the assumption that the low capital input in shifting cultivation leads to low productivity of labour, and that by adding capital labour will also be used more efficiently. Boserup used data on Southeast Asia to argue that any process of agricultural intensification would imply greater use of labour with a less than proportional rise in output.

The argument can be made clearer by going through her model of agricultural development. In a first phase, population growth reduces the amount of available land and forces the reduction of fallow time. With long fallow the preparation of a plot only requires a superficial slash followed by fire. This is sufficient to remove all the weeds and leave the soil ready for agricultural use. But the transition to short fallow—1 to 6 years—demands a technological upgrade:

> [W]*hen the period of fallow is shortened and, therefore, the natural vegetation before clearing is thin or grassy the land must be prepared with a hoe or similar instrument before the seeds or roots can be placed. Thus, the hoe is not introduced just as a technical perfection of the digging stick. It is introduced, typically, when an additional operation becomes necessary, i.e. when forest fallow is replaced by bush fallow*.
>
> — (Boserup, 1965, p. 16).

The technological shift raises product per hectare but also increases labour requirements. This is so because the work of fertility reposition that was done by fallowing time, forest

[10] While this crucial point was generalized by Boserup, it was first made by Geertz (1963).

cover, burning and ashes is now replaced by labour and weeding. The shortening of the fallow period means that there is no time for secondary forest to cover the soil and eliminate weeds, so the farmer has to employ a hoe. Hence he is forced to substitute leisure for work. In the subsequent transition, to an annual cropping system, fallow time is further reduced to a few months every year, and still another technological shift is required. Soil preparation now demands not only weeding but also manuring. In the context of annual cropping the use of a hoe is hardly conceivable, so another shift is implemented, to the plough. This, however, means that the superficial form of soil cleaning that was sufficient in the long fallow system must now be replaced by full removal of roots. It also means that draught animals must be raised and fed, all of which imply that labour requirements per hectare are again raised.

To be sure, the central proposition by Boserup that marginal productivity of labour declines when land use is intensified has generated strong criticism (Hunt, 2000). However, Vosti et al. (2002) present empirically-derived technical coefficients for three types of dairy production systems in the State of Acre, going from traditional to intensified, and show that labour requirements grow almost threefold with intensification, the same happening for capital requirements (pp. 120-124). Moreover, a financial viability analysis of agroforestry—a land management strategy championed by ecologists that increases yields by diversifying production and keeping trees close to pasture / crop fields—in one municipality in Rondônia found that labour costs account for over one third of the total costs of production (Gama et al., 2005).

Yet a less restrictive assumption may be easier to embrace. A central hypothesis in this thesis is that laggard farming is a rational productive decision that optimizes labour productivity rather than a strategy to maximize financial gains. For this to hold, all that is needed is that marginal productivity of labour falls when expansion of markets pushes farmers to intensify *under a given technology*. For example, if the transition from fallowing to annual and thence to multi-cropping is implemented with the hoe as the only technology, then labour requirements are almost certain to increase more than output. This important point was made by Winfrey and Darity (1997) who argued that a declining marginal productivity of labour is a realistic assumption if intensification is implemented within the boundaries of a given cropping system. For them, the transition from one cropping system to another happens precisely to raise marginal productivity of labour, which then falls again with intensification until the next switch.

The induced intensification literature, a Boserupian branch of agricultural studies, proposes three possible reactions to pressure (either from the market or from population) to intensify. Farmers may either follow an "innovative intensification" strategy, increasing the use of technology, or put further pressure on soils to raise output using the same technology but at the same time taking action not to exhaust soils—"noninnovative intensification". The third strategy is called "excessive cropping frequency", and is associated with declining soil fertility (Turner and Ali, 1996; Turner and Fischer, 2010; Laney, 2002). Farmers who opt for any of the last two are technological laggards.

Labour productivity can then be safely assumed to see a steep rise whenever a switch is made to a more intensive technomanagerial system. But in the context of farmers who cannot incorporate technologies because they don't have the means or the skills to, intensification does imply a falling rate of labour productivity. With the further assumption that the technology that generates the steep rise in marginal labour productivity is uncertain and expensive, the behaviour of laggards can be rationally explained: by avoiding intensification when technology is given, they are sticking to a higher labour productivity at the margin.

Migration

How does migration enter the story? Following the treadmill paradigm, early adopters will realize extra-profits when there are still few adopters of the new technology, and thus will be able to buy up new land. This idea is in line with a von-Thünean model of land rents. Phelps et al. (2013) have shown that increased productivity resulting in larger surplus agricultural production drives up land rents and thus land prices. Laggard farmers see an increase in the opportunity cost of the land they own, so they are motivated to become land speculators (Levins and Cochrane, 1996).

Land prices will keep rising as long as agriculture continues incorporating technologies. Farmers with a tendency to be laggards will either become rentiers (speculators) who realize capital gains from land, or sell out their land and migrate to a frontier in order to optimize their labour's productivity. If they stay, they will either see a falling marginal labour productivity due to degraded pastures (less output being generated from the same area) or due to having to intensify in a noninnovative way. If they instead migrate, they will see their marginal labour productivity increase immediately due to a larger and less degraded pasture area. This outcome was central to Boserup's original model, as she saw dispersion of rural populations as a response to falling rates of labour productivity (Kjaerby, 1980). The essential feature of this model is that the technological treadmill is the fuel to rising land prices. Then, the amount of land speculators vis-à-vis optimizers depends on (1) land markets and (2) the share of laggards with respect to early adopters. More on this in Chapter 4.

Migration to frontier areas has been studied by demographers with interesting results. A stylized model by VanWey et al. (2005) synthesizes the findings of a broad array of literature and advances a hierarchical sequence of responses to population pressure: (i) intensify, (ii) provide off-farm labour, (iii) migrate, and (iv) reduce fertility. In line with the Boserupian model, farmers will first respond to increased land scarcity by using land more intensively—employing more capital / labour. When a technological threshold is reached and switching to a more advanced land use system is unfeasible, they will work off-farm to compensate for rising food prices; the plot is thus turned into a residence that allows family members to work for a wage.

The fact that a group of elite farmers pursues the intensification strategy raises demand for labour and encourages marginalized farmers to remain as off-farm workers in consolidated areas. This well-known hypothesis relies on the Boserupian assumption that intensification is labour-intensive, and it has been confirmed by a general-equilibrium land use model of the Brazilian Amazon (Cattaneo, 2002). The off-farm response hypothesis has been further confirmed by Tachibana et al. (2001) and Maertens et al. (2006) for frontier locations in Vietnam and Indonesia, where the development of improved, labour-intensive irrigation systems for paddy cultivation in consolidated lowlands reduced agricultural expansion at the forest margins.

The off-farm labour response to intensification, however, may be unsustainable in the long run, for two reasons. The first is that urban areas pay higher wages (especially when transportation costs in rural areas are accounted for) so there is an incentive to sell out and buy a house in the town. The second reason is that the skill set changes rapidly as more farmers adopt modern technologies, with rural wages for low skilled workers further declining. Eventually, marginalized farmers will be crowded out and engage in migration, often going to urban areas but otherwise choosing new frontiers where land prices are lower. When migration still proves insufficient, fertility reduction becomes the last coping strategy.

The evidence on rural-urban migration is imprecise. Carr (2009) makes a thorough assessment of rural migration in Latin-America and only mentions one study from 1994 that properly measured rural-urban migration in Brazil. He argues that rural-urban migration tends to be overestimated and that the rural-rural pattern may be more prevalent in Latin America. Barbieri et al. (2009) study rural-urban versus rural-rural migration in Ecuador and find that approximately one third of rural out-migrants head to urban areas. They look at the determinants of one and the other types of migration, and find the rural-rural strategy is followed mostly by young, unskilled, marginalized small farmers who face economic stress and cannot cope with a tougher labour market (which is confirmed by Bell (2011) for the case of Rondônia).

Separating out migrants who go to urban from those who go to rural areas in response to the inability to cope with processes of land use change in consolidated areas is key to understanding the link between intensification and deforestation. Yet demographers have a hard time grappling with the analysis of such a moving target. If the idea that rural areas become hollow as settlements evolve seems not to be an accurate generalization of agricultural development in the Amazon, it is nonetheless the case that migrants tend to flow from distant settlements to more densely populated areas.

For example, Perz et al. (2012) study the effect of road paving on migration patterns comparing Peru, Bolivia and Brazil (the State of Acre), and find that in Brazil road paving leads to net out-migration from rural areas, but that the opposite is true for areas close to the capital Rio Branco, where net immigration rate is instead prevailing. Parry et al. (2010)

also find evidence of areas closer to urban centres receiving immigrants from areas farther away, even if total rural population rises. What this suggests is a movement where part of migrants flow to urban areas possibly in search of better employment opportunities as well as better education and health. In fact, the most marginalized farmers tend to move to peri-urban areas first, where they can more easily adapt to a new lifestyle (Macdonald and Winklerprins, 2014).

Whereas in the empirical part of this thesis I approach migration in a simplified way, it is nevertheless important to acknowledge that the decision to move out can involve different members of the household in varying degrees. For example, Diniz (2002) showed that in the State of Roraima frontier occupation was being segmented at the household level between women and younger children (in school age) who lived in the "urbanized frontier", and men and older children, who stayed in rural frontiers doing subsistence agriculture. A similar case is where part of the household out-migrate (normally the offspring) and part stay and implement changes in the land use system. VanWey et al. (2012) present evidence that households adopt out-migration as a strategy to gain resilience, but only some members emigrate in most cases. These will then either provide remittances (if they are far away) or labour (if they are close) to the original household, supporting a process of land use change.

Frontier migration followed by deforestation is one of many possible responses to the intensification process. Some evidence suggests that soil exhaustion may be a cause of frontier migration (Carr, 2008). A recent paper by Caviglia-Harris et al. (2013) studies the determinants of frontier migration in a region of the State of Rondônia, and strongly confirms most of the hypotheses of the population literature. While they do not find a significant effect of ecological factors—soil depletion, pasture degradation—on the probability of out-migration, they do find that up to 17% of out-migrants move due to farm failure, and that up to 66% move to buy larger, better plots. These two pieces of evidence, however, are arguably in line with the idea that ecological factors have at least some influence on the decision to migrate.

In brief, frontier migration is in part the outcome of agrarian dynamics where a reduced group of able farmers follows an innovative intensification path while a larger group of laggard farmers either become land speculators or adopt a labour productivity-optimizing strategy and migrate to a new frontier. Migration thus enables the substitution of labour and capital, required for an intensification process, for natural soil fertility in virgin lands. Farmers who for any reason adopt a strategy of excessive cropping frequency, where no measure is taken to circumvent soil exhaustion, will eventually become either rentiers or migrants, as the gap between the opportunity cost of their lands and their farming output becomes insurmountable. Land markets are thus intermediating factors to these dynamics, as a rising demand for land increases the gains that marginalized farmers can have by selling out.

1.4. Conclusion

In this chapter I discussed the concepts and theories that underlie the theoretical propositions I advance in this thesis. The idea of a frontier that starts off by attracting agents with the lowest opportunity costs—marginalized farmers, often in a situation of penury—and evolves into a new type of rural settlement, where competition becomes a chief driving force, is central to this thesis. It is an alternative to the theory of a hollow frontier, which predicts a full failure of the colonization process: decreasing population, eroding soils and backward types of land use. Such an alternative paradigm is in place inasmuch as recent evidence on frontier dynamics in the Amazon falsify the main predictions of the hollow frontier theory.

The added value of this chapter is fourfold. First, I make the link between hollow frontier theories and more contemporaneous ideas of speculative frontier, idle farming and involutional agriculture, and argue that they have a comparable vein in that they share predictions for the fate of rural settlements in the Amazon. Second, I summarize recent empirical evidence that contradict the above propositions, and call for a theory that better fits the reality of rural settlements resulting in improving agricultural productivity and rising population. Third, I build on the Boserupian idea of intensification as optimization of labour's marginal productivity by joining Hudson's model of rural settlement and

Cochrane's treadmill hypothesis. I develop a more nuanced picture of post-frontier settlements, leaving room for an intensification process that runs parallel to the continuous occupation of new frontiers—even if at a decreasing rate—and to a form of optimizing behaviour that can be wrongly seen as pure speculation.

Fourth, I briefly discuss the migration literature and show how the definition of a link between intensification and deforestation is hindered by the complex and changing nature of migration patterns. If marginalized farmers may respond to rising land prices and degrading pastures by migrating to new frontiers, they may also respond by staying where they are and increasing the supply of off-farm labour, migrating to urban areas, or selecting some members of the household to migrate while others stay and implement changes to the land use system. These considerations will prove important to explain the results I obtain in Chapters 4 and 5 regarding the impact of intensification on frontier deforestation.

The contribution of this chapter is based on the theories and evidence put together by others. In Chapter 2 I mobilize the conclusions above to advance a set of theoretical propositions that are one way of explaining recent land use developments in the Amazon. My subsequent effort in Part Two of the thesis is then to scrutinize the hypotheses advanced using purposely collected primary survey data: I use Chapter 3 to present the procedures of data collection, and Chapter 4 for the analysis and empirical results.

Chapter 2

Theoretical propositions

The intensification-migration-deforestation link

In this chapter I advance the theoretical propositions that are tested in Parts Two and Three of the thesis. I combine the conclusions from the literature review with insights I obtained during fieldwork to come up with a set of hypotheses that can explain the livestock intensification process on the one hand, and a possible rebound effect of intensification on deforestation on the other.

I spell out three essential conditions that have led to a rising land scarcity which has in turn spurred a process of land use intensification in cattle ranching. I then propose three other conditions that would in principle lead the observed intensification to push laggard farmers to forest margins and cause deforestation to rise.

In the first section of this chapter I argue that the intensification process is a consequence of a set of restrictions to horizontal expansion. These restrictions are: (i) higher costs to deforestation due to an increased enforcement of the environmental legislation; (ii) a process of soil degradation that decreases the stocking capacity of pastures; and (iii) rising land prices. All of them operate more or less synchronically to tax the farmer's production function, causing a growing number of farmers to have negative profits, which calls for a response that is either in the form of more off-farm labour or out-migration. These are intrinsically related to a rapid integration of the Amazon to national and global commodity markets in the last two decades (Walker et al., 2009; Pacheco and Poccard-Chapuis, 2012; Lapola et al., 2014).

None of the three conditions for vertical expansion above is entirely met in frontier locations, where markets are still underdeveloped and large portions of cheap lands are available. It is only when a settlement starts to be crowded by newcomers, and a competitive phase emerges, that land prices respond. Along with competition come markets and infrastructure: roads, slaughterhouses, and a government bureaucracy. The transition between a frontier situation and a more consolidated pattern of rural settlement is often characterized by a crisis. In this second, more advanced phase of settlement, planted pastures start to bear the effects of age. Poorly capitalized farmers meet a situation where pastures have decreased in quality, land prices are surging and new clearances are costly due to a stiff environmental legislation. Many will then face the crucial decision of either vertically expanding by investing in pasture recovery or selling out.

The competition phase implies a land consolidation process that may be associated with an indirect frontier migration effect. A sort of boomerang effect whereby intensification in more established areas is associated with new deforestation in frontier locations would thus cause a flow of poor farmers who sell out their plots where land prices are high to buy bigger, more fertile lots in frontier locations and migrate therein.

In the second section, I propose three necessary conditions for a rebound effect of cattle intensification on deforestation to emerge. These are: (i) a group of technological laggards who cannot cope with the changing technological conditions coexists with a group of elite farmers who have accumulated enough to intensify and increase landholdings at the same time; (ii) a frontier where land prices are near-zero exists and is widely known; and (iii) in spite of high transaction costs, land markets operate well enough to allocate land from the most marginalized technological laggards to elite farmers. In the presence of these conditions agricultural competition and land markets should prompt an indirect land use effect whereby more productive farmers take up the place of less productive ones who then take up the remaining place at the frontier.

2.1. Intensification as a response to rising costs to horizontal expansion

I start by defining the term 'intensification'. The definitions of intensive, extensive, and traditional systems are somewhat confusing in the literature. The most common usage of the terms is the one that differentiates extensive from intensive by the level of land productivity, such as in Herrero et al. (2010). This distinction, however, requires the very difficult choice of a threshold productivity of land, and in any case it is not of much analytical use. There is also a more elaborate terminology that I use in some passages, that defines intensive systems as having 'inward' growth in yields, where the existing cleared land is used more intensively, and extensive ones having 'outward' production growth, where the amount of cleared land is extended and productivity of land (yield per area per unit of time) is kept relatively constant (Matson and Vitousek, 2006; Walker et al., 2009; Rudel et al., 2009).

The latter concepts, however, are problematic for three reasons. First, they do not allow for the static classification of a production system, as they are dynamic in nature; second, they do not capture an important group of hybrid situations, where efficiency and scale changes take place simultaneously—production growth is done both inwards and outwards; third, and most importantly, even the most land-efficient systems are likely to grow outwards as the technological frontier is reached, yet it would be misleading to classify systems in the technological frontier as extensive.

To account for that, and given the purpose of this research, I adopt definitions more in line with the agronomical and zootechnical literatures (*e.g.*: Abreu and Lopes, 2005, and especially Vosti et al., 2001). 'Extensive systems' are hereby defined as those based on natural grassland instead of planted pastures; 'intensive systems' as those where the stocking ratio (heads of cattle per hectare) is endogenously determined by the farmer, based on the relation between input and output prices; and 'traditional systems' as those where the stocking ratio is exogenously given to the farmer by the natural fertility of soil and other climatic / edaphic conditions. The main distinction—in line with Boserup (1965)—is now between traditional and intensive systems.

I use the term 'intensification' to allude to the dynamic process that allows cattle farmers to reach and outdo an intensive production system. I also refer to it as 'vertical expansion', to hint at the fact that output is raised without addition of land. 'Horizontal expansion' then refers to increasing output by using more land, either newly or previously cleared. Moreover, it must be noted that land can be added to a production system even when there is an intensification process in place, in which case horizontal and vertical expansion happen at the same time. In fact, it is precisely because horizontal and vertical expansion can take place contemporaneously that a *univocal* relationship between land use intensification and deforestation cannot be established.

The shift from traditional to intensive cattle rearing is a continuous, technically calculated process aimed at allowing farmers to administer the stocking ratio of their pastures. A process of technological change does not have to stop when the borderline between traditional and intensive rearing is surpassed. Indeed, intensification will normally go on as intensive farmers keep increasing productivity, ceasing only when land yields reach a stagnant condition.

Technologies are defined as *observable artefacts (hardware) or techniques (software) that, when combined in technological packages, impact the productivity of land*. In this thesis I am not interested in discussing agricultural technologies *per se*, but rather in assessing the impact that a given set of known, existing tools and techniques can have on the process of intensification and thereby on deforestation. I therefore select a few technologies that, based on the results of a purposely designed fieldwork (Vale and Andrade, 2011), are currently being employed with success, are the object of policies geared towards prevention of deforestation, and are easily measurable.

Internalizing the environmental cost of deforestation

Horizontal expansion of agricultural areas onto forest margins through slash-and-burn is the natural way in which agriculture has historically developed (Boserup, 1965). To make her point clear, Boserup argued that in the presence of free lands, intensification can only take place if the marginalized parcels of society are enslaved, for otherwise simple economic rationality impels poor farmers to explore lands in marginal areas under traditional systems of long or short fallowing. An essential feature of Boserup's seminal model was that horizontal expansion would only be deterred by endogenous processes of densification and crowding. In the case of the Brazilian Amazon, however, population growth is not by itself a potential driver of land scarcity, as there still is an immense stock of land upon which settlements could potentially expand (more than 80% of the Brazilian Amazon is still forested).

Deforestation became a central policy concern in Brazil as of the early 1990s. The conference Rio-92 and a combination of foreign pressure[11] and a favourable internal context pushed the government to impose a firm burden on deforestation. This was done by increasing enforcement of a 1965 command-and-control forest protection law (known as the 'forest code') that had been largely ignored until then. The first measure was to change the law itself: in 1996 the amount of land to be kept forested in private areas within the Amazon was raised from 50% to 80%, and in 1998 illegal deforestation became a criminal offence. In the early 2000s the Federal authorities started to impose heavy fines on farmers who failed to comply with the forest code. The perceived probability of punishment has thenceforth increased continuously. Today most farmers will agree that the costs of a new clearance plus the risk of a fine largely outweigh any potential benefits from a new clearing.

Deforestation has now been drastically reduced as compared to the levels of the late 1990s, and there is some agreement that increased enforcement of the forest code is part of the cause (Hargrave and Kis-Katos, 2013; Arima et al., 2014; Assunção et al., 2014). A rising cost of deforestation implies a decreasing relative cost of the intensification strategy with respect to horizontal expansion. Despite important deficiencies in the forest code law (Stickler et al., 2013), it is one of the vectors that has contributed to reduce horizontal expansion of pasturelands, and it can be argued that it was primarily an exogenous vector in that it clearly did not result from any within-region political force. All the opposite of the next vector I discuss, which is a genuinely endogenous, biophysical factor.

[11] Wade (2011) provides a detailed description of the pressure exerted by global NGOs and other environmental organizations on colonization projects in the Amazon in the 1980s / 1990s.

Pasture degradation and traditional ranching

> *As long as the population of a given area is very sparse, food can be produced with little input of labour per unit of output and with virtually no capital investment, since a very long fallow period helps to preserve soil fertility. As the density of population in the area increases, the fertility of the soil can no longer be preserved by means of long fallow and it becomes necessary to introduce other systems which require a much larger agricultural labour force.*
>
> — (Boserup, 1965, p. 104)

The main argument in this sub-section is that pasture degradation must be seen as a process that effectively decreases the amount of land that is available to a given farmer, and thus forces a re-allocation of the other inputs in the production function. The new allocation may come in the form of further clearances to replace the lost stock of productive land, or it may come in the form of capital investment to curb the degradation process. What path farmers take is a central question to the intensification debate.

The evidence on productivity loss in the Amazon in the initial years of agricultural exploitation is compelling. Weinhold (1999) found that crop productivity felt by an average 30% per year in the first 5 years of land use in the Amazon between 1970 and 1985. Her measure did not account for productivity of pastures, where a degradation process typically sets in at a later stage due to lower demand for nutrients, so the estimated productivity loss is likely to last longer when pasture productivity is included.

The idea that pasture quality declines after a few years of grazing and causes a drop in productivity is widely accepted in the land use literature. It is also generally recognized by farmers who take it for granted that pastures need to be properly managed if they are not to become nutritiously poor. However, there is little agreement as to what exactly constitutes pasture degradation, let alone how it can be measured. In this thesis I follow Szott et al. (2000, Ch. 2) in defining pasture degradation as a change in pasture condition, associated with ecological and environmental factors, that affects pasture quality (physical and chemical components as well as weed invasions) and leads to a reduction in productivity, when the management system is kept constant.

The problem is made of two parts. On the one hand, it can be argued that soils have some fixed characteristics that make them better or worse for sustaining agricultural / pastoral activities. This is the essential idea behind a measure of 'soil aptitude' that I use extensively in Chapter 4, and that takes physical and chemical information from soils to determine whether they are better for cropping, pasture or forestry. For example, Witcover et al. (2006) look at land use and welfare outcomes according to soil type, and find that the best soils yield 44% more income to farmers, all else constant. They assume that all soil types go through a process of degradation that decreases yields and forces farmers to trade-off degradation for profitability.

On the other hand, management is an important factor to be considered. Whatever the soil type, techniques and technologies can greatly impact yields and up to a point make up for biophysical restrictions. For example, the idea of 'nutrient mining' as used by Schneider (1995) implies that farmers avoid the costs of sustainable management because the costs-benefit ratio of mining is much more attractive. Muchagata and Brown (2003) explore the role of pasture management on the degradation process and show that undergrazing can lead to as much degradation as overgrazing. They also point to weed control as a key component of management, weed invasion being a typical driver of pasture degradation.

The relative impacts that biophysical conditions and management have on degradation, however, are subject to debate. In a study of 17 ranches in Rondônia, Numata et al. (2007) found that soil type has a significant effect on soil fertility, but that management and pasture age have almost no effect. Similar conclusions were obtained by Desjardins et al. (2000) for two regions in the Amazon. Yet most of the evidence is geared towards a positive effect of pasture age on degradation, with a stronger effect when pastures are overgrazed (Numata et al., 2007a; Martinez and Zinck, 2004; Cerri et al., 2005; Martha, 2010; Dias-Filho, 2011).

The role of biophysical constraints on land use decisions is a central part of this thesis. Rather than using the notion of nutrient mining, which alludes at one time to the degradation process, to the farmers' management technique, and to the migration pattern, I stick to the idea of pasture degradation. This allows me to look at the three components above—degradation, management and migration—separately.

As frontier settlements evolve into consolidated rural areas and cattle continues expanding, natural capital starts to show signs of depletion. After a little more than a decade of grazing, the typical farmer will notice that his herd is taking longer to fatten to a given weight level and will realize that the soil can no longer sustain a traditional type of cattle rearing—that which only subtracts from the natural fertility of soils. He will decrease his stocking ratio in response, but without proper management of soil fertility land productivity will keep falling, and faster (Townsend, Costa and Pereira, 2010). The rancher eventually realizes that without investment in agricultural technologies the soil will become completely depleted, and he will be forced to shift either to an intensive production system, where soil fertility is administrated, or move out of business (sell or rent out lands). Clearing remaining forested areas within the ranch (when still existent) is less of an option at the more advanced stages of a settlement, as the probability of enforcement of the forest code rises.

The option of selling or renting out depleted lands is nonetheless only feasible if there is demand for those lands in the first place. If no other farmer wishes to invest in recovering exhausted soils, then owners of depleted lands (technological laggards) will be tied to their plots and will have to resort to some kind of cheap, easily accessible technique to recover the soil, such as slash-and-burn. If instead depleted soils are sold or rented out, part of the sellers may decide to migrate to a frontier region where land is much cheaper and buy a new, bigger plot with full natural fertility to start all over again. Which, following Boserup, is a labour-optimization strategy. Whereas some, more skilled and capitalized farmers stay and incorporate new lands into their properties, others migrate further into the frontier and reignite the cycle. Which bears the question: what generates demand for depleted lands, and does the existence of such a demand cause new deforestation from migration to frontier areas?

Rising land prices

> *Competition to define or redefine the rules of land and capital access takes place (frequently involving violent conflict), and leads to winners and losers—those increasing land holdings and those pushed/pulled onwards to expanding the agricultural frontier further, where land is still cheap. Since cattle provides the largest economic rewards, given market conditions and/or government subsidies, for the winners, large-scale land conversion to pasture follows. This, in turn, drives up land prices, leading to further land consolidation*.
>
> — (Lambin et al., 2001, p. 263).

Market penetration and population densification cause demand for land to rise. Land prices in the Brazilian Amazon are low with respect to more developed parts of the country, but with a clear tendency of appreciation (Sills and Caviglia-Harris, 2009). Land prices are a function of factors that are endogenous to the farm (investment) as well as exogenous factors that have to do with the government building infrastructure and with neighbouring farmers investing in their plots (Muller, 1997; Sills & Caviglia-Harris, 2009). Even if a given farmer makes zero investment, the price of his land is still likely to rise due to exogenous forces. When there is a process of technological advancement in place, such as theorized by Levins and Cochrane's (1996) agricultural treadmill, early adopters of technologies use abnormal profits to buy land. Land prices thus rise and technological laggards have an increased incentive to either become rentiers or sell out. In such a model, land prices keep rising as long as agriculture continues incorporating technologies. Hence, farmers with a tendency to be laggards will either become rentiers, migrate to frontier areas or migrate to other businesses.

Farmers who intend to sell (or rent) out their plots but wish to remain in the cattle business will balance out the net benefits of staying against the net benefits of migrating to the new frontier. With a falling productivity of land due to pasture degradation, marginal labour productivity declines if farmers stay and do not invest in intensification, whereas by migrating the farmers do not need to intensify and can see their marginal labour productivity rise. If they decide to migrate to a frontier area, where probability of punishment for illegal deforestation is lower, buy out bigger plots and start all over again, then a relation of positive causality between increased land productivity in consolidated areas and deforestation in frontier areas may exist—Arima et al. (2011) show evidence of a similar effect for soya expansion.

However, it may also be that those farmers who sell or rent out their lands simply migrate to other businesses, thus allowing for a net decrease in deforestation—Macedo et al. (2012) substantiate this view for the case of soya. Of course these outcomes may depend on what types of technologies are employed, as different combinations of input and output prices may deliver distinct outcomes in terms of land productivity, profitability, demand for new lands, and frontier migration. If, for example, the intensification process is based on labour-intensive technologies, then a rising demand for labour in consolidated rural areas may prevent the process of migration to the frontier; if labour-saving technologies are adopted instead, then intensification may stimulate out-migration (Angelsen, 2010).

The three conditions I just presented must be present for an intensification process to take place, and I provide some evidence of this in Chapter 4. What I will now discuss are the conditions under which a process of frontier migration is likely to emerge in tandem with intensification of land use. First, there needs to be a technological gap that fuels land prices, with a group of laggard farmers who consider liquidating their assets in order to cope with the inability to intensify, alongside a group of elite farmers who have the means to intensify. Second, there need to exist new frontiers where land prices are near-zero. Third, there need to exist functional land markets that allow for some degree of efficient allocation of land.

2.2. Does intensification in consolidated areas rebound onto frontier deforestation?

Technological treadmill and the growing disparity between laggards and elite farmers

For farmers to demand depleted pastures, they need to possess the means (technical and financial) to recover those lands, and expect a positive return from the investment. Such conditions are typically met when there is a process of land use intensification in place, so that some farmers dominate the techniques of recovering depleted pasturelands into productive agricultural or grazing fields, and know from experience that it is profitable—as in the agricultural treadmill model. This group of 'elite' farmers may come from within the cattle ranching sector or, in more advanced areas, increasingly from the soya sector. In fact, according to the Brazilian agricultural agency Embrapa, soya production in Brazil has the highest average yield per hectare in the world, and as its production belt heads north less land-efficient and profitable activities, such as traditional cattle rearing, tend to be displaced further on to the agricultural frontier (Morton et al., 2006; Arima et al., 2011).

Capitalists coming from the soya sector—a slightly different social group than cattle ranchers—will often lease degraded pastures to implement crop-livestock production systems, thus associating their expertise in agriculture with the existing infrastructure in the lands they rent (Zanine et al., 2006). In such mixed production systems annual crops such as soya, sorghum, maize, millet, rice or sunflower, are intercalated with grass on a yearly basis, or every 2-6 years in order to balance the flow of nutrients in the soil (Zanine et al., 2006; Townsend, Costa and Pereira, 2012; Herrero et al., 2010). The advantages of these systems are plentiful: protection against market fluctuations through investment diversification, prevention of soil erosion and compaction, natural fertilization through manure and straw, amongst others.

If farmers who operate intensive production systems coexist with farmers who become increasingly unviable due to pasture degradation, the more productive ones will eventually demand (and buy up) land from the less productive farmers (Barbier, 1997). Unsuccessful farmers then face the crucial choice between intensifying and selling out.

Expanding horizontally is less of an option as probability of punishment for deforestation rises with settlement age and land titling increases, so that agents face a higher opportunity cost—thus having more to lose. If they wait for too long before selling (or renting) out they may lose the opportunity of rising land prices, as the falling stocking capacity of their pastures has a negative effect on the lot's price. Some farmers will cash out the plot and migrate to urban areas or to other parts of the country. Others will continue as cattle ranchers elsewhere. In other words, in the presence of a large enough gap in land productivity between those who effectively adopt modern agricultural technologies and those who do not, the existence of a well-functioning land market will stimulate the less successful ones to cash out their lands.

Reproduction of the frontier

The outset and evolution of frontier areas in the Amazon has interested numerous scholars since the early days of the internal colonization process. A number of explanations have been advanced, a good synthesis of which is made by Browder et al. (2008). In present-day frontier settlements, as government-induced colonization has become less and less important, 'spontaneous colonization' gained ground. New frontier settlements today result from the actions of individual pathfinders who colonize areas previously unsettled or underused: a different process from the induced type of settlement which was the norm in the beginning of the colonization of the Amazon from the 1960s to the early 1990s.

A paper by Caldas et al. (2010) studies the spark that may or may not give rise to a fully-fledged spontaneous frontier settlement. Their findings are in line with what I observed in Rondônia, where frontiers born in the last 10 years were in most cases the result of invasions of private lands, often motivated by social movements of landless people. According to the narratives of 36 farmers that I interviewed in April 2012 in 4 frontier areas, the formation of a new spontaneous settlement can be depicted in the following schematic way. The very first pioneers, normally in small groups of less than 10, cut the initial paths and brave the new settlement in areas previously abandoned or isolated. Those pathfinders parcel out the land in the same way as the public land distribution agency does, and sell them to newcomers for a relatively low price. Such sale is almost always illegal, and some newcomers seem to be aware of that, but many are either deceived to believe they are buying lands legitimately or do not care.

As newcomers start buying up plots, a flow of settlers sets forth and the word spreads that cheap lands are available in a new frontier. The settlement soon becomes self-enforcing and from that point there is little the legitimate landlord can do to prevent the settlement from continuing. Such new frontier settlements continue popping up across the Amazon (even if at a slower pace than a decade ago). In fact, since the supply of unoccupied lands is still high in the Amazon, the opening up of new frontiers can be assumed to be exogenous to existing settlements, as it only depends on the existence of farmers with a vocation for pioneering and on the level of property right enforcement in the unoccupied lands. Hence the existence at any point in time of at least one new frontier where land prices are near-zero (but rising rapidly).

Land markets link intensification to frontier migration

When settlements become dense enough that competition raises land prices, farmers who are unable to cope with the technological treadmill will look at better options in frontiers regions. For more productive farmers to take up the space of less productive ones, who then take up the remaining place at the frontier, land markets need to function well enough to allow for the reallocation process. The existence of markets capable of allocating land between laggard and elite farmers is the third and last necessary condition for a rebound effect.

Land markets in Brazil and in Amazonia are recognized as particularly imperfect, with high transaction costs due to low contract enforcement and tenure insecurity (Heath and Binswager, 1998; Buchmann, 2006). All else constant, the higher the costs to land market transactions the lower the effective opportunity costs—the best return to resources on an alternative investment—faced by agents. If transaction costs are higher than the price differential between comparable lands in consolidated vis-à-vis frontier areas, then no indirect land use effect should be observed. However, there is plenty of evidence of indirect land use effect from soya to cattle ranching in the Amazon, so to some degree land markets do reallocate and foster land use displacement.

Qualitative evidence from fieldwork in Rondônia in 2010 (Vale and Andrade, 2011) suggests that land rental markets expand as settlements evolve to transition and consolidated areas. This has to do with increased tenure security (land titling) and the presence of contract enforcing authorities (courts). If farmers can rent land instead of buying it then the cost for a landless peasant to become a farmer diminishes and land allocation becomes more efficient. Hence, provided that transaction costs are lower than price differentials with frontier regions, the fact that land markets become more efficient over time can spur competition for land and cause the displacement of marginalized farmers to new frontiers.

2.3. Conclusion

In this chapter I develop theoretical elements that have been either insufficiently covered or left aside altogether by existing theories, preventing a fuller understanding of the recent tendencies of land use intensification and reduction of deforestation in Amazonia. These are: the role of an increasingly enforced environmental legislation, the effect of a decreasing pasture stocking capacity on ranchers' decisions, the technological gap between low skilled and high skilled farmers, and the role of price differentials between consolidated (older settlements) and frontier areas (recent settlement).

The interaction between these elements is such that areas previously seen as suffering from agricultural involution may instead be going through a transition between traditional and intensive land use systems. Pasture degradation has been largely pointed out as an important constraint that is added to farmers' production functions after some years or decades of initial settlement. Because the curve of fertility loss can be steep when no preventive action is taken, areas that see a degradation process may go from boom to crisis in a very short span of time.

An intensification process can emerge if horizontal expansion of pastures is restrained. In the case of the Amazon, this has happened as a consequence of a combination of pasture degradation and enforcement of the environmental legislation. Areas where this process is set in motion are distinguishable from agricultural frontiers, as farmers are facing the key decision of intensifying or selling out. I call these 'transition areas'. As the intensification process evolves, property rights become increasingly enforced, the economic infrastructure converges to the levels of the rest of the country, and land prices rise sharply along with opportunity costs. Eventually the crisis is over and a more dynamic, consolidated rural settlement is born. In this third phase of development, deforestation is very low and agriculture is on track with the process of modernization that is seen in many parts of the country.

Cattle farmers who survive the process of competition that is inherent to the densification of rural settlements are those that manage to keep up with the technological treadmill. They concentrate in consolidated rural areas, where the occupation process has settled down. These agents tend to be more capitalized and thus have more at stake, which makes them less prone to taking the risk of punishment for not complying with the forest code. Consolidated areas also have more developed policing and enforcement infrastructures, which increases the probability of being caught when clearing land illegally. All this makes cattle ranchers in consolidated rural areas less interested in horizontal expansion than their counterparts in less advanced settlements.

This, however, does not necessarily mean that the activities of those ranchers have no impact on deforestation. Indeed, my fieldwork shows that there is a tendency for land rental markets to develop steeply in those areas, which increases the total demand for cleared land, stimulating deforestation in areas where opportunity costs, enforcement infrastructure and forest relative prices are lower: the agricultural frontier.

Farmers often take time to notice that productivity is declining, and given the high costs of pasture recovery (liming, fertilizing) the delay between the first signs of degradation and action is often long. Given some degree of social stratification after one or two decades of settlement—when pasture degradation normally becomes noticeable—a small group of successful farmers will adopt the innovative intensification strategy (early adopters, in the technological treadmill's language), while most will either be noninnovative intensifiers or overgraze their pastures. In line with the ideas presented in

Chapter 1, the latter two groups will either become rentiers or optimizing migrants, depending on land markets and the share of laggards with respect to early adopters. Those who migrate may end up in a new frontier and reignite the deforestation cycle, or they may abandon the rural areas and thus neutralize the indirect land use effect of productivity. The distinction between and measurement of these two alternative outcomes is the key to defining whether more productive cattle ranching causes more or less deforestation.

Part Two

Primary research

Cross-sectional evidence on the intensification-migration-deforestation link

This part of the thesis contains two core chapters. Chapter 3 presents and evaluates the data collection strategy and procedures. Its added value is twofold. First, it introduces new household data from four regions in one representative State of the Brazilian Amazon. The data include areas of recent (agricultural frontiers), moderately recent (transition areas) and older settlement (consolidated areas), and capture a trend of intensification of cattle ranching as settlements evolve. Second, it adds new elements to the standard data collection procedures allowing for a more efficient use of time and money in the gathering of spatially explicit survey data. It does not, however, provide a discussion of the research methods relevant for the thesis as whole, which is instead done within each relevant chapter, starting from the introduction.

Chapter 4 is a long piece containing three parts. The first is a description of the cases studied that sets the context to the subsequent analysis. The second section is the proper analysis of the the survey data, where I evaluate the theoretical elements advanced in Chapter 2 with respect to how more intensive forms of land-use relate to migration and deforestation. In the last section of Chapter 4 I outline a procedure to distinguish speculative from productive behaviour in farmers' land use decisions. I then use the survey data to test it and find that while there is evidence of a statistically significant 'speculative effect', the 'productive effect' is much more important.

Chapter 3

Data collection method: GIS without GPS[12]

Where mules were concerned, I had no choice: within a radius of thirty miles around Cuiaba there were not more than fifteen for sale.

— (Claude Lévi-Strauss, Tristes Tropiques, 1961, p. 253)

What challenges are involved in collecting primary data in a harsh environment such as the Amazon? If the question were asked about eighty years ago, the answer might have been that difficulties were close to insurmountable. When Claude Lévi-Strauss collected the first systematic ethnographic evidence on the Nambikwara tribe, back in 1938, he assembled no less than "*fifteen men, fifteen mules, and thirty oxen*" to operationalize the trip (ibidem). Committed to spending one year in the deepness of the wild bushes of Mato Grosso and today's Rondônia, he literally used all the resources available, as in the quote above. In spite of that, as soon as the adventure started, his transportation animals, one after the other, "*began to suffer great pain from the fact that saddles bit into their skins (…) These skeletal, festering beasts were my first casualties*" (ibidem). The fieldwork was eventually cut down to six months due to a generalized lack of resources.

Luckily, the toolkit available to researchers and surveyors has much evolved since then. In a book that offers a snapshot of the state of the art in household survey methodology in the early 2000s, with particular emphasis on the challenge of linking social science data to

[12] This chapter is based on fieldwork that I designed and led in partnership with Marcelo Stabile (IPAM) and Leonardo Ventura (Embrapa Porto Velho). The survey design benefited from the collaboration of Diana Weinhold (LSE), Henrique Neder and Daniel Andrade (Federal University of Uberlândia, Brazil). The research was funded by the Brazilian Ministry of Science and Technology (CNPq), the Brazilian Ministry of Education (CAPES), and IPAM. The survey also had the crucial support of the State of Rondônia's agency for cattle sanitation control (IDARON) and the secretary of environment (Sedam).

remotely sensed information, Fox et al. (2004) put together articles by contemporary social scientists that show how in the modern era of fieldwork mules, oxen, and paper have been replaced by airplanes, 4x4 vehicles, and GPS (Global Positioning System) devices. For example, the land use scientists Moran, Siqueira and Brondizio (2003) started off with a property grid and satellite images, spent large amounts of time doing computational work in the pre-field phase, trained interviewers in the use of GPS and GIS (Geographical Information Systems) technologies, and had six teams of investigators travel across the surveyed region in rented vehicles and speak to farmers by visiting their homes. In the era of internet and technology-based fieldwork, researchers are in many ways spared the operational problems faced by Lévi-Strauss back in the 1930s, even as novel and equally challenging difficulties arise.

Surprising as it may be, some technological options that nowadays seem obvious—such as letting subjects interact with a computer screen to draw maps of their properties—have not yet been put to the test on the field in scientific surveys, at least in what concerns the type of data relevant for this thesis. If taking space into account became widely accessible in science as in other domains, linking people and place still requires considerable financial and human resources, restricting the usage of a much demanded analytical kit to a small group of well-funded scholars. But being limited on the possibility of attaching spatial coordinates to survey data is highly restrictive, and increasingly so as GIS data have the potential to leverage the amount of information available to the researcher by many orders of magnitude.

In this chapter I present an approach to survey data collection that employs technology in an innovative way. The information a surveyor can collect on the ground is just a grain of sand if compared to the layers of spatially explicit data that are nowadays freely available in GIS data repositories around the world. The most common spatially referenced data that can be readily linked to a grid map are satellite images with information on land cover, water availability, carbon content and others, but there are countless other data layers such as household censuses. By having detailed spatial information on households or farms, researchers can put together an immense amount of information.

To overcome the challenge of collecting relevant spatial data with limited time and resources, my approach makes use of recent technologies and opportunities in institutional design. The main innovation in terms of technology use is to generate a property grid using farmers' visual input directly on a computer screen. To my knowledge, this is the first scientific survey to apply such procedure. One key feature of this approach is that it makes the best possible use of the detailed knowledge that farmers have of their own farm. This has important consequences for data quality. By drawing maps based on the interaction between farmers and satellite images, I let the farmer provide detailed input on the shape and location of the boundaries. Since many plots have gone through successive waves of cuts and redraws, this approach minimizes errors by capturing fine-grained detail on the boundaries. The same result could in principle be achieved by using a GPS, but it would take the farmer to walk the boundaries of the plot with the surveyor.

I study eight municipalities in the State of Rondônia, collecting data from cattle-oriented rural properties on a number of topics, including land use patterns, adoption of technologies, migration history, quality of pastures, availability of capital, land values, and attitudes towards pasture management and environmental preservation. With the assistance of 12 paid enumerators, I interviewed a total of 384 farmers in April / May 2013, generating spatial information (a property grid containing the boundaries of properties) for 95.5% of the surveyed farms (368 individual properties).

Before presenting and discussing my approach to data collection, including how I obtained GIS information without using a GPS and how I interviewed farmers without travelling to their plots, I survey the literature for the standard data collection procedures and their limitations. I then discuss the results of my survey by assessing the degree to which they approximate a random sample. I conclude by arguing that the new approach to collecting spatially explicit data in a more time and money-efficient manner was successful in many ways, is replicable in different contexts, but cannot be used in multiple waves of a longitudinal survey.

3.1. Methodological challenges - an overview of the existing literature

I start by discussing challenges to data collection in land use studies. The most common difficulty is the absence of reliable cadastral bases for the sampling procedure. The displacement of people in rural areas is normally such that in few occasions is an updated database of farmers and their locations available. A second problem, specific to the Brazilian Amazon, is that due to stronger enforcement of the environmental legislation in the recent past, farmers have grown suspicious of strangers. This leads to a potential bias in answers if trust cannot be created. Moreover, at the operational level infrastructure limitations pose difficulties to data synchronization during fieldwork and to accessing online materials.

Scholars have responded to the issues above in four ways. One option that at first may seem to be the most straightforward, requiring only limited resources, is to rely on an existing, often outdated, cadastral base. For example, Caviglia-Harris and Harris (2008) used Brazilian government's official maps from INCRA (the Federal government's agency for colonization and agrarian reform) as property grid both for sampling and spatial analysis. Yet without correction for changing boundaries, lot aggregation / disaggregation and farmers' relocation, this procedure is far from ideal. The best solution for an outdated property grid is to apply some correction procedure to account for unrecorded changes. This will normally consist of visits to the sampled farms and recording of GPS readings of the property's boundaries, such as in Lorena and Lambin (2009) and McCracken et al. (1999). Visits can be structured in different ways, but invariably require a lot of financial and human resources, as each team of researchers is normally able to make only between one and two successful in-situ interviews per day (Moran, Siqueira and Brondizio, 2004).

Alternatively, a cadastral base can be created from scratch. This is of course ideal, but implies a large operational effort and even more funds than the previous strategy, as it amounts to a mini-census of the population studied. A derivation of this strategy is to do the sampling first, based on an existing non-spatial cadastral base, then to draw the maps. One extreme example is given by Turner II and Geoghegan (2003) who describe a survey where the property grid was drawn by walking each property with the household members and taking GPS readings of the borders of each subpart of the plot. A less extreme example is that of Futemma and Brondizio (2003), who also use GPS readings to draw the property grid.

The third possibility is to estimate a property grid based on information on the spatial pattern of settlement. Here the property maps are derived from algorithms that take satellite pictures as input to estimate boundaries, then validated with farmers who are shown the resulting grid either on printed or digital format (Walsh and Welsh, 2003). For instance, Walsh et al. (2004) used algorithm-generated property grids for sampling, validated boundaries with farmers by visiting their plots and showing them paper sketch-maps of their farms, and took GPS readings for final validation. They used the farmer's visual input on the printed sketch, but with limited room for interaction as they could not zoom in/out or show / hide different layers of information as can be done on a computer screen.

The fourth group of sampling strategies is that of selecting subjects directly at some physical location where they normally gather, such as a government agency or a church. For example, Bell (2011) interviews farmers who show up at a government agency to request free technical assistance or to register for government programmes. This is a cheap and straightforward strategy, yet it carries one major drawback. Provided that the subjects who show up at the government agency where the interviews are conducted self-select to do so, the resulting sampling is fundamentally selection biased, as the probability of being sampled is determined by characteristics of the subjects.

There is no obviously superior approach to be followed, and the choice very much depends on the individual requirements of each survey. For my survey, the fact that the first three solutions described above rely on GPS readings is highly problematic. The advantage of spatial information generated by a GPS is of course precision, but there are downsides. First, visiting each single plot is highly time and money-consuming, especially with an elevated incidence of absentee farmers, which is common and worsens as rural areas become more connected with towns. Secondly, collecting GPS readings implies a high level of commitment by the farmer, which is difficult to obtain, especially in situations where there is suspicion as to strangers being agents of environmental protection services. Third, when plots have an irregular shape, GPS coordinates can be an inadequate solution.

Given the drawbacks of solutions that rely on a GPS, I used netbooks to collect spatially explicit survey data while forgoing the use of a GPS. I also took advantage of an institutional opportunity that allowed me to obtain a random sample at a much lower cost by avoiding the need to travel to the subjects' houses. In Rondônia all ranchers are legally obliged to report the vaccination of their herds to a government agency, so I interviewed them at those agencies. Farmers who do not comply have their cattle herd prevented from being physically displaced by a number of enforcement barriers spread across the State. As a result, the share of cattle farmers who failed to comply with the reporting obligation in 2010 was negligible—about 1.2% (data from IDARON). Moreover, non-compliers tend to be subsistence farmers with very small herds who trade little or no cattle—and are thus not affected by trading restrictions. Even if the sample may be slightly biased against subsistence farmers, these account for a very small share of deforestation so their absence should not significantly impact results.

With respect to the property grid, a limited budget forced me to figure out a strategy that circumvented the common procedure of in-situ interviews. The solution was to draw the maps right after the interview at the government agency, using satellite pictures and other layers of spatial information that would allow for a quick localization of the respondent's farm. One of the layers was an official cadastral map that allowed me to browse directly to the plot number reported by the farmer (in case he[13] had it). After that, I needed the respondent to look at the satellite picture (outdated by 5 years) and confirm that I had picked the correct plot (the possibility of zooming in and out as needed and showing / hiding layers was very helpful). The next step was to redraw the boundaries (with respect to the official property grid) and save the final property map.

[13] 90.8% of respondents were male, so I it is safe to use the masculine.

3.2. New roads to linking space and people

I now turn to present and discuss the details of the method I employed. I start by briefly describing the population of the study and the sampling strategy. I then go through the details of the data collection strategy, discussing the options I considered, why, and how I went on implementing the survey. The results are presented in section 3.3.

Population and sampling

The analytical units are cattle ranchers[14] and their land use decisions. I chose the State of Rondônia as a representative case of land use dynamics in the Brazilian Amazon. The State has high within-variation in forest cover (the dependent variable), with two thirds of the territory still forested, and is also a leader in cattle herd growth, with high between farm variation in cattle productivity (the independent variable).

A central topic of this study is land use dynamics in areas of agricultural frontier and how that relates to an intensification process that takes place mostly in consolidated areas, where migration and deforestation have stabilized. The theoretical approach further distinguishes transition settlement areas, where the unfolding of key social and ecological processes will define the fate of the future consolidated area, and by extension, of the yet-to-be-born frontiers. To fully capture within-variation in each of the relevant categories advanced by the theory, I adopt stratified sampling with four groups of municipalities: pre-frontier, frontier, transition and consolidated, defined on the basis of deforestation rates and extent[15]. This permits the testing of both within and between-group implications of the theory. The data collected is summarized below:

[14] 82.3% of all farmers in the State of Rondônia in 2010 (IDARON).

[15] See appendix A for the full definitions of these categories. For the demarcation in this and the following chapter, I adapt the method by Rodrigues et al. (2009) to create the groups. First, I calculate deforestation outside of protected areas. Second, I estimate a k-means clustering model with 4 clusters and two variables: municipality cumulative deforestation in 2000 and deforestation growth from 2000 to 2010. K-means is a method of clustering that partitions points into k pre-defined groups, randomly assings k centroids to the data and calculates the distance from each point to the nearest centroid. The algorithm keeps switching the centroids until the sum of squares from points to the centres of the groups is minimized.

Table 3.1. Summary of the key variables collected in the survey

Variable	Source	Observation unit	Years
Stock of cleared area: pasture, degraded pasture, fallow, crops, reforestation	Survey	Property	2000; 2005; 2010; 2013
Perceived quality of pastures	Survey	Property	2010-2013
Cattle sales (AU[1] / year)	Survey	Property	2012-2013
Cattle stocking ratio (AU[1] / ha)	Survey	Property	2013
Technology use: limestone, fertilizer, number of paddocks, artificial insemination, tractors	Survey	Property	2013
Total assets (herd, land, capital)	Survey	Property	2013
Perceived enforcement of forest law	Survey	Property	2013
Tenancy contracts (area of rented land, time of tenure)	Survey	Farmer	2013
Land price (R$ / ha)	Survey	Property	2013; 2016 (expected)
Migration history, intention to migrate	Survey	Farmer	2000-2013
Farm's boundaries	GIS	Property	2013

Note: A detailed description of each variable as collected in the survey is provided in the questionnaire (appendix B2). The resulting statistics are presented and discussed in Chapter 4, especially in tables 4.1 and 4.2.

[1]Animal Units (1 AU = 450 Kg).

Pre-frontier areas are where no colonization process took place, and social dynamics are only weakly influenced by the induced settlement logic observed elsewhere. In the pre-frontier category are both riverine communities with forest-based economies and standard Amazon economies practising agriculture and cattle ranching. The latter locations are subject to a similar institutional context as other regions, but with the crucial difference that migration and land use processes are detached from the logic that dominates the areas that have been settled since the middle 1960s. Hence pre-frontiers can work as counterfactuals to theories that express a causal role for settlement-related processes. In the case of Rondônia, there is one such pre-frontier area in the municipality of Guajará-Mirim. Because this location has only 0.5% of the State's cattle farms, it was oversampled to assure within-case variation.

For the other strata, I started by picking two municipalities (Ouro Preto and Machadinho do Oeste) that I can use for data validation by relating the results to longitudinal data available from other studies. To minimize transportation costs, I excluded 6 municipalities with three or more IDARON agencies (where the interviews were conducted). I created four geographical clusters along and across the main road of the State, and sampled 5 municipalities from those. The resulting sample includes 8 out of 52 municipalities (1 pre-frontier, 3 frontier, 2 transition and 2 consolidated), accounting for 19.2% of the total population (84,594 cattle farmers). The final sample includes 384 farmers, or 0.45% of the studied population, and can be said to be roughly representative of the State and of each one of the four categories. The map below shows the sampled municipalities and farms.

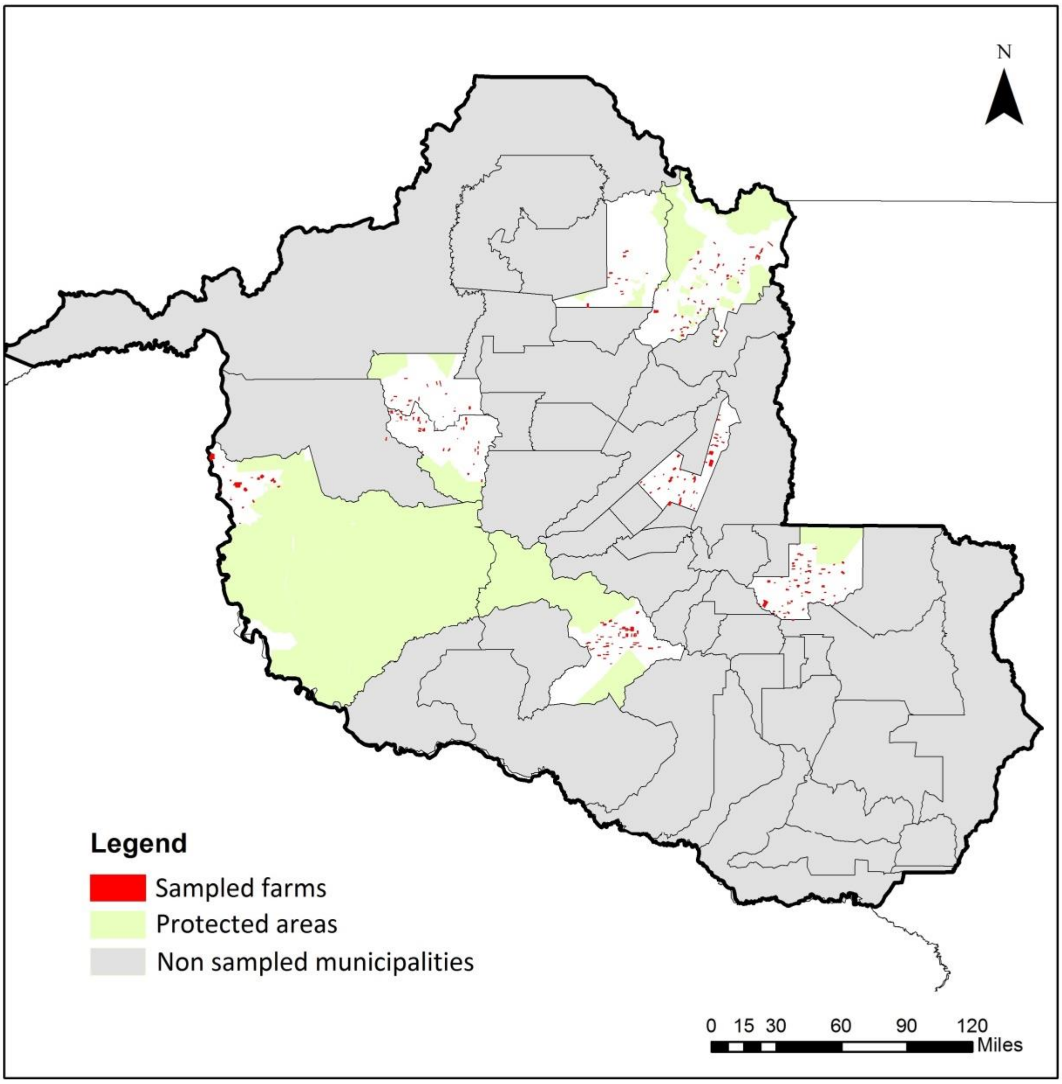

Figure 3.1. Sampled municipalities and farms. Colours: white are sampled municipalities, light green are protected areas, and red are sampled farms.

Methodological innovations and procedures

This thesis studies how the migration of farmers affects deforestation, so I randomize on households rather than plots, obtaining when applicable a limited amount of information on plots previously occupied by the respondents (see item 'I' of the questionnaire, appendix B2). I take advantage of an institutional opportunity provided by the law to simplify randomization and avoid having to travel to surveyed plots. Cattle farmers are legally bound to go to a government agency (IDARON) every year to report that they have vaccinated their herds. They may come anytime in a one-month period, and there is strong enforcement in place, so it is one of the few pieces of State legislation with very high compliance. Hence, I could obtain a random sample of farmers by sitting at the IDARON agency and interviewing subjects as they arrived. This way I avoided the problem of absentee farmers that makes random sampling procedures tricky and that can be severe with in-situ data collection.

I (and a team of surveyors) approached farmers who came to IDARON to report their herd's vaccination, excluding those who came for other reasons (see the interview protocol, appendix B3). Every IDARON report form is linked to one 'property', defined as a closed boundary spatial unit that is managed by the respondent. The property does not need to be owned by the respondent. As farmers were prepared to answer the agency's questions regarding their respective properties, I took advantage of that cognitive link and structured the survey around the so defined 'properties'. Since approximately 22% of respondents were in charge of multiple properties, for time-constraint reasons I chose to record the size of all properties but only conduct the full survey on the oldest one (see questionnaire, appendix B2).

To reduce selection bias, the randomization protocol consisted of interviewing the first farmer who stepped in immediately after the preceding interview was over. IDARON provided surveyors with a comfortable space, sometimes a dedicated room, to conduct the interviews. Probability of arrival of potential subjects depends on farm distance and other farmers' characteristics, such as management skills (planning the reporting ahead to avoid congestion). Arrivals not being completely random, there is a risk of bias if the probability of a farmer being surveyed is different from his probability of arrival. I thus allocated interviews according to prior knowledge of weekly and weekday frequencies of arrivals, and made sure to use all available hours of the day. Farmers not willing to be surveyed (41.6% of total) where asked three auxiliary questions that I use to check for non-response bias (see the 'baseline questionnaire' in the interview protocol, appendix B3).

Another important advantage of this approach is that being supported by IDARON helps to create trust. Surveys that rely on foreign or non-local surveyors, or that ask a high level of commitment from the farmer in terms of time, physically showing their farm, or answering detailed questions about sensitive issues, tend to score low in the trust requisite thus compromising answer quality. One way of creating trust is to link the research team to people or institutions that farmers know and recognize as trustful. Because IDARON is seen as an institution that supports the cattle sector and is not related to the environmental agency, it is largely recognized by farmers as trustful. To reinforce the link between the survey and IDARON I gave farmers one particular type of non-monetary incentive.

Studies on the effect of monetary and non-monetary incentives on survey response rates have consistently shown a positive effect (Mizes, Fleece and Roos, 1984; Davern et al., 2003). When the incentives are in the form of a lottery, however, it is not clear that response rates increase (Singer, 2002; Porter and Whitcomb, 2003). Studies have also pointed out that incentives may have a positive effect on response quality, even if the evidence is mixed (Hansen, 1980; Willimack et al., 1995). In all cases, incentives do not seem to cause response bias, especially those of the non-monetary type. Given the many pros and few cons, and given the problem of farmers being highly suspicious of strangers, I adopted two strategies to motivate individuals to take part in the survey.

First, I provided refreshers and cookies during the interview, which I expect to have had an effect on response completeness. Second, I offered farmers the possibility of taking part in a raffle in which two vaccination guns would be drawn among the respondents (see appendix B2 for the exact procedure I followed). Vaccination guns are essential items for every cattle rancher, and there is an important symbolism attached to them. They are at once seen as emblems of manhood and the power of ranchers over their beasts, and as a symbol of responsible cattle ranching. More importantly, vaccination guns can be said to convey a (subtle) message that goes in the opposite direction of environmental and conservationist narratives.

The drawing of vaccination guns is thus expected to have increased response quality by creating a cognitive link—thus an implicit resonance—between the survey, the sanitation agency (IDARON), and the farmers, and away from the feared environmental agency. Also, being relatively expensive items[16], they may have had a positive effect on the response rate. This, however, could also have biased the sample in favour of poorer farmers, thus counterbalancing the bias against subsistence farmers mentioned before.

I initially planned to use tablets to collect spatial data, but soon concluded that with current technology that would have been unrealistic. I needed satellite pictures with a high resolution (1 : 5,000), so either the images would be stored on the device's memory or accessed online. Neither was feasible: internet connections are unreliable, and tablets could not store 500 Gb of data. I ended up using netbooks, and I soon realized that both surveyors and farmers were far more comfortable with netbooks than tablets.

To draw property boundaries, I loaded the following data on a free access GIS software (QuantumGIS): 2008 SPOT satellite pictures, a detailed map of the road network, a cadastral map provided by the government (INCRA), and maps of protected areas. I placed the GIS section in the last part of the interview to avoid suspicion contaminating other relevant parts of the questionnaire. I would start by explaining that the research includes spatial information of properties and how the data would be used, then would ask for the respondent's consent to provide that information (see informed consent form, appendix B4). If approved, I would ask for the plot number, as this could easily direct me to the correct location through the cadastral map, and otherwise use the address and visual information to locate the farm. I would then zoom in and discuss the picture with the farmer to make sure the location was correct. I would follow the farmer's instructions to draw the boundaries and validate the final shape with him (figure 3.2).

I collected two types of sensitive information (see research ethics checklist, appendix B1). One is data on how much land farmers have cleared, how much land they own, how much cattle they own, etc. On their own, these data would not have raised privacy concerns as I did not identify the farmers, so there could be no way to link them back to

[16] R$ 185 (£49) each—approximately the value of 3 daily wages of an unskilled rural worker, or the price of the cheapest smartphone available.

the data once the interview was over. The second type of sensitive information are the georeferenced images of the farms. This is more problematic, as knowing the location of the farm I am in principle able to get back to the respondent's plot, which is often also used as a residence. For this reason, the GIS part of the dataset will remain strictly confidential and only for the use of the team that is collecting the data, which in turn is strictly for academic aims. The parts of the dataset that instead cannot be linked back to respondents may be made available to other researchers upon request.

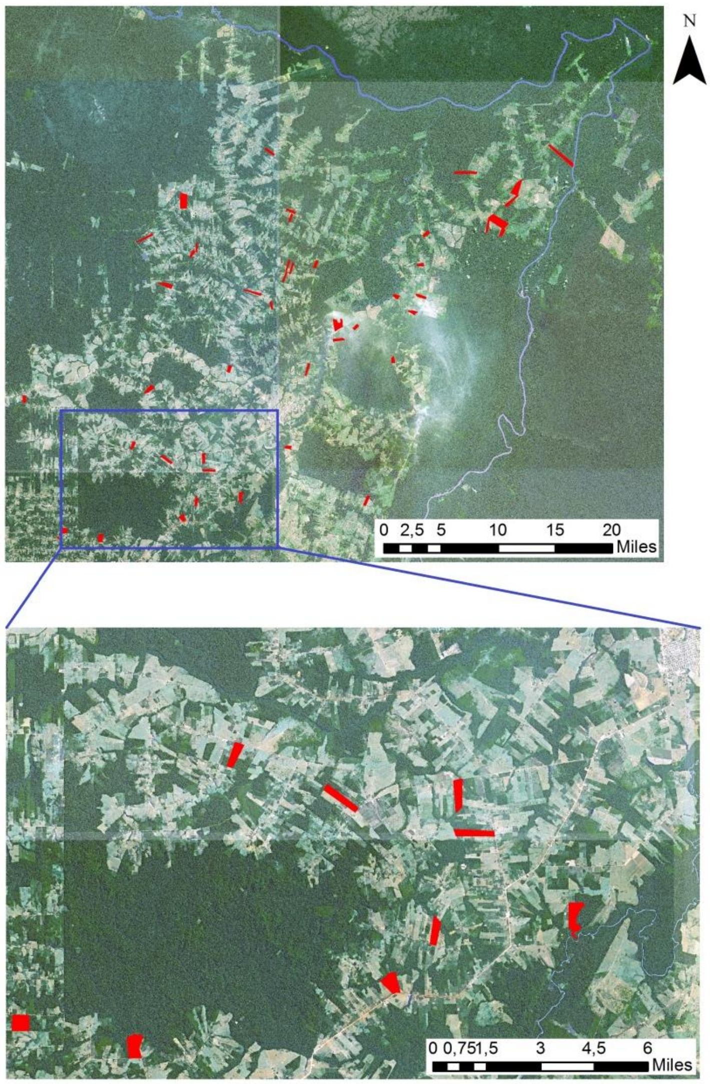

Figure 3.2. Mapped farms in one municipality in the State of Rondônia.

Source: Spot (2008) satellite pictures provided by Rondônia's Secretary of the Environment.

Lack of trust can induce response bias, so my 12 surveyors were locals. Undergraduate students were hired whenever possible, and otherwise young people with knowledge of the cattle business. I and Marcelo Stabile provided one full day's theoretical and one full day's practical training. On the first day we went through the questionnaire, the randomization procedure, the ethics protocol, and the GIS software. In the second day each surveyor interviewed real subjects under my supervision and received feedback.

Another issue I considered was whether to use paper or computers to record data. Paper would probably have made subjects feel more at ease, but that had to be weighed against the difficulty of synchronizing paper data and the consequent delay in verification and correction. Since I had one researcher verifying all the questionnaires for common mistakes, data synchronization would allow for faster correction of errors at early stages of the survey, so I opted for netbooks rather than paper. I used an online software ('survey gizmo') that allows for offline recording of data and synchronization with an online server whenever an internet connection is available. I would upload questionnaires from all surveyors and proceed with verification and correction every evening. This was instrumental in spotting common mistakes and discussing them with the team.

To match polygons (saved on a shapefile) and survey IDs (saved on a spreadsheet) I used a combination of identifiers (surveyor name, municipality, date, time, and lot size) rather than a dedicated code, thus reducing the risk of typing mistakes compromising the matching. I still could not match 9 polygons to any questionnaire, as well as 8 polygons whose questionnaires were lost due to synchronization problems.

*

The above are pragmatic solutions to the challenges presented by the standard methodological procedures. The solutions I adopted were specifically leaned towards reducing operational costs and making collection of spatial survey data more accessible. But cost reduction often entails losses in at least some important aspects of the desired outcome. In the next section I evaluate the results of the survey, assessing aspects of data quality and presenting the challenges and potential trade-offs that I faced.

3.3. Results

Two of the most common concerns in the evaluation of any survey are representativeness and non-response bias. Lack of proper randomization can invalidate generalizations and in some cases make results meaningless, while a high incidence of non-response may lead to important biases that can likewise have a negative impact on analytical outcomes. More importantly, lack of independence between drawn observations may invalidate statistical inference, so it is very important to test for random sampling. In this section I make a detailed analysis of the data collected with respect to these two key aspects, with the aim of measuring the quality of the sampling procedure.

Non-reponse

Non-response bias is an increasingly important topic in survey design as drop-out rates have increased substantially in the last decades (Särndal and Lündstrom, 2005). My survey's response rate was 58.5%, falling well within the normal range for surveys where individuals are interviewed in person[17]. To estimate the degree of bias that may be associated with drop-outs in the survey I collected three pieces of auxiliary information from non-respondents: pasture area, cattle herd size and time in the plot.

I follow Särndal and Lündstrom's (2005) procedure to estimate the impact of non-response. I compute a binary variable for the response / non-response outcome and model it as a dependent variable in a logistic model. If the auxiliary vector is a good predictor of the probability of response, then there is evidence that some degree of bias was generated by the omission of non-respondents from the sample. If the auxiliary vector is instead a poor predictor of the response outcome, then there is no evidence of bias. The table below shows the results of fitting a logistic model of the binary response / non-response outcome on the auxiliary vector.

[17] 54% for Pocewicz et al. (2008); 41% for Kamtsiuris et al. (2013); 53% for Baruch and Holtom (2008).

Table 3.2. Logit regression of response to survey on auxiliary variables
Binary dependent variable: response to survey (0 / 1)

	(1)	(2)	(3)	(4)
Cattle herd	-0.000409	5.10E-05	3.54E-05	4.76E-05
Pasture area	5.76E-05	-0.00122	-0.00116	-0.00112
Time in plot	0.00595	0.0138*	0.0133	0.0136
LR test (p-value)[1]	—	0.1473	0.173	0.195
Single municipalities	no	yes	yes	yes
Single surveyors	no	no	yes	yes
surveyors*municipalities	no	no	no	yes
Constant	0.235	0.23	-12.38***	-0.0463
Observations	620	620	620	615
Adj. Pseudo R-squared	0.00267	0.0387	0.0458	0.0513

[1]Likelihood-Ratio test: tests the joint significance of the auxiliary variables by comparing the fit of two models, one being nested within the other.

Robust z-statistics *** p<0.01, ** p<0.05, * p<0.1

The results show no correlation between the auxiliary variables and the probability of response. In column 1 the auxiliary variables show no individual statistical significance to predict the probability of a farmer responding to the survey. In column 2 I add municipality dummies as independent variables, and the coefficient for the variable time in the plot becomes significant at the 10% level, but a Likelihood-Ratio test[18] for all auxiliary variables rejects the hypothesis that their coefficients are jointly different from zero. In columns 3 and 4 I add dummies for surveyors as well as interactions between surveyors and municipalities, and the auxiliary variables remain individually as well as jointly non-significant. Therefore, even if the non-response rate was high (around 42%) non-respondents seem not to have been systematically similar to each other, so non-response can be assumed not to have biased the sampling.

Randomization

I use IDARON data on the population of cattle ranchers and farm sizes in the State of Rondônia from the year 2010 to test for selection bias. I also test for spatial randomization using the survey's property grid as well as INCRA's property grid. I start by confronting

[18] Analogous to the F-test in linear regression, compares two nested models by checking whether the extra variables in the full model significantly increase the log-likelihood statistic of the model.

the cattle herd population data with the sample data, then do the same for farm size and location. I calculate double-sided t-tests for the equality between the sampled cattle herd means and the true population means from three years earlier. I do this for both the full sample and each of the four strata. I further generate random samples from the population with equal size to the survey's samples and calculate correlations between the two. The results are below.

Table 3.3. Comparing population and sample cattle herd data, Rondônia

	Population (2010)		Survey sample (2013)			Tests		
						Bi-caudal equality test p-values[1]		
Location	Size (N)	Mean	Size (n)	Mean	Standard -error	t-test	K-S test of distributions[2]	Correlation[3]
Rondônia	84,594	117.98	384	145.03[a]	21.41	0.19	0.459	0.92
Pre-frontier	550	183.36	21	204.76	70.62	0.76	0.120	0.94
Frontier	32,523	128.56	99	126.37	21.02	0.91	0.077	0.89
Transition	24,161	104.36	144	68.79	9.57	0.00	0.246	0.88
Consolidated	27,035	114.39	120	196.55	32.16	0.01	<0.001	0.98

[1]If lower than the significance level (normally 5%) the null hypothesis—of random sampling—can be rejected.

[2]The Kolmogorov-Smirnov test is a non-parametric test of equality of continuous, one-dimensional probability distributions. The null hypothesis is that the sample distribution is a random draw from the population distribution. The test is run by calculating a distance between the sample and population cumulative probability distribution functions.

[3]Correlation between sampled observations and a random sample of the same size taken from the population.

[a] Weighted for sample selection: due to oversampling of the pre-frontier stratum, in the absence of proper weighting the overall State statistics would be biased against the other strata. When taking the State mean I account for that by multiplying observations by the following weight: $\frac{n_m}{\sum n_m} / \frac{N_m}{\sum N_m}$, where n is the sample size, N is the population size, and m is municipality. The non-weighted mean is 131 and yields the same t-test result.

The first thing to note in table 3.3 is that correlations between the sample and a random sample from the population are very high, indicating that the sample's distribution resembles that of a true random sample. Looking at averages, it can be seen for the State as a whole (upper line of the table) that the sample's mean herd size is 12% higher than the population's mean, but a t-test fails to reject the null hypothesis of sample randomness. For pre-frontier and frontier areas too it can be said that sample means are not statistically different from the population's. For transition and consolidated areas, on the other hand, the sample means are statistically different from the population means.

For the latter, this is most likely due to an important growth of the herd from 2010 to 2013, not to sampling. For transition areas, however, the result suggests that the sample is not representative. This is due to the municipality of Machadinho having particularly low herd sizes as compared to the rest of the State.

In terms of distributions, a Kolmogorov-Smirnov test for the equality of cumulative distribution functions only rejects the null hypothesis—of random sampling—for consolidated areas. For the state as a whole, the test suggests that the sampled distribution is indistinguishable from the population distribution. The figure below allows for visual inspection of the behaviour of the distributions. It confirms that the sample is a good representation of the overall distribution, but leaves doubts as to how well the pre-frontier, transition and consolidated samples, taken individually, represent their respective populations. It should be noted, however, that all t-tests for single municipalities' sample means fail to reject the hypothesis of random sampling.

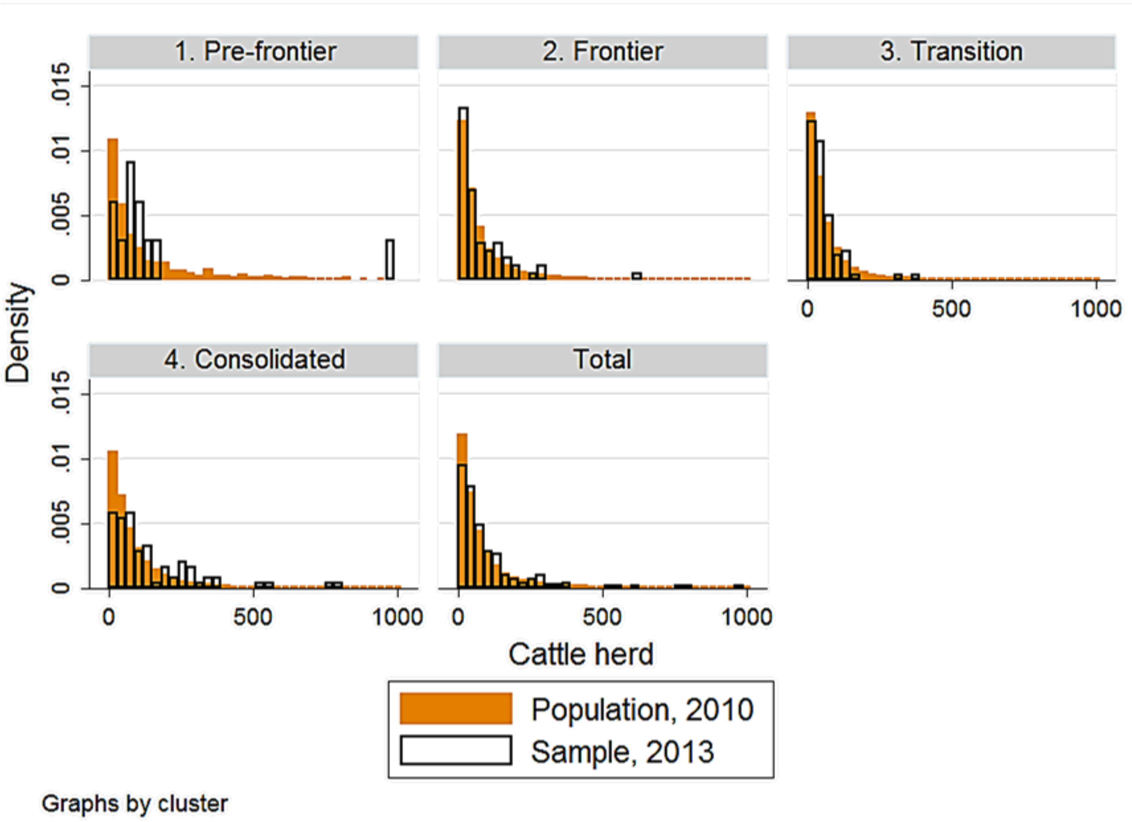

Figure 3.3. Comparing population and sample cattle herd distributions[1], Rondônia.

[1]Values higher than 1,000 are omitted from the graphs to facilitate visualization.

I further compare the sampled farm size distribution with the population's distribution. In this case, however, the population data is very noisy as the government agency that collects it (IDARON) is focused on herd sizes, not farm sizes, so I use farm size intervals to reduce error. The figure below shows that the distribution of sampled observations is again very close to the population's distribution.

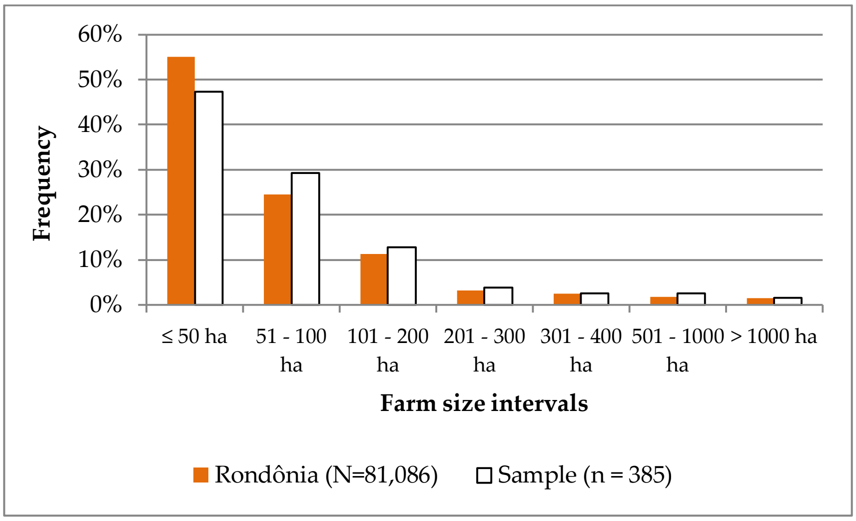

Figure 3.4. Comparing farm size data between population (year=2010) and sample (year=2013), Rondônia.

Finally, I test for spatial randomization. Taking the INCRA property grid as a proxy for the population of farm locations[19], I calculate the average number of neighbours for every plot in the population and in the sample, compute municipality averages and run tests of equality between sample and population. A spatially random sample is expected to be clustered (high number of neighbours) where the population is clustered, and disperse (low number of neighbours) where the population is spread, so I also run non-parametric tests of equality between distributions. Table 3.4 presents the results.

[19] Being outdated and including both plots with and without cattle, this property grid is only a very raw approximation of the current spatial distribution of cattle farms.

Table 3.4. Comparing population and sampled locations. Average number of neighbours (spatial clustering), Rondônia

	Population		Sample		Bi-caudal equality test p-values[2]	
Municipality	Size (*N*)	Mean[1]	Size (*n*)	Mean[1]	t-test	Kolmogorov-Smirnov test of distributions[3]
Cacoal	2,947	33.92	66	33.40	0.994	0.844
Cujubim	3,796	70.88	13	79.38	0.315	0.356
Machadinho	7,098	71.37	75	75.73	0.126	0.178
Guajará	1,770	48.20	18	37.11	0.054	0.160
Ouro Preto	2,015	12.90	41	12.02	0.111	0.054
Buritis	4,245	100.41	17	72.41	0.016	0.048
Campo Novo	1,799	51.37	35	41.17	0.029	0.028
São Miguel	3,115	54.03	57	60.54	0.027	0.009

[1]Calculated using an Euclidean distance band.

[2]If lower than the significance level (normally 5%) the null hypothesis—of random sampling—can be rejected.
[3]The Kolmogorov-Smirnov test is a non-parametric test of equality of continuous, one-dimensional probability distributions. The null hypothesis is that the sample distribution is a random draw from the population distribution. The test is run by calculating a distance between the sample and population cumulative probability distribution functions.

The average number of neighbours is sensible to the distance band, so I used two different methods—same band for all municipalities, and a different band for each (the smallest band that allocates at least one neighbour to every plot), obtaining similar results. The upper lines in the table above show municipalities where the sampling was successful in spatial randomization. In Cacoal, Cujubim and Machadinho, both the t-test the k-s test indicate random sampling. As for the other municipalities, Ouro Preto and Guajará show ambiguous results. Ouro Preto has a thin shape which increases the problem of counting neighbours on edges, but from plotting the sample on the map it is clear that the sampling was spatially random. In Guajará-Mirim the overall sample is small (25), and a few farmers did not provide spatial data, so results are probably biased indeed.

As for the three lower lines in the table, the results indicate one downside to the sampling strategy, which is the fact that it is affected by the spatial distribution of the IDARON agencies. Farmers can do their paperwork at any of the agencies across the State, no matter where their farm is located, and very often agencies are placed near municipal borders, so farmers from one municipality will visit the agency at a neighbouring municipality. This was exactly the case for Buritis, Campo Novo and São Miguel, where the sampling missed some parts of the municipalities.

In all cases, the results clearly suggest that the sampling procedure was reasonable for the State as a whole. This assures that inference can be made for the State with no presumption of selection bias. When inspected individually, some municipalities and one stratum—transition areas—display evidence of non-random selection. In the case of individual municipalities, this is not very serious as inference is not being made for single cases. Some concern must be raised, however, for transition areas, as both the stratum as a whole and its composing municipalities (Machadinho and São Miguel) have evidence of selection bias. How can this be explained and dealt with?

This result has to do with the fact that transition areas are the category that is most difficult to define, as what characterizes them is precisely a situation of change. Municipalities going through a transition from the early frontier stage to the post-frontier phase are easy to spot in real life, but not as easy to classify in a dataset. They are easy to spot because they have the atmosphere of a busting place, very much in the spirit of a hollow frontier, as defined by James Preston and subsequent authors. These are places where the difference between successful and failed farmers is the clearest, as many have remained as technological laggards and have not been able to tackle the various ecological problems that emerge as soils are used without proper fertilization.

3.4. Conclusion

Data collection in a vast area such as the Amazon where subjects are dispersed over the wilderness and transport infrastructure is poor tends to be a strenuous enterprise whatever the epoch. While modern technologies have made the task easier, spatially referenced household surveys do still demand a considerable amount of resources, making it challenging for researchers with limited funds to collect spatially explicit survey data. In this chapter I present a new method to take advantage of the facility provided by the internet and ever smaller computers to generate data on cattle ranching in the Amazon in a more time and money-efficient manner. No sampling protocol can be perfect; populational structures are seldom known in advance, and when known it is in an imperfect way as cadastral maps and bases get rapidly outdated. In this context, the strategy of randomizing by approaching farmers in a central place was a way of circumventing some of the key challenges that are faced by land use surveys. As a result, despite potential room for sampling bias in individual strata and municipalities, the sample passed all tests in what regards the overall population, so generalizations can be made based on the survey data at an acceptable risk.

Two standard data collection procedures make georeferenced surveys especially expensive and time-consuming: in-situ interviews and farmer-assisted GPS readings. Interviewing subjects in-situ implies the use of a property grid for the sampling framework, which creates the challenge of obtaining (or generating from scratch) a property grid of the whole population under study. Once the property grid is retrieved, surveyors must travel long hours to reach the sampled plots, with no guarantee that a person entitled to take the survey will be present. If the farmer is absent, surveyors will try once or twice more before sampling another farm in a different location. The procedure is tedious and resource-consuming. Secondly, obtaining a boundary map of the property by using a GPS requires farmers to be willing to give not only their time, but also to give out sensible locational information on their plots. Besides being highly time consuming, this requires a non-trivial level of commitment by the farmer.

Is all the effort worthwhile? It probably is. Generating spatially explicit survey data enables the prompt linkage between the information collected on the ground and myriad other sources of data—as long as they can be projected to a GIS coordinate system. I therefore adopt two major methodological innovations to conduct a standard household survey while also generating a detailed property grid of the surveyed farms. First, I bypass the problem of sampling from a previously existing property grid and travelling to sampled plots by taking advantage of a simple institutional opportunity. I explore the fact that all farmers raising cattle in the State of Rondônia (as in other States) are legally obliged to appear in person at a government agency (IDARON) to report the vaccination of their cattle herds, within a 30-day interval in April / May every year. Since 98.75% of farmers do comply with this particular law (according to official figures), it can be safely assumed that by and large the full population of farmers appears at IDARON sometime in a 30 days window.

It follows that a sampling procedure that randomizes on arrivals at the IDARON agency is approximately free of the gravest of all biases: self-selection. It is of course to be expected that the probability of arrival is not totally random. To account for the various factors that can influence the likelihood of a farmer showing up at IDARON at a given time, I randomize based on previously known frequency of arrivals to the IDARON agency. For example, a large share of farmers appear in the last few days of the vaccination reporting period, so a proportional frequency of interviews was allocated to that period. The result is a sample that is stratified in time, with five strata representing weeks, and randomized within weeks.

More generally, using the institutional opportunity allowed me to avoid relying on an existing property grid, which is arguably positive since official property grids are systematically outdated (I was able to confirm this by using the official property grid as an accessory tool to locate the plots on the satellite picture), as well as avoiding the costly work of travelling to each sampled plot to conduct the interview. Moreover, the fact that the survey was being supported by the government's livestock sanitation agency (IDARON) was instrumental in creating trust vis-à-vis farmers, who tend to have a positive view of that agency while being suspicious of strangers (who may be related to the environmental enforcement agency).

The second innovation consisted in drawing property maps by using the visual input given by the subjects on a computer screen. This procedure not only totally avoids the use of a GPS, but is likely to be more accurate inasmuch as the borders of the plot can be drawn in whatever irregular shape is necessary, sufficing that the farmer is able to correctly visualize the satellite picture and recognize its constitutive features (which was true in most cases). Additionally, farmers have responded to this procedure in an unexpectedly positive way. Most of them had never visualized their land from above and were keen to learn from the experience and discuss the details of their land cover and that of their neighbours. More than an amusement effect, they seemed to have become more conscious of the extent to which their activities can be monitored by others: many were shocked to learn that anyone with access to the internet can see every change they make to their land cover.

The crucial advantage of the above innovations for my research, therefore, is that they reduce financial and time costs to a manageable level. I expect that this should be true also for the work of others, as the research strategy can be easily replicated in different contexts and the institutional opportunity I used is available in other States as well as domains.

In addition to operational advantages, the approach I describe also seems to have passed the test of sample representativeness. In the results section I run randomization tests and find robust evidence in support of the random sampling hypothesis. I first look at the possibility of non-response bias. I analyse the effect of 3 key characteristics of farmers on the probability of a subject having dropped out of the survey, and find that despite the dropout rate of 42%, there is no evidence of non-response bias. I then compare the sample estimates of cattle herd and farm size to data on the full population, and find that the sample is representative of the population at the State level, even though it may be non-representative in one stratum, that of transition municipalities. Finally, I use the sampled and the official government's property grids to test for spatial randomization, and find consistent evidence of random sampling in 5 out of 8 sampled municipalities.

One drawback of the approach I describe is that it cannot be employed in different waves of a balanced panel survey, as it is based on randomly approaching subjects as they step out of a government office. If a fixed set of individuals is to be followed over time, then in the second and subsequent waves farmers must be interviewed in-situ, as it is impossible to foresee when and where they will appear to do their yearly vaccination reporting. For the first wave, however, the proposed method is an efficient way of building a random sample and creating a cadastral base that may then be used and updated in subsequent waves. Moreover, the use of a GPS can in principle be totally avoided in all waves of the survey.

In the next chapter I present the data and do the empirical analysis. The questions that derive from the discussion presented in this and the previous chapters will be far from answered in any definitive way, but the analysis does certainly contribute new evidence to the propositions that have been raised. In some aspects the exercise will be mostly descriptive, trying to look at testable propositions from different angles and reduce the scope of possible explanations, and in some fewer parts the data enables analyses that have a more important quantitative aspect. The key results are then carried over to the following chapter where I use secondary data to make a further test of the relation between intensification and deforestation.

Chapter 4

Survey data analysis

Land use intensification and deforestation

(…)
Just as outsentries,
We are fearless pioneers
Who in these whereabouts of the setting
Cry heartily: we are Brazilians!

In these frontiers, of our fatherland,
Rondônia works feverishly
(...)

Anthem of the Rondônia State (1982)
Free translation from Portuguese[20]

The excerpt from the anthem of the State of Rondônia illustrates how the quest for pioneering frontiers was an organic part of the official discourse in the 1980s. The state-led colonization narrative consisted of integrating the unexplored wilderness into the fatherland while at the same time allowing landless workers from across the country the opportunity to farm their own land and build up a State of their own. An almost incomprehensible rhetoric for those accustomed to today's dominant narrative of sustainable development—one that has been duly appropriated by most State governments to this day. Just how conflicting are the two discourses? Has the settlement process been a failure according to a notion of development that incorporates the environment? Are the "fearless pioneers" becoming forest sentries, or does their feverish work still imply mounting deforestation?

[20] Original: (...) *Como sentinelas avançadas,* | *Somos destemidos pioneiros* | *Que nestas paragens do poente* | *Gritam com força: somos Brasileiros*! | *Nestas fronteiras, de nossa pátria,* | *Rondônia trabalha febrilmente* (...)

The above are background questions whose surfaces I scratch in this chapter. By looking at land use intensification as a logical consequence of the settlement process, and by making frontier migration a function of this process, I add a new perspective to the discussion of whether the half-century old induced colonization effort was any successful. For one thing, it now seems clear that agriculture in the Amazon is not doomed to stagnation (a discussion that I address in Chapter 6), even if soils are often fragile and the removal of the forest cover implies the adoption of forms of fertility management that cannot be taken for granted. Yet a significant share of settlements show consistent signs of sustained welfare improvement, and a land use intensification process, unequal and heterogeneous as it may be, is evident in consolidated areas. At the same time, the environmental damage inflicted by the colonization effort, with the removal of up to one fifth of the forested area in the Brazilian Amazon, has been considerable and is still growing, albeit the rate has fallen dramatically.

Can the positive scenario of rising land yields also lead to the adoption of more environmentally friendly forms of land use? In this chapter and the next I employ complementary methods of analysis to scrutinize two competing explanations of the relationship between land use intensification and deforestation. The first, often referred to as the 'Borlaug hypothesis', predicts and optimistic land-sparing effect of land use intensification. Under this postulate, farmers who substitute horizontal expansion for vertical expansion would be a majority that pulls deforestation rates down, all else constant. The competing 'Boserup hypothesis' predicts that farmers who resist intensification and opt for migration to new frontiers end up causing a rise in deforestation.

The optimistic standpoint tends to prevail: most governments, funding agencies, and NGOs will (often implicitly) prefer a land-sparing assumption. The alternative view is commonly acknowledged by the land use literature and tends to be embraced by those sceptic of agricultural development in the Amazon, such as Phillip Fearnside (2004). In both cases, however, the causal mechanisms are poorly understood and the empirical evidence is scarce or inexistent. My first contribution is thus to depict the chain of causation that would lead to an undesirable rise in deforestation when land use is intensified. For this I use the survey data from Rondônia. My second contribution is to formally test the Boserup hypothesis by using municipality data, which I do in Chapter 5.

In the first main section of this chapter I discuss the key counterfactual conditional that underpins the interpretation of the cross-sectional data. I do an exhaustive contextualization of the four categories of municipalities that I study, pre-frontier, frontier, transition and consolidated, including a historical account that should help the reader to get familiarized with the broader development process in the areas where the case studies were conducted.

The second main section contains the analysis. It involves a careful process of tracing causation mechanisms by enunciating a hypothesis, establishing its likely route of causation, and inspecting the data for the presence or absence of those mechanisms. The analysis relies on inferential statistics, particularly multivariate regression, either Ordinary Least Squares (OLS) regressions or logistic models for binary outcomes. At this point a caution note is in place: rather than producing an ingenious empirical strategy to identify a key causal effect, my effort is that of extracting enough information from cross-sectional variation (using standard statistical tools) to produce a coherent account of the processes of interest. By looking at multiple intervening variables—I focus on the consequences of a rise in productivity on deforestation as intermediated by soil fertility, technological change, land markets, economic behaviour, and migration—I gain breadth at the expense of depth, at least in the narrow econometric sense of depth as causal 'identification'.

In the third and last main section I inspect the data based on the confrontation between the competing postulates of a speculative frontier and an evolving frontier. I look for evidence of the premises that support each of these conjectures: that farmers' behaviour can be explained by speculative motivations, meaning that they take decisions that maximize financial gains whatever the source, or else that their decisions are guided by productive motivations.

4.1. The context: an evolving frontier?

In studying the development of settlements in the Amazon, I examine four categories of municipalities. Three of these (frontier, transition and consolidated) are presumed to be realizations of the same process that are only separated by time and a set of observed covariates. The process in question is a massive flow of immigrants that rapidly changes the economic, social and ecological structures of these localities. Consolidated municipalities have outdated the settlement process and are now on a trajectory that some have called post-frontier (Browder et al., 2008; Pacheco, 2012). But new frontiers do exist, and the counterfactual conditional here is that once the first settlement spark is lit, the rest of the process unfolds in a similar way for today's frontiers as it did for those of yesterday.

Pre-frontier areas are where induced colonization projects have been inexistent or insignificant. Without the initial migration flow, social and economic dynamics remain similar to those that prevailed across the Amazon before the major colonization movement of the 1960s. These can be called 'forest economies' or 'extractive economies', for their reliance on the forest as a source of economic value. Pre-frontier locations are a counterfactual to the settlement process itself. The comparison between municipalities in the pre-frontier and in any other group, therefore, shows what might have happened in the absence of a colonization process.

In a Boserupian framework, land use intensification is a result of land scarcity, which in turn has both exogenous and endogenous determinants. The key exogenous determinant in the Amazon is the environmental legislation (forest code) and especially an upward shift in enforcement resulting from a growing international concern with deforestation in the Amazon. The endogenous determinants are biophysical constraints leading to soil degradation, which arises naturally as a function of settlement age and quality of soils. Using the pre-frontier counterfactual can suggest what would have happened if settlements had not been sparked, and hence if the endogenous determinants had not been lighted. Comparing frontier, transition and consolidated municipalities, on the other hand, permits the visualization of the evolution of settlements and the timing of its endogenous effects.

How appropriate is it to see different categories of municipalities as stages of a common process only separated by time (and observable characteristics)? In assuming a single dynamic path I am on the same side as the vast majority of studies on land use change in the Amazon (Moran, 1989, *apud* Castro and Singer, 2012; Celentano et al., 2012; Pacheco, 2012; Browder et al., 2008). The key reason why it is sensible to assume a counterfactual conditional for municipalities in Rondônia is that they have a similar history and a shared set of institutions, two desirable features for a counterfactual (this assumption, however, is not reasonable for all municipalities in the Legal Amazon, as I show in the next chapter).

The process of settlement in the Amazon, and in Rondônia in particular, has gone through different phases since the 1960s, when the Federal government started paving roads that connected the Amazon region to the rest of the country. From 'Operation Amazonia' to 'Poloamazonia' to 'Polonoroeste', the pattern until the late 1980s was one of displacing gigantic numbers of peasant families from the Northeast and the Centre-South of Brazil to the Amazon. Rondônia was largely colonized by Southern migrants[21]. Only in the 1990s did environmental concerns change the direction of policy in a fundamental way, halting the migration process and starting a period centred on the creation of forest reserves (Andersen et al., 2002, Ch. 2). In spite of that, spontaneous frontier settlements continued popping up in the Amazon, in most cases getting eventually sanctioned by the Federal government's colonization and agrarian reform institute (INCRA) as official settlements (Caldas et al., 2010).

Notwithstanding differences in design, size of plots, tenure regime and other fundamental factors, almost all settlements had / have agricultural production as their leitmotif (there are exceptions, as the 'Nova Samuel' settlement I discuss below). While some started with a focus on crops and others were from the start oriented towards cattle

[21] According to Census data, the Northern Region's population grew from 4.18 to 6.76 million between 1970 and 1980, 26% more than the Brazilian population growth. In Rondônia, the growth was 236% higher than the Brazilian average in the same period. From all migrants who arrived in Rondônia between 1980 and 1991, 45% came from the South, 46% from the North, and 9% from abroad or from an unknown origin (Andersen et al., 2002, p. 25).

ranching, in practice all settlements finish by converging to cattle ranching (Pacheco and Poccard-Chapuis, 2012), and the increasing use of the term 'cattelization' (*pecuarização*) attests to the generalization of this process. The switch to pastures as a major form of land use is true for a variety of contexts in the Amazon, but less so to pre-frontier areas. While settlements do exhibit variation in deforestation and land use patterns, the dynamics of the key endogenous constraints that are central to the indirect land use effect I depict are strikingly similar across settlements.

I now turn to a general description of each one of the four categories of municipalities. The aim of this contextualization is to qualify the discussion above, as well as to provide essential hard facts that will support the analyses in the following sections.

4.1.1. Pre-frontier

In areas where little or no induced colonization process took place, social dynamics remained more or less preserved from the influence of immigrants who flowed to the Amazon since the mid-1960s. Guajará-Mirim is the single municipality with such characteristics in Rondônia: according to my sample, 52% of farmers were born within Rondônia, a share 5 times higher than in the rest of the sample. With less immigration, pre-frontier areas have a higher forest cover (10 times higher than the State's average in 2010) and lower rural population density (5 times lower). Numerous protected areas have been created and more than 80% of the municipality is now state-protected, with total deforestation amounting to 5.8% of the municipality's surface as of 2012.

Guajará-Mirim is the oldest settlement in the State, dating back to the 18th Century, and the second largest municipality (24,000 Km^2, 20% larger than Wales, for example). The town was founded in 1928 and has since been subject to one settlement project ('projeto Iata'), dating back to 1945. The current pattern of land distribution is partly a result of that settlement, with the original 200 plots sized to only 25 hectares and idealized for a forest-based extractive economy (Cunha, 2011), and partly the result of a historic settlement for large rubber extraction units called *seringais*. Tremendous land concentration has pushed the average farm size to 417 ha today, higher than in the rest of the State (see table 4.1

below, which presents a summary of the results of the survey for all four strata. Note that data on pre-frontier are subject to a larger sampling error due to a smaller sample size).

Table 4.1. Descriptive statistics for 384 surveyed farmers, Rondônia (2013)

Variable	Rondônia[1]	Pre-frontier	Frontier	Transition	Consolidated
Average herd size (AU[2])	95.35	134.5	82.9	44.1***	128.4***
Farm size (ha)	189.5	417.7**	137	143.8	144.1
Cleared area within farm (% of total)[3]	0.83	0.74	0.78	0.79	0.87
Fallow area (% of total)	0.03	0.02	0.04***	0.03	0.005***
Land price (R$ / ha)[4]	R$ 5,880	R$ 1,445	R$ 3,813***	R$ 3,815***	R$ 12,290***
Yearly expected land price growth[4]	10%	13.1%	10.5%	9.78%	9.2%
Land titling[5]	49.4%	52%	15%	47.90%	79%
Gross return to labour[6]	R$ 21,561	R$ 28,297	R$ 11,992	R$ 9,998**	R$ 36,933***
Time in the plot (years)	14.9	13.7	11.9***	15.1	19.5***
Recent settlers (< 4 years in plot)	11.3%	4.8%	21.6%***	9.1%**	14.4%
Household residents	3.77	3.95	4.38***	3.48*	3.55
Years of schooling	3.46	4.48**	3.28	3.18	3.51
Skill index[7]	1.57	1.5	1.55	1.48	1.83**
Previous migrations (since 2000)	0.18	0.05	0.19	0.14	0.18
Farmers taking credit	36%	23.8%	33.3%	48.3%	30%
Farmers dwelling in town	15.6%	62%	11.1%	9.65%	15.8%
Liquid capital[8]	R$ 24,074	_	R$ 17,272	R$ 8,508***	R$ 30,485***
Distance to slaughterhouse (Km)	114.8	149	179.5***	113.8	43.5***
Incidence of pasture degradation[9]	28.2%	19%	26.3%	37.8%***	19.3%***

Note: A detailed description of each variable as collected in the survey is provided in the questionnaire (appendix B2).

[1]Weighted for sampling: due to oversampling of the pre-frontier stratum, in the absence of proper weighting the overall State statistics would be biased against the other strata. When taking the State mean I account for that by multiplying observations by the following weight: $\frac{n_m}{\Sigma n_m} / \frac{N_m}{\Sigma N_m}$, where *n* is the sample size, *N* is the population size, and *m* is municipality.

[2]Animal Units (1 AU = 450 Kg).

[3]Includes fallow.

[4]Estimated by the farmer.

[5]Full land title.

[6]Income from own's cattle ranching only.

[7]Latent variable based on two groups of measures: one that indicates knowledge of basic legislation applying to agriculture, and another based on knowledge of technological possibilities in cattle ranching.

[8]Capital available for immediate use.

[9]Includes two bottom grades in a scale of seven grades of pasture quality variation in the previous three years, where the three bottom grades indicate different degradation levels, the middle grade indicates no variation, and the three top grades indicate improvement. While farmers were asked to distinguish *degradation* from *secondary growth*, they were not asked to distinguish between different types of degradation, notably physical versus chemical. It would be challenging to provide farmers with a common definition of pasture degradation due to heterogeneous experiences and cognitive capabilities. With this in mind, degradation was simply equalled with worsening pastures. To the extent that what matters in the analysis is whether the potential output of pastures decreases, any distinction between different types of degradation was judged to imply more costs than benefits.

*** Significantly different from the rest of sample at the 1% level on a bi-caudal t-test.

Even though migration to Guajará-Mirim was the lowest in the State, cattle ranching became a dominant activity there too, with the total herd being among the largest in the State and average herd size not statistically different from what it is in consolidated areas. Cleared area as a proportion of farm size is not statistically different in pre-frontier areas than in the rest of the State, which suggests that the absence of induced settlements does not necessarily lead to more environmentally friendly outcomes. Gross returns to labour are not far from the State's average, and potentially higher, but lower than in consolidated areas. Interestingly, schooling is 35% higher than in the rest of the State, possibly due to a more urbanized population.

These results indicate that, in spite of the history of no induced settlement, pre-frontier areas do not look very different from consolidated areas in what relates to cattle ranching. This is in line with the findings of Caviglia-Harris and Sills (2005) who compared production functions of colonist and traditional *caboclos* looking for evidence of cultural determinacy, and found that socioeconomic conditions predict land use outcomes much better than cultural factors. Indeed, an intensification process is also clear in Guajará-Mirim, thwarting its use as a counterfactual to the intensification process. It can instead be used as a counterfactual to the colonization effort, indicating that even where there was no or little induced colonization there have been similar land use dynamics. The difference is that at the pre-frontier, intensification seems to be associated with far less out-migration than in other areas. This in turn indicates that the absence of induced colonization may be associated with a more sedentary pattern of land use.

4.1.2. Frontier areas

The pattern of frontier settlement in the Amazon has changed from interregional to intraregional migration. As the Federal government shifted its colonization policy out of induced settlement and onto the analysis and sanctioning of autonomous claims of land possession, social movements have emerged to promote *direct action for land reform* (Perz et al., 2010). Since the early 1990s, spontaneous colonization followed by legitimation by the government is the principal driver of new frontier settlements. Despite the end of induced colonization projects, settlements continued popping up in Rondônia during the 2000s, as shown in the map below. The concentration of black coloured areas indicates clusters of very recent deforestation activity, and the close association between recent deforestation and new settlements is confirmed in a formal analysis by Soler and Verburg (2010), who show that areas of recent colonization (between 2000 and 2006) have significantly higher deforestation activity than areas of older settlement (before 1989) in Rondônia.

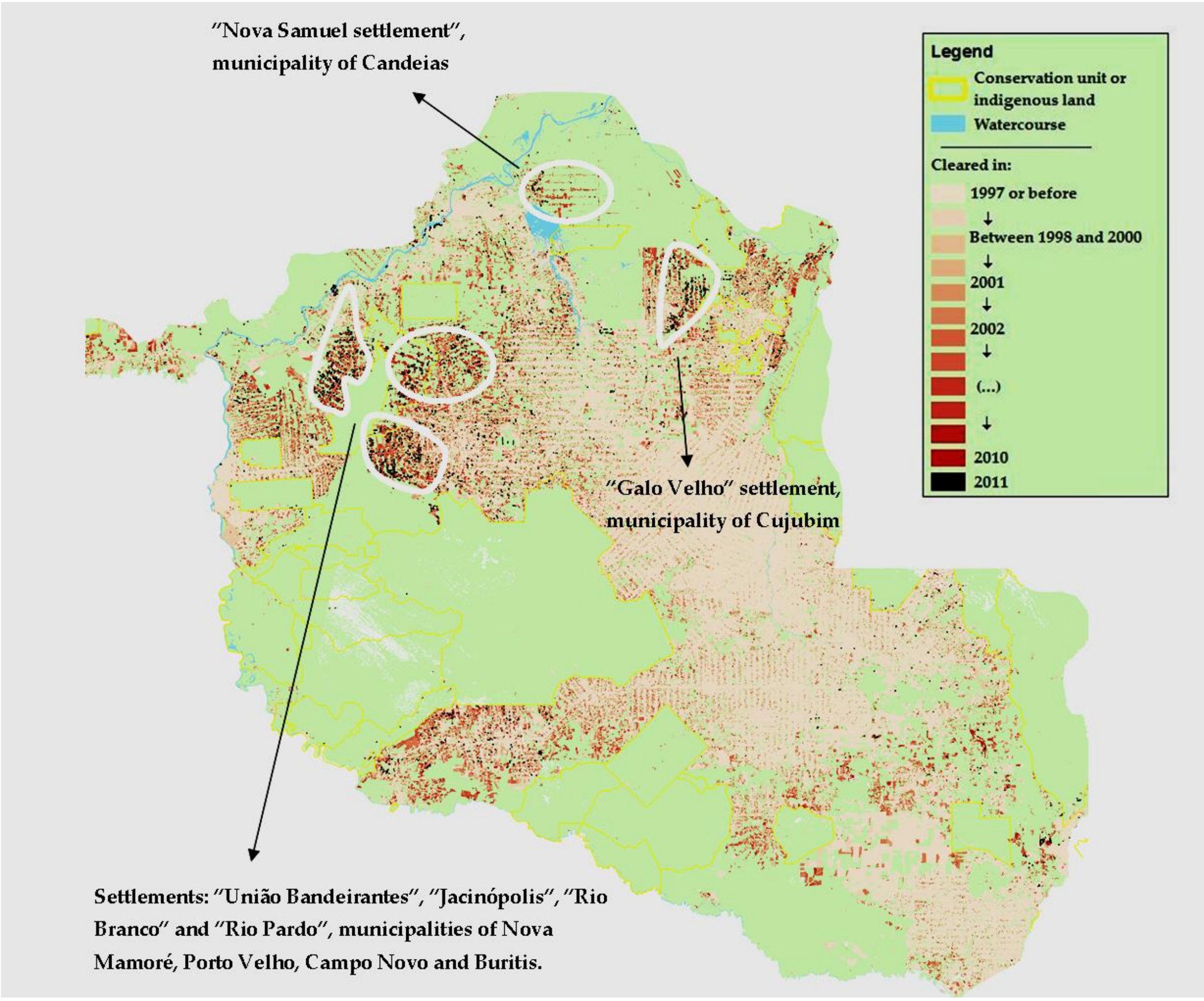

Figure 4.1. Deforestation activity in new settlements (started since 2000), Rondônia.

Source: Landsat deforestation data (INPE) and fieldwork conducted in frontier locations in April / May 2012.

A short description of three contrasting settlements in Rondônia will illustrate some of the points I make in this chapter (the data are from fieldwork I did in 2012, when I interviewed 36 settlers and 4 other informants in 6 new frontier locations in Rondônia, using convenience sampling). The União Bandeirantes settlement, on the leftmost side of figure 4.1, started approximately in the year 2000 as the result of invasions of a vast, semi-abandoned farm. One colonist who arrived two years after the initial invasion reported having hired a topographer to parcel out his plot in the exact same size as the government colonization agency (INCRA) does, 50 hectares, expecting that INCRA would have followed by granting him a land title. While all settlers aim at getting a land title, which not only secures property rights but also increases the value of land, the process is slow: it was common for settlers to be still waiting for a land title ten years after the initial occupation of the plot[22].

The settler's narrative about the obtainment of property rights was reiterated by other informants and in other locations, confirming that the colonization process has taken a regional character, whereby peasants from within the Amazon circulate in search of new lands (Perz et al., 2010). Indeed, no less than 92% of the 36 farmers I spoke to had come from within the State of Rondônia, and virtually the full sample came from within the Amazon region. The average time since arrival at the frontier was 5.4 years. Interestingly, 31% of the sampled immigrants have come from urban areas, showing that a process of urban-rural migration is present alongside the better known and more substantial rural-urban migration. This was confirmed by informants from government agencies, who argued that the bulk of frontier settlement consists of poor marginalized people coming from both rural and urban areas.

Respondents justify their migration by the need to "increase landholdings", a motivation that is prevalent in the Amazon as elsewhere. For example, Barbieri et al. (2009) study drivers of migration to a frontier area in Ecuador and find a strong negative association with farm size. Carr (2008) finds the same prevalent "increase land" motivation for the case of frontier areas in Guatemala, while Sills and Caviglia-Harris (2009) find the same for Rondônia.

Price differentials between regions of older settlement, where most migrants come from, and the frontier were the main reason mentioned by informants to explain why they

[22] It must be noted that the time when farmers needed to prove that they used the land for *agricultural production* in order to get a title are gone. Under the current legislation (a 2009 Presidential decree called *Programa Terra Legal*), there is a simplified process for farmers to establish possession and productive use, which can be the exploitation of forest products such as acai and others. If the claimed land is not disputed by other claimants (or by state protection), and the occupation took place before 2004, the title is granted.

moved. Many would speak of situations of penury that forced them to sell out their lands—sudden illness, inability to repay loans, etc. Other narratives alluded to demographic factors, whereby land became too small for a growing number of family-members and some had to out migrate. Finally, a few would explicitly mention the central hypothesis of this thesis, that land yields were decreasing and they opted for selling out and buying a larger landholding with more fertile land. A stress situation typical of this last case is that during the dry season highly degraded pastures will simply not sustain any stock, so farmers have no choice but to look for better lands.

Land prices in União Bandeirantes were reported to have risen considerably in 10 years. Open-access plots (unclaimed lands that can be freely occupied by squatters) were still available in 2003, and many of the farmers I interviewed had arrived during that period, but ever since newcomers have had to purchase plots from previous colonists, pushing land prices up to an average in 2012 that was equal to 42% of the average in Rondônia. This was of course much higher than ten years before, but still low enough for immigrants to continue arriving and buying lands, especially in the more distant areas of the frontier settlements, where prices were lower. The recent deforestation depicted in figure 4.1 is often a result of these new arrivals.

Frontier immigrants to União Bandeirantes arrived mostly from two municipalities in Rondônia, Urupá and Jaru. Migration dynamics where networks of individuals flow from one particular location to another seem to be the rule, showing the importance of social ties. This 'diaspora effect' is in line with a comprehensive review of the literature on frontier migration by Carr (2009), which confirms that rural-rural migration is highly influenced by networks of people belonging to the same community[23]. It also confirms that low education is a very good predictor of frontier migration. Moreover, it emphasizes that ecological issues—related to soil exhaustion—may play an important role on migration to new settlements. A rigorous qualitative analysis by Sartre et al. (2005) of the logics of reproduction of peasants in frontier areas in the Amazon further confirms that

[23] "[D]*iffusion of out-migration in a community, households or smaller units, to kin networks. Migrant networks act as a social structure to facilitate migration by reducing its costs—transportation, labour search, and psychological stress from leaving family and community*" (Barbieri et al., 2009, p. 296).

price differentials associated with land degradation explain at least part of the migration flow to pioneer fronts.

The rural economy in União Bandeirantes was thriving at the time of fieldwork. There was an important cluster of fruit production aimed at the urban markets in Porto Velho (the State capital), and farms with good soils had productive plantations of coffee and cocoa. A cattle ranching sector was expanding rapidly at the expense of natural fertility. The general atmosphere was one of optimism and people felt that their lives were improving, with social differentiation having been still much lower there than in more established parts of the State.

A very different frontier settlement is that of Galo Velho, the result of the violent invasion of a large farm in 2004. In 2012 it was still under legal dispute, so there was a tense atmosphere, quite the opposite of União Bandeirantes. The general feeling in Galo Velho was one of conflict, with people unwilling to trust their neighbours and having an unwelcoming approach to outsiders. No public services could be provided within the area of the settlement as the township would risk legal action for doing so, so there was also resentment towards the local authorities. There was more violence than usual. Farmers reported frequent criminal fires set off on their coffee plantations, something inexistent elsewhere. Illegal timber extraction was widespread, with evident action in the evenings when policing was less frequent, another indication that the settlement was unable to engage in the kind of productive economy that is characteristic of more developed areas. Cattle ranching was particularly low in input use.

The Nova Samuel settlement, on the upmost part of figure 4.1, was born in 2002 out of a reallocation programme for dwellers from a village that had been previously affected by a damn. Nova Samuel is an example of how local institutions—as captured in narratives of community life—can be forged and moulded when the settlement process is well organized and monitored since the start. On top of the originally relocated population, this settlement has received a flow of immigrants from other areas, with the majority arriving from the municipality of Vilhena, in the opposite end of the State.

INCRA managed the colonization process from the beginning—a situation more resembling the induced types of settlement from the 1980s—and distributed plots of 233 ha, where only 10% could be cleared, according to INCRA's own rules. INCRA made it clear that settlers not complying with the rule would be denied titling and would risk expulsion, so the dominant narrative in 2012 was in support of compliance with the rules. This is a novel situation. In spite of being suspicious of strangers, farmers are normally not afraid of saying the truth as long as their specific plot is not being asked about. In Nova Samuel, they were in agreement that forestry was the best economic option if they wanted to secure titling. This is a new scenario as normally the environmental legislation is seen as weak and not to be respected, especially in new settlements. As a result, the satellite picture in figure 4.1 shows that clearances have remained small in 2011, and since then there is no sign of a deforestation boom in Nova Samuel.

I now turn to succinctly describe the frontier municipalities covered by my 2013 survey. These include areas that have seen an intense flow of newcomers in the previous 10 years, which is reflected in the recent settlement variable (table 4.1) twice as high in frontier areas. The average time farmers spent in their plots since they first arrived is lower in frontier municipalities, but still high at almost 12 years. It can be compared to an average time in the plot of 5.4 years for the qualitative interviews I did in 2012, when I travelled to the core of the newest frontiers. This difference is due to spatial heterogeneity within frontier municipalities, where only some districts are actually new settlements, the rest being somewhat older settlements that would probably be best classified as transition areas. Since the survey randomization is based on the full municipalities, new and not so new settlements are lumped together in the frontier category. Notwithstanding that, the variable land titling, more than three times lower in the frontier category, confirms that sampled frontier municipalities are indeed areas of relatively new settlement overall.

The variable distance to slaughterhouse shows that frontiers have poorer access to markets than more developed areas, in line with a von Thünean model. This is even truer since roads leading to frontier areas tend to be of less quality than elsewhere. Even so, gross returns to labour are higher in frontier than in transition areas, while land prices are almost the same. This is a pre-condition for productively oriented farmers to consider migrating to frontier areas when faced with the need for costly investments in intensification. Another important pull factor is that frontier municipalities have a much lower incidence of pasture degradation than transition areas.

The common feature to all frontier settlements is that colonizers arrive with a view to having their own land and being able to assure subsistence to their families. Farmers I spoke to while visiting frontier areas were either landless day-labourers or small landholders who were in the edge of subsistence even as part-time off-farm workers. They recognize that infrastructure and supply of public services in frontier areas are much less attractive, but still see better perspectives in migrating—53% give "life improvement" as the reason for migration, often implying a larger landholding as the definitive evidence of an improving wellbeing.

Farmers in regions of older settlement—transition and consolidated—are reasonably knowledgeable of the existence of frontiers. I have measured that that by asking respondents how many people they knew in districts that are strictly frontier settlements. The share of respondents reporting at least one acquaintance in frontier locations was 66.6% for consolidated areas, 42.7% for transition areas and 28.6% for the pre-frontier. Since municipalities in the consolidated category are the farthest away from frontier settlements, and the pre-frontier is the geographically closest, these figures are one way to show that frontier areas are much better connected through social ties than space.

4.1.3. Transition

Transition areas are easier to spot than to define: their key feature is change. The well-known model by Emilio Moran (1989, *apud* Schneider, 1995) of stages of settlement included an initial phase of evaluation and planning, a second period of early colonization, a phase of experimentation, and a period of consolidation that would not arrive before one decade of settlement. Learning is central to this model. A group of able farmers manages to cross the bridge between the frontier and the consolidated worlds, thus expanding landholdings and achieving higher levels of productivity, while a bigger group of unsuccessful farmers lags behind and eventually out-migrates. This transitory phase is characterized by a situation of crisis, in which between 25% and 75% of farmers abandon or sell out their plots (ibidem). Yet it is precisely in these contexts of crisis that the seeds for a land use intensification process are (literally) planted, as I argue in section 4.2.

Transition areas are on an intermediary situation between thriving frontiers, where institutions and the social fabric are being constructed, and consolidated areas, where revenues are higher, markets more developed, and competition has pushed farmers to operate at a higher technological level. Transition municipalities are also on an intermediary stage of the settlement process: the average time since farmers first arrived to their plots is 15 years, compared to 19.5 in consolidated areas (table 4.1).

Machadinho do Oeste, a settlement in northeastern Rondônia whose creation dates back to a World Bank-funded project ('Polonoroeste') in the 1980s, is a transition municipality covered in my survey. After a detailed study of the area's ecology and the elaboration of an innovative settlement design that accounted for topography and hydrology, the colonization project was implemented by INCRA in 1984, distributing 2,094 plots. Since then, 5,384 more plots have been allocated, often in response to spontaneous settlements. Moreover, by 2013 there were at least another 1,903 plots whose possession was being claimed after INCRA, the majority of which by the offspring of settlers from the original Polonoroeste project (data obtained from EMATER, the main state-funded agricultural extension agency). "*From hundreds of inhabitants in the early 1980s, in 1991 Machadinho's population had increased to 16,756, and reached 22,739 in 2000* (3.5 % annual population increase, 1990s)" (Sydenstricker, 2012, p. 89).

One frequent characteristic of pasture degradation processes in the Amazon is the attack by leafhoppers (Desjardins et al., 2000). In the municipality of Machadinho, farmers have reported an average 32.9% (p-value=0.0001) of pasturelands having been affected by leafhoppers sometime in the past. This compares to 19% for the rest of the State, and 14.3% for consolidated areas. The implications of the pasture degradation process were captured by a long-term Embrapa study that has monitored land use in Machadinho since 1986 (Mangabeira, 2010): the average cattle ranching density has risen steadily from 0.57 heads per hectare in 1986 through 5 waves of data collection to 1.78 in 2005, but then fallen to 1.59 in 2008[24]. At the same time, the use of limestone for soil correction rose from 0 Kg/ha of pasture in 1986 to 0.18 in 1999, 0.59 in 2005 and 1.42 in 2008.

Farms in transition areas are going through a stark process of pasture degradation, and as people realize that the initial boom is over the social atmosphere shifts from the generalized optimism that I found in União Bandeirantes to a widespread pessimism. Competition and soil degradation force farmers to envisage land use systems other than the traditional, low-input cattle ranching. However, given the capital and labour constraints this transition is only successfully implemented by a few. As a consequence, transition municipalities don't attract nearly as many migrants as do frontiers: they have a much lower rate of recent settlement than frontiers and even consolidated areas. Transition areas have about the same average farm size as frontier and consolidated municipalities, but with a much lower cattle herd. The resulting lower cattle density, in part caused by pasture degradation, depresses revenues in transition areas and causes returns to labour to be the lowest between all groups of municipalities.

Averages, however, can be misleading when distributions are skewed. Figure 4.2 shows box plots of farm sizes, and it is clear that there is a higher frequency of larger landholdings in consolidated areas than in frontiers and transition areas, in spite of the means and medians being quite similar. Another way to look at this is to calculate the share of farms that are above the threshold of 200 ha (the upper adjacent value of the overall distribution): 5.5% in transition as opposed to 17.5% in consolidated areas. This is in line with the idea that land consolidation is parallel to the intensification process. Averages are not pushed upwards because a contemporaneous process of landholding stratification due to demographic factors takes place (Aldrich et al., 2006).

[24] More on this case and the Embrapa dataset in section 6.3.3.

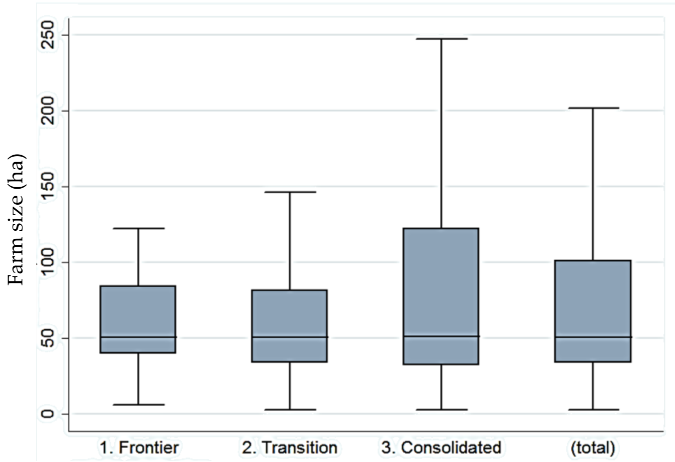

Figure 4.2. Box plots of farm sizes in frontier, transition and consolidated areas, and in the total distribution. Values falling outside the adjacent values (the brackets of lower / upper quartile +- 1.5*interquartile range) are omitted.

Land prices are apparently no higher in transition than in consolidated areas. This would be surprising since land titling is 3 times higher, which would have to cause a rise in land prices, but poorer soils in transition areas offset part of the effect of titling. Even so, the average expected yearly rise in land values is approximately the same in all regions, about 10%, so despite differences in soils and titling there seems to be an agreement on the dynamics of land markets, and a shared expectation that transition areas will eventually start growing again.

Finally, the capitalization variable indicates that farmers in transition areas stand out as having very low capital availability, with an average 50% and 27% of the level of those in frontier and consolidated areas, respectively. Transition areas also have the highest rate of farmers taking credit, with 93% of credit takers using Pronaf (compared to 47% in consolidated areas), a credit line for poor rural households that is the main channel of government subsidies to agriculture in Brazil, often with negative interest rates (Stella et al., 2013). Low capital availability and high incidence of Pronaf credit are both indicators of a situation of crisis. This, however, is not likely to be the end of the story. Just as transition municipalities were in the past very similar to today's frontier areas, with comparable processes of settlement and booms in agricultural production, they should also have the means to overcome the crisis.

4.1.4. Consolidated

Consolidated areas are where the initial phases of settlement have faded and conditions are in the process of catching up with the rest of the country. The average consolidated municipality in Rondônia had in 2010 a per capita GDP equal to 81% of the national average. From table 4.1 it can be seen that farmers in consolidated areas have much better conditions than others: higher revenues, returns to labour, land titling, capital availability, land prices, and cattle herds, with a significantly lower fallow area. Fallow area is a frequently used proxy for the stage of development of a location. Following Boserup, fallowing is how traditional forms of agriculture recover soil fertility, and as land becomes scarcer due to a growing population, peasants increasingly switch from long to short-fallow, and thence to annual and rotational cropping[25]. Looking at table 4.1 it is clear that consolidated areas in Rondônia allocate much less land to fallow, which is indicative of more intensive forms of production.

The fact that markets are better constituted in consolidated areas is clear from the variable distance to slaughterhouses. Beef (and milk to a lesser extent) processing facilities are clustered in consolidated municipalities, which means not only that transportation costs are reduced, but also that employment is generated outside the primary sector. The appearance of a network of slaughterhouses is indicative of a process of agro-industrialization that is very clear in States whose settlement began only a few decades earlier than the Amazon, such as Goiás and Mato Grosso do Sul[26]. Such a process tends to reinforce itself due to important back and forward chaining effects, as evidenced by Costa (2012) with an input-output model for the State of Pará.

> *A two-way interaction exists between the increase in processing capacity and cattle sector expansion. On the one hand, slaughterhouses are set up in areas with a relatively sizable local supply of beef cattle and, on the other hand, landholder*

[25] Pascual and Barbier (2006) make an updated discussion of these ideas.

[26] See Mueller and Martha (2008) for a detailed account of the evolution of frontier settlements in the Brazilian savannah region (*Cerrado*). See Van Wey et al. (2013) for a similar perspective on the State of Mato Grosso.

investors are attracted to areas with processing capacities already in place and a secure local demand for live cattle.

— (Pacheco and Poccard-Chapuis, 2012, p. 1376).

Recent panel data evidence based on the consolidated municipality of Ouro Preto (surveyed in this thesis) and surroundings suggests that an "agricultural life cycle" is a more appropriate explanation for the development path than boom-and-bust theories, as a trajectory of growth followed by consolidation of markets and firms is more likely than sustained economic depression. "*This result is in contrast to the boom—bust cycles that may be linked to past trends, while providing the context to explain the 'contemporary' Amazon that may be more likely to experience booms followed by consolidation*" (Hall and Caviglia-Harris, 2013, p. 349). An agricultural life cycle model is in line with Hudson's 3-phased model of colonization, settlement and competition.

Competition and consolidation is precisely what the data I present here seems to indicate.

4.2. Frontier migration as a productive response to declining land productivity

In this section I explore the data from Rondônia to scrutinize three sets of propositions regarding the role of intensification in fostering frontier migration. First, the dynamics of soil fertility that lead to pasture degradation have a function on land use outcomes that has been overlooked by the literature. Pasture degradation works as a driver of land scarcity. I make use of spatial information to recover biophysical data on soils from different sources and explore the association between soils, pasture degradation, land productivity and land prices. Second, a technological gap between highly and lowly skilled farmers interacts with soil fertility to produce increasing heterogeneity in land productivity levels. Successful farmers adopt new technologies but at the same time demand more land to expand production, raising land values for all farmers. Third, price differentials between frontier and consolidated areas widen over time, and farmers weigh this against their productivity levels in deciding whether to settle land or migrate further. Those who lag behind will be displaced when the price differential with frontiers is sufficiently high to compensate transaction and transportation costs. Marginalized farmers may also sell out and migrate to an urban centre or to another part of the country.

I start by showing that the survey data corroborates the idea that productivity of land has been rising even in cattle ranching, an activity that is typically seen as more backward that agriculture. Second, I inspect the proposed causation mechanisms and show that, where farmers behave according to productive motivations, frontier migration can be a logical consequence of an intensification process. In the subsequent section I then focus on investigating farmers' behaviour and differencing out productive from unproductive motivations.

4.2.1. Is there intensification?

Productivity of cattle ranching is a term widely used in this thesis, and it will always refer to land productivity, to the detriment of any other measure of input use efficiency (*e.g.*, productivity of capital, total factor productivity). When other productivity measures are meant they will be duly specified, notably the productivity of labour. Land productivity is calculated as a flow: *output* per unit *land* per unit *time*, with *output* being measured either in value or quantity. When measured in value, it needs correction for spatial variation in prices if it is to reflect the true underlying productivity instead of factors that influence prices, such as distance to markets. Quality of products has a negligible effect on prices as the market by and large does not price quality differentials in either beef or milk. If measured in quantity, land productivity can take two forms: a precise measure of *kilograms of beef* or *litres of milk*, or a simple count of heads of cattle. The weight measure of productivity is often reported as *Animal Units* (AU) / *hectare* (ha) / *year*, where 1 AU = 450 Kg of live mass.

Stocking and offtake rates are zootechnical concepts that I use extensively in the empirical analysis. Stocking rate, also known as cattle density, depicts the amount of cattle that is stocked in an area of land at a given time. It is measured as *stock of cattle* (either *total weight* or *number of heads*) divided by *grazing area* (*hectares of pastureland*). Offtake rate is formally defined as *animals slaughtered* over *total herd* (except suckling calves) per unit *time*. It depicts the output flow of cattle from a given stock at a time interval, and tells how long it takes for a herd to be completely passed on to the market. For example, if a given farm has 100 heads of cattle weighing 500 Kg each, and every year 20 heads are sold out for slaughter, then the offtake rate is (20*500/100*500) = 0.2. This implies that it takes 5 years for the herd to be fully replaced.

The stocking rate is inversely related to the offtake rate: for a constant nutritional supply of pastures, and in a farm operating at the maximum stocking rate, an increase in the speed at which the herd gains weight must be compensated by a proportional decrease in the size of the herd, or else overgrazing will exhaust the pasture's nutrient supply in the long run. A higher offtake therefore does not imply land sparing, unless the nutritional supply is also increased and with it the stocking rate. Typically, production systems using confinement of cattle (where feed is administered from sources other than grass) for fattening tend to display higher cattle densities, but the overall offtake will also depend on the quality of the grass that feeds the herd in the non-confinement phases. Farmers who instead rely on grass feeding will prioritize soil fertilization, pasture management and genetic improvement, and should display lower cattle densities but possibly higher offtake rates. Since the outcome of interest in this thesis is land productivity, the two zootechnical indicators must be considered in conjunction.

In all cases, it must be recognized that the measures above are often lower bounds, as argued by Knight (1971). Land productivity and stocking rate, both having *area* in the denominator, suffer from the fact that pasturelands are rarely used to feed bovine cattle only, instead most of the time being grazed by other types of bovid stock, such as sheep and buffaloes, that do not always enter the *output* measure. Moreover, the numerator may be capturing only part of the output that is generated by a given production system, for example by measuring beef sales and ignoring dairy production, or vice-versa. Hence the productivity measure tends to underestimate the true value. The offtake rate, on the other hand, suffers from the fact that the denominator, *cattle herd*, changes from year to year, and the numerator, *slaughtered cattle*, would need to be based on the herd measure from the relevant year in the past, but the denominator is normally measured in the same year as the numerator. Where cattle herd is constant over time the offtake measure is correct, but if the herd increases then the calculated rate will underestimate the true value.

The regressions in this chapter that have productivity as a dependent variable will always have production system dummies, a set of four categorical variables that indicate whether a farm specializes in milk, breeding, rearing and / or fattening, in order to account for farm-level heterogeneity. This should also deal with the problem of farmers responding to cattle cycles in different ways—strategic management of supply according to expectations of market relative prices. For example, the decision of whether to breed or slaughter a mature female—as long as farmers within a given production system category respond in approximately the same way.

The data shows how productivity of cattle ranching varies between consolidated, transition and frontier areas today. I go one step further and do time-related inferences from the cross-sectional variation. This must be done carefully. The questionnaire was designed to include memory recall questions that go back up to 3 years whenever possible, giving the survey an effective time-series component even if subject to recall bias. Moreover, studies using time-series data have concluded that there has been an intensification process in the Amazon since at least the year 2000 (Martha et al., 2012; Barretto et al., 2013; Phelps et al., 2013), so the results I present are better interpreted as further confirmation of the existing evidence than as completely new evidence.

Table 4.2. Sample estimates of cattle ranching productivity, Rondônia (2013)

Location	Sample size (n)	Productivity (R$ / ha / year)	Productivity (AU / ha / year)	Stocking rate (AU / ha)	Offtake rate (AU sold / AU)
Rondônia[1]	368	419.6 (333.1 - 506.0)	0.39 (0.29 - 0.48)	1.34 (1.16 - 1.52)	0.38 (0.28 - 0.49)
Pre-frontier	21	446.3	0.37	1.37	0.31
Frontier	98	270.8***	0.26**	1.14**	0.29
Transition	129	436.8	0.47	1.08***	0.45
Consolidated	120	601.1***	0.48	1.74***	0.44

Note: AU = Animal Unit (450 Kg).

[1]Weighted for sample selection: each observation is multiplied by the following weight: $\frac{n_m}{\Sigma n_m} / \frac{N_m}{\Sigma N_m}$, where n is the sample size, N is the population size, and m is municipality.

*** Statistically significant at 1%.

95% confidence interval in brackets.

The results in table 4.2 show a substantially positive difference between productivity in consolidated and frontier areas, with transition areas falling in between, not far from the State's average. Controlling for distance to markets does not change the results. This favours the idea that there is an intensification process in place.

Table 4.3. OLS regression of productivity (R$/ha/year) on settlement age[1]
Dependent variable: ln (productivity)

	(1)	(2)	(3)	(4)	(5)	(6)
Settlement age	**0.0620*** **	**0.0942*** **	**0.0952*** **	**0.0943*** **	**0.0626*** **	**0.0614*** **
Distance to markets (Km)	—	0.00769***	0.00758***	0.00740***	0.00460**	0.00442**
Time in plot	—	—	0.001	0.003	0.001	-0.001
Number of previous migrations (since 2000)	—	—	—	0.237	0.302*	0.376**
Highly degraded pastures	—	—	—	—	—	0.0399
Production system dummies (milk, breeding, rearing, fattening)	no	no	no	no	yes	yes
Soil aptitude[2]	no	no	no	no	yes	yes
Constant	3.424***	1.922**	1.760**	1.745**	2.571***	2.625***
Observations	*198*	*198*	*198*	*198*	*198*	*196*
R-squared	*0.060*	*0.135*	*0.152*	*0.155*	*0.320*	*0.317*
Adj. R-squared	*0.0547*	*0.126*	*0.130*	*0.129*	*0.268*	*0.260*

Notes: the aim of this regression is to show that that productivity and settlement age are positively associated, contrary to the hypothesis that newly settled areas would have higher productivity due to biophysical factors. Distance to markets, measured as distance from cattle farms to buyers (slaughterhouses and dairy industries), is a key control variable that proxies for demand-driven determinants of productivity; the coefficient in column (6) indicate that a 1 Km increase in distance is associated with a 0.44% rise in productivity (all else constant). The variable time in plot controls for learning about the local environment. Number of previous migrations controls for long term learning, and its coefficient in column (6) suggests that one more migration is associated with a 45.6% higher productivity (the maximum number of moves is 3, and the average is 0.16; this might indicate that more experienced farmers are better able to select plots with higher productivity). The variables highly degraded pastures and soil aptitude control for biophysical factors. Different production systems adopt different technologies and yield different productivity levels, and the production system dummies are means to account for this variation by attributing different intercepts to each production system. The fact that the coefficient drops from columns (1-4) to (5-6) suggests that biophysical factors (soil aptitude) and technology (production systems) may explain part of the positive association between settlement age and productivity, although the overall association remains positive and statistically significant.

[1]Measured at the municipality level, this variable indicates the number of years passed since the initial settlement.

[2]Variable based on a detailed assessment (scale 1:250.000) of soils' aptitude for agricultural uses made by the State government and the World Bank in the 1990s. Based on this, and with the GIS grid-map collected in the survey, a measure of soil aptitude is retrieved for each farm in the sample. Soils are classified as apt for two alternative uses: crops, or cattle / forest. The aptest soils can sustain agriculture while soils of medium to low aptitude are prescribed for cattle ranching and forestry.

*** p<0.01, ** p<0.05, * p<0.1

Errors adjusted for 46 clusters in surveyor / municipality

One argument that runs counter to the evidence on intensification is that recent productivity gains may have been caused by deforestation peaks from the early 2000's, up to 2004. Newly cleared areas having higher soil fertility, the increased production observed since 2004 would be an ecological artefact of natural fertility gains, not the result of a genuine intensification process (Barreto and Silva, 2013). While I do find evidence that pastures in new areas are in a better condition than in transition areas, I also find that consolidated regions have a much higher productivity and pasture quality. The variable settlement age has a significant positive association with productivity, so the data suggests that the bulk of productivity gains are attributable to consolidated rather than frontier areas (table 4.3).

Most studies use stocking rate as a proxy for productivity, as data constraints make it difficult to have a proper productivity measure. However, as table 4.2 shows, the two are different and must not be confounded. While they often do exhibit similar trends, it cannot be assumed that they always do. Land productivity equals stocking rate multiplied by offtake rate[27], and the dynamic path of the latter two can be divergent, as I show below.

Farmers in the Amazon will increase cattle densities as they capitalize and accumulate stock in the initial phases of settlement, after having cleared their parcels to the optimum level. Typically, the first main investment is land clearing, and the second is cattle stock. At a later stage, technological improvements such as the use of more efficient breeds and improved farm management will boost offtake rates. Productivity rises in both stages, but at some point the growth is checked by soil nutrient restrictions. Unable to resort to slash-and-burn to sustain nutrient inflows, traditional cattle ranching reaches a biophysical limit and causes stocking rates to fall. At this point, farmers respond by increasing offtake, which keeps productivity artificially constant for a limited amount of time. These ideas will be further developed.

While productivity is higher in transition than in frontier areas, this is associated with an increase in offtake rather than an increase in the stocking rate (table 4.2). In simple words, farmers in transition areas would be keeping stock for shorter periods in order to compensate for a lower capacity of pastures to sustain cattle densities. This, however,

[27] Land productivity [Kg sold / ha / year] = stocking rate [Kg / ha] * offtake rate [Kg sold / Kg / year]

cannot be sustained for long as soils tend to deplete quickly and recovery costs rise exponentially. While it may well be that such a combination of productivity, cattle density and offtake rate has to do with some unobserved factor, I argue that land degradation in transition areas reduces the capacity of pastures to sustain cattle and pushes farmers to sell out quicker in order to keep their income flows.

From transition to consolidated areas the pattern returns to the norm and productivity increases in parallel with stocking rates. This suggests that the average farmer in consolidated regions is successful in controlling pasture degradation and manages to increase the capacity of pastures to sustain stock while keeping offtake rates constant. This is a key finding that I will elaborate further in the next sections.

4.2.2. Explaining frontier migration

An institutional framework that fosters intensification

Forested areas have low market value in Amazonia. With the exception of big enterprises operating in the timber sector, demand for forests is low. Even under a tough environmental law, producers tend to (wrongly) believe that they are not liable for illegal deforestation that took place before they purchased the land. Consequently, a premium is paid to cleared land irrespective of its potential environmental liability. The less forested a plot, the higher its per hectare market value.

Most farmers were not able to report a figure for the price of one hectare of forest. This is because what is transacted in the market are plots with some forest, not forests on their own. I thus reformulated the question to ask for the price of a property with little forest cover—10%—and for the price of a property with a comparatively high forest cover—40%. From that I estimate that increasing forest area from 10% to 40% implies a price reduction of 26.1%, which indicates that forests have a near-zero value. The data does not capture how much a larger proportion of forest affects the price of land, but it is likely that land values will approach zero as forest cover approaches 100%, with the exception of logging enterprises as mentioned. Why?

There are two ways to explain land values. The first has to do with the potential flow of profits that can be generated by a given piece of land. According to this perspective, land value equals the sum of the income flow that the land can produce in the long term brought to present value through a discount rate. However, many argue that in Brazil, especially in the Amazon, land works as a store of value. This is the second perspective. In this case, land will be demanded not because of its potential profits, but because it can work as a form of capital gain-generating asset. In the first theory the low value of forested areas is explained by the absence of potential profitability from the standing forest. Adepts of the second theory will instead argue that forested areas are subject to invasion by squatters and thus cannot work as stores of value, and that is why forests have a low market price. While both explanations may have elements of truth, the first is the one that predominates in farmers' narratives.

Land prices rise substantially with settlement age: from pre-frontier to consolidated areas. The difference is particularly significant in consolidated areas, where the average land price is 8 times higher than in pre-frontier regions. Table 4.4 confirms that cleared area has a strong positive association with prices and that the difference between regions according to settlement age is consistent even when soils are controlled for. Moreover, land value inequality is also greatly increased with settlement age: the Gini coefficient rises from 0.27 to 0.33 to 0.39 from frontier to transition to consolidated areas. This mounting heterogeneity is one of the key ingredients in inducing marginalized farmers to out-migrate.

Land conversion from forests to agricultural uses is regulated in Brazil by a specific legislative code, the 'forest code'. The original piece of legislation dates back to 1934 and was meant to keep a minimum supply of timber within farms at a time when firewood was a key source of energy. It is a command-and-control instrument that stipulates how much of private lands can be cleared. A revision in 1996, following international pressure to conserve the Amazon, increased the mandatory rate of preservation from 50% to 80% of individual farms in most of the Legal Amazon[28]. While enforcement was close to inexistent until the first half of the 1990s and only started to increase towards the end of

[28] The rate varies spatially (from 20% to 80%) according to biome and agroecological zoning.

the decade, it became much stronger in the 2000s and is perceived as one of the reasons for the decline in the rate of deforestation since 2004.

Table 4.4. OLS regression of land values (R$) on region
Dependent variable: ln (land value)

	(1)	(2)	(3)	(4)	(5)
Region[1]					
Frontier	1.000***	0.739	0.779	0.578	1.433***
Transition	0.820***	0.610	0.659	0.356	1.628***
Consolidated	1.951***	1.544***	1.576***	1.401***	2.122***
Cleared area (%)	—	2.160***	2.126***	2.133***	1.860***
Degraded pastures	—	—	-0.119	-0.0846	-0.115
Soil aptitude[2]	no	no	no	yes	yes
Soil type[3]	no	no	no	no	yes
Constant	0.354**	-1.134**	-1.111**	-0.941*	-1.966***
Observations	*236*	*236*	*236*	*236*	*236*
R-squared	*0.411*	*0.573*	*0.577*	*0.632*	*0.751*
Adj. R-squared	*0.404*	*0.566*	*0.568*	*0.617*	*0.725*

Note: cleared area varies from 0 to 1, so in column (5) a 10% increase is associated with land values 20% higher (all else constant).

[1]Pre-frontier is the baseline category.

[2]Variable based on a detailed assessment (scale 1:250.000) of soils' aptitude for agricultural uses made by the State government and the World Bank in the 1990s. Based on this, and with the GIS grid-map collected in the survey, a measure of soil aptitude is retrieved for each farm in the sample. Soils are classified as apt for two alternative uses: crops, or cattle / forest. The aptest soils can sustain agriculture while soils of medium to low aptitude are prescribed for cattle ranching and forestry.

[3]Retrieved from Embrapa detailed soil maps.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Errors adjusted for 47 clusters in surveyor / municipality.

After almost two decades of constant alterations in the institutional framework and changes in the enforcement mechanism, the law is now fully acknowledged by farmers. One contribution of this study is to measure the perceived strength of forest code enforcement. Farmers were asked whether they expect to be approached by enforcement agents and fined if they were to conduct a new clearing on their plot. The results are clear in that enforcement is the lowest in frontier areas (68%, p-value = 0.005) and higher in transition (74%, p-value = 0.84) and consolidated areas (76%, p-value = 0.33), as expected[29],

[29] Transition and consolidated areas are not statistically different from the State as a whole, but are statistically different from frontiers: p-values 0.045 and 0.021, respectively.

suggesting that deforestation in frontier areas should be higher than elsewhere, all else constant. Pre-frontier areas have been identified as conservation priorities since the 1990s because the opportunity cost of land was very low, so they have the highest perceived forest code enforcement (88%). Moreover, qualitative data raised in the survey shows that the Federal and State environmental agencies are much present in the narratives of farmers.

With a restrictive deforestation allowance—20% of private land surface for the average farm, although the parameter does vary spatially—and high perceived enforcement, the forest code institutional framework is a key deterrent of horizontal agricultural expansion in the Amazon. If farmers cannot expand production in existing lands with a given technology, they are forced to choose between intensification and new clearings. Farmers weigh potential gains against potential losses to decide whether to clear. In frontier areas farmers have few assets and not very much to lose—land titling is scarce and land values are low. So horizontal expansion is a lot more likely at the frontier than in more advanced settlements where enforcement is stronger and farmers have more to lose. This partly explains why intensification is more prevalent in consolidated areas.

Biophysical constraints: soil fertility loss as land scarcity

To explore the role of biophysical constraints on the intensification process I use a detailed assessment (scale 1:250.000) of soils' aptitude for agricultural uses made by the State government and the World Bank in the 1990s. With the GIS grid-map collected in the survey I retrieve a measure of soil aptitude for each farm in the sample. Soils are classified as apt for two alternative uses: crops, or cattle / forest. The aptest soils can sustain agriculture while soils of medium to low aptitude are prescribed for cattle ranching and forestry. The figure below shows the expected value of productivity given six agricultural aptitude categories, controlling for distance to markets. In frontier regions there is relatively little variation, with the difference between the lowest and the highest amounting to 0.23 of a standard-deviation, and productivity of cattle is highest in soils categorized as apt for agriculture. In transition areas there is much higher dispersion, with 0.86 of one standard-deviation gap between the lowest and the highest, while in consolidated regions the gap shrinks to 0.31 of one standard-deviation.

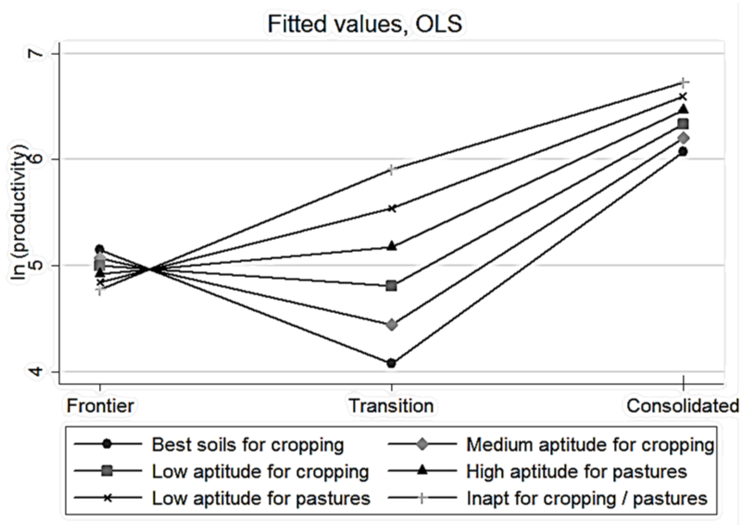

Figure 4.3. Productivity levels (R$/ha/year) according to region and soil aptitude, controlling for distance to markets.

In transition and consolidated areas the pattern is inverted, with the highest productivity being associated with lands deemed as inapt for agriculture / apt only for cattle ranching. This shows that cattle is indeed being allocated to areas that have lower potential for agriculture and that it is being more productive where soils are poorer. Additionally, the fact that the best soils for cropping have the highest yields for cattle ranching in frontier locations but then the pattern is inverted in transition and consolidated areas could be evidence that farmers learn about local ecological conditions after a few years, as argued by Moran (1989, *apud* Castro and Singer, 2012).

The fact that heterogeneity in productivity increases in transition areas with respect to frontiers is central to understanding the dynamics of land use in the Amazon. In the first years of settlement there is a rapid process of forest clearance, with low-input agriculture being practised along with traditional cattle ranching. At a certain point a process of pasture degradation breaks out. This is clear from the measure of how farmers perceive the change in the quality of their pastures in the previous 3 years. Figure 4.4 shows confidence intervals for the probability density functions of the variable 'perceived change in pasture quality in the last 3 years' as estimated from kernel densities[30]. Although most of the curves overlap, the parts that do not overlap suggest *possible* statistically significant differences in the prevalence of pasture quality levels.

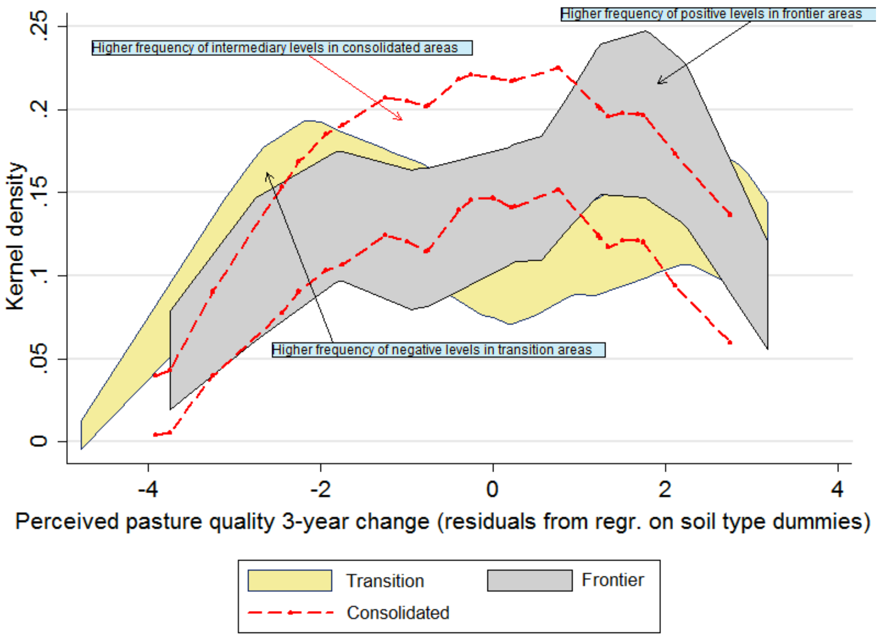

Figure 4.4. Kernel densities (upper and lower boundaries of a 95% confidence interval) of perceived change in pasture quality in the previous 3 years, controlling for soil quality.

The blue area shows frontier areas, where there are two peaks, the highest in positive values, indicating that most farmers have seen an improvement in the quality of their pastures, and a second one in negative values, indicating a deterioration of pasture quality. The yellow area shows transitions locations, where the pattern from frontiers is inverted: the first peak is now on the negative side and the second one on the pasture improvement side.

The frontier curve shows a situation where improving pastures dominate. This is the key reason for rural dwellers to migrate to frontier areas. The transition curve instead suggests

[30] A data smoothing method that allows for visualization of the distribution without the bins of a histogram. Uses a non-parametric method to estimate the probability distribution function of the population based on sample observations.

an inverted pattern where deteriorating pastures are more frequent. This in turn is a driver of out-migration. The curve for consolidated areas looks closer to a normal centred slightly above zero, suggesting that most farmers perceive their pastures either as slightly deteriorating, stable, or as slightly improving. Since soil quality is controlled for in these data, the particular shape of transition areas must be due to the quality of grazing and to pasture age. This suggests a degradation process that is at its highest at the transition phase, and that shrinks as time passes, leading to a more stable situation where there is no polarization but a dominant group of farmers who are seeing slow improvement.

Degradation curves tend to be steep. Because there is a time gap between the first signs of degradation and the farmer's cognition of them, it is often the case that when the rancher becomes aware of the need to act, action is urgent (Townsend, Costa and Pereira, 2012). The occupation of different lots in a given settlement area starts more or less at the same time, so pasture degradation typically presents itself in a somewhat synchronic fashion, with the majority of farmers becoming aware of the need for action at roughly the same time. That is what I call the transition phase. Farmers in transition areas are much more likely to report a process of pasture degradation than farmers anywhere else, even when soil aptitude is controlled for. The exact opposite is true of farmers in consolidated areas (table 4.5).

Table 4.5. Incidence of highly degraded pastures by region, controlling for soil aptitude, Rondônia (2013)

Region	Highly degraded pastures[1]
Pre-frontier	22%***
Frontier	25%***
Transition	44%***
Consolidated	19%***

Note: sample includes 384 farms.

[1]Fitted probabilities of a binary logistic model of degraded pastures on region, controlling for soil aptitude.

*** Coefficients statistically significant at 1%.

The general pattern that emerges here is that farmers in frontier areas are confronted with a benign context in terms of natural fertility that generates a fairly homogeneous distribution of cattle productivity. In transition areas the situation is shattered by a process of pasture degradation that catches most farmers unprepared[31]. The fact that in poorer soils farmers are better able to halt the degradation process tells something about the building up of capabilities to cope with environmental change. Moreover, the fact that heterogeneity in terms of productivity is much increased in transition areas indicates that learning is unequally distributed. However, consolidated areas see a sharp increase in productivity, which suggests that a group of farmers is successful in intensifying.

Intensification impacts deforestation in two ways. First, there is a direct land-saving effect. Vertical production increasing saves land. Second, there is a less obvious effect that has to do with the polarization between improving and degrading pastures discussed above. In the transition phase, those elite ranchers who manage to have improving pasturelands will be more profitable and consolidate their landholdings by buying up the land from the less productive farmers[32]. Laggard farmers who sell or rent out their degraded lands may end up migrating to frontier areas and reigniting the deforestation cycle by clearing new, non-degraded lands. This is indeed the case in some instances. It is a rational decision for a family of peasants to sell out their lands at a high price in a transition region and to migrate to the frontier, where they can buy land that is more fertile and cheaper. Out-migration is a rational alternative to intensification.

The cattle ranching technological treadmill[33]

Cattle ranching technologies can be divided into four groups: macro-management of farm (choice of grazing system and its parameters), genetic improvement, animal feed, and

[31] In a sample of 378 farmers, 106 reported badly degrading pastures in the previous three years. Yet when asked what action they intended to take, 11.3% said they would do nothing. In transition areas, 18.5% of those with badly degraded pastures were not going to act.
[32] I calculate inequality indexes for the variable 'change in pasture quality' and find that in frontier areas the Gini / Theil index is 0.32 / 0.22, while in transition areas it is 0.40 / 0.38, and in consolidated areas 0.38 / 0.18. This again shows that the transition phase sees an increase in heterogeneity of pasture quality, with the consolidated phase seeing the opposite movement. The same happens to the size of landholdings—increased homogeneity at the consolidated phase.
[33] The technical information in the subsection was obtained from semi-structured interviews with cattle ranchers and other informants in April / May 2011. The results came out in Portuguese (Vale and Andrade, 2011).

fertility management. Grazing systems are either continuous or rotational, with the latter including pasture subdivisions (paddocks) for herd rotation. Labour requirements grow more than proportionately with the number of paddocks, and the extreme case of rotation is the *Voisin* system, where grass size is kept within a range that maximizes its productivity. Cutting the farm into paddocks represents a significant fixed cost as it requires a lot of fence building.

Small settlers in frontier areas will normally start from continuous grazing systems that require no subdivision and thus minimize labour and capital costs, allocating the initial capital to stock instead. Only in subsequent phases do farmers find it rewarding to invest in subdivisions, when adding more stock to the continuous system yields lower returns than upgrading the management system with a fixed herd. Besides being more capital and labour-intensive, rotational systems are of course more productive but also more resilient to pasture degradation as each subdivision becomes an independent unit whose fertility is dedicatedly administered by the farmer.

Genetic improvement is aimed at increasing the efficiency with which cattle turn feed into weight / milk. In the case of breeding systems it is implemented by artificial insemination or by mating cows with bulls of high breed. The former is a rather cheap and easy to implement option that can generate fast productivity gains, but more efficient animals are also a lot more requiring in terms of feed and sanitation care, so genetic improvement cannot be implemented on its own. Given the relative abundance of land, animal feed in Brazil is in most cases almost entirely reliant on forage. More intensive systems, however, especially when specialized in fattening, will supplement feed in order to get a faster animal termination. This is done either by using industrialized supplements or by home-grown crops (typically sugar-cane, corn or sorghum) that are hayed / ensiled for feed.

Fertility management is the quintessential feature of land use intensification. Traditional livestock systems in Brazil used to rely on slash-and-burn to replenish soil fertility, a rational and efficient system when labour is constrained and land is not, but not otherwise. As land becomes increasingly scarce due to the environmental law and to fertility loss, more intensive systems of land use become necessary. Intensive systems need to implement a combination of liming and fertilizing to manage soil chemistry, with smaller farms tending to use some type of agroecological system where biological processes are preponderant, and bigger farms recurring more often to chemical inputs.

I report proxies for three categories of cattle ranching technologies: number of paddocks is the indicator of macro-management, number of inseminated cows proxies for genetic improvement, and limed area and hours of tractor use account for fertility management. All technologies display the expected behaviour: lower values in frontier and higher in consolidated areas. The pre-frontier category sometimes shows unexpectedly higher technological intake than other locations, and this may be due to: much larger average property size; higher settlement age; or small sample. The data on technology in pre-frontiers, however, is not central to the argument. Interestingly, limed pastures and inseminated cows have higher values in transition than in consolidated areas. This is consistent with the finding that offtake rates are higher in transition areas—investment in genetic improvement is the most accessible way to increase offtake. Farmers faced with degrading pastures make the best use of capital by investing in genetics to increase offtake and stabilize income flows, but this cannot be sustained for long if fertility loss is not curbed. Hence the significantly higher incidence of limed pastures:

Table 4.6. Use of cattle ranching technologies by region

Location	Paddocks[1]	Inseminated cows (%)	Tractor hours[2]	Limed pastures (%)
Rondônia[3]	19.51	3.59	21.68	2.74
Pre-frontier	23.97	4.74	30.89	0.48
Frontier	11.06**	1.93	12.22	0.52**
Transition	22.21	5.19	24.97	6.97***
Consolidated	31.18*	3.08	26.80	3.29
Obs. (n)	369	341	375	385

[1]per 100 ha.

[2]per 100 ha / year

[3]Weighted for sample selection: each observation is multiplied by the following weight: $\frac{n_m}{\sum n_m} / \frac{N_m}{\sum N_m}$, where n is the sample size, N is the population size, and m is municipality.

*** Statistically significant at 1%.

I use principal component analysis[34] to create three synthetic indicators of technology based on six variables (those on table 4.6 plus high breed bulls and use of fertilizers). The resulting indicators account for 71.4% of the variation in the data. Using the first synthetic indicator only, which accounts for one third of the overall variation in technology, it is easy to see that the technological gap widens strongly in the transition phase (figure 4.5). This is in line with the idea of increased heterogeneity in terms of pasture degradation and productivity. A wider technological gap means that farmers who are unable to cope with biophysical constraints coexist with farmers who are capitalized and able to embark on an intensification process. In consolidated areas the gap narrows but remains wider than in frontier areas. This pattern is similar for the other two synthetic indicators.

Each indicator is closely associated with one component of productivity, stocking and offtake rate. The synthetic indexes can thus be said to represent technological packages that are employed by farmers to increase either offtake or stocking rate: density and offtake-enhancing technologies. I find that only density-enhancing technologies have an association with overall land productivity, and the effect—if only weakly significant—is ambiguous as the coefficient becomes negative when productivity is measured in values (appendix C1).

Now that the essential technical background is introduced, I can concentrate on the relation between technological packages and productivity. The first noteworthy observation is that there is an important variation according to the type of productive system. There are three main types of productive systems: milk, dual purpose, and beef, with subtypes according to whether beef producers specialize on breeding, rearing or fattening. Each productive system requires a particular combination of technologies. Where farms specialize on milk, inseminated cows and use of tractor are positively associated with productivity, and where farms are transitioning to beef production, use of tractor is positively associated with productivity (controlling for distance to markets).

[34] Linear combination of data to reduce the number of dimensions while maximizing variance: *When large multivariate datasets are analysed, it is often desirable to reduce their dimensionality. Principal component analysis is one technique for doing this. It replaces the* p *original variables by a smaller number,* q, *of derived variables, the principal components, which are linear combinations of the original variables. Often, it is possible to retain most of the variability in the original variables with q very much smaller than* p (Joliffe, 2005, p. 1).

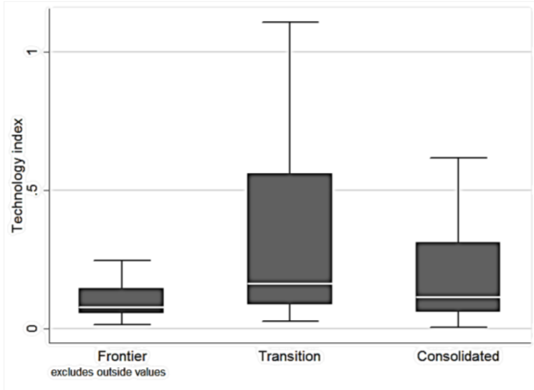

Figure 4.5. Box plots of technological index*.

* First unrotated principal component of the variables: paddocks / 100 ha; inseminated cows (%) / year; tractor hours / 100 ha / year; limed pasture (%) / year; fertilized pasture (%) / year; high breed bulls (%).

Secondly, adoption of technologies is a direct function of changes in biophysical conditions. Where soil aptitude is lower, technologies have a greater impact on productivity. In particular, I find that number of paddocks and liming are positively associated with productivity where soils are of medium to low quality, precisely where cattle ranching tends to be more productive. Paddocks have an especially strong association with productivity where soils are categorized as of low quality and apt only for cattle ranching or reforestation, suggesting that rotational systems are an effective way of dealing with soil deficiencies.

Investment in pasture recovery normally follows the realization that pastures are degrading and that livestock production will not be sustained in the long term if fertility is not replenished. It is thus an investment aimed at the long run and typically undertaken by productive farmers (rather than speculative ones). I asked farmers how much they have been investing in pasture recovery in the previous 12 months, and the resulting variable is significantly associated with density-enhancing technologies (table 4.7). This suggests that stocking rate is the main vector by which farmers increase sustainability and resilience to biophysical constraints.

Offtake technologies are much cheaper than density technologies. For example, liming one hectare of pasture costs US$ 400 while inseminating three cows costs US$ 75. Indeed, adoption of density technologies is positively associated with capital availability, but adoption of offtake technologies is not. Adoption of density technologies is also associated with lower levels of pasture degradation, and it is much more prevalent in transition than in frontier areas (table 4.8). Farmers who are not capitalized, whose pastures are highly degraded and who are in transition areas may underinvest in density technologies and see a process of declining productivity. Underinvesting in density technologies, however, is likely to lead to decreasing returns to labour, for pasture degradation reduces output when pasture size is given. When faced with decreasing returns to labour, farmers may start looking for opportunities to sell out and migrate to a frontier where they can buy a bigger plot with better fertility conditions.

Table 4.7. OLS regression of investment in pasture recovery on technology indexes

Dependent variable: ln (investment in pasture recovery)

Technology index	
Density technologies	0.223***
Offtake technologies	-0.426
Offtake technologies 2	0.0342
Constant	-1.461**
Observations	131
R-squared	0.065
Adj. R-squared	0.0426

*** p<0.01, ** p<0.05, * p<0.1

Errors adjusted for 45 clusters in surveyor / municipality

Table 4.8. OLS regression of density technologies index on capital availability. Dependent variable: ln (adoption of density technologies)

	(1)	(2)
Capital / ha	0.282***	0.303***
Region[1]		
Transition	0.779***	0.710**
Consolidated	0.340	0.255
Pasture quality	0.164**	0.190***
Productive system dummies	no	yes
Constant	-1.014***	-0.821
Observations	95	95
R-squared	0.220	0.293
Adj. R-squared	0.185	0.227

[1]Frontier is the baseline category.

*** p<0.01, ** p<0.05, * p<0.1; Robust standard-errors.

In sum, technological trajectories are associated with productivity outcomes according to particular systems of livestock production, soil aptitude categories and the degree to which pastures are degraded. Farmers who become technological leaders are those who in the critical phase when biophysical constraints push them to invest or leave are able to transition from a traditional to a more intensive system of cattle ranching. Those who are unable will become technological laggards and eventually sell out and leave. This is the technological treadmill. Land markets are the key mechanism through which farmers can weigh the benefits of selling out and migrating further into the frontier against the benefits of staying.

Land markets and competition spur frontier migration

Land markets are the essential factor linking frontiers to areas of older settlement, and the evidence confirms that markets are better established in transition than in frontier areas. I calculate the amount of leased in and out land for each farmer as a percentage of their pastureland, and find a significant increase from pre-frontier to frontier areas, and between frontier and transition areas, but no significant difference between frontiers and consolidated areas controlling for land values, land titling and others (appendix C2). This shows that land markets do deepen as frontiers evolve, particularly in transition areas, in line with the indirect land use effect model.

If laggard farmers decide between out-migrating and intensifying, they do so based on potential costs and benefits. The benefit of migrating to a frontier is a direct function of the price differential between local and frontier lands. The higher the price gap, the larger the plot that can be bought at the frontier as compared to the existing plot. Provided that at any given time there is at least one new settlement where lands can be bought at near-zero cost, the essential variable to be monitored are local land prices. These will guide the decision as to the optimal time to sell out.

There is some evidence that in transition and consolidated areas land prices rise when productivity of neighbours rise. I apply a standard spatial weights matrix based on Euclidean distance (see equations 5.2 and 5.3 in Chapter 5 for more details) to the survey grid-map to estimate the average productivity of neighbours within each municipality.

Controlling for distance to markets, cleared area, soil aptitude and productivity, increasing the average productivity of neighbours from the first to the ninth decile (R$ 171 to R$ 849/ha/year) is associated with an increase in the (level of) pasture price of one twelfth of a standard-deviation (R$ 750/ha) (appendix C3). If the productivity of neighbours affects land prices in non-frontier areas, then laggard farmers benefit from an intensification process. The emergence of a class of elite farmers would thus accelerate the process that leads some marginalized farmers to out-migrate.

Another factor that precipitates farmers to consider migrating is degradation of pastures. The continued use of degrading pastures implies a falling output. Farmers with degrading pastures who have limited resources to invest in countering the process start monitoring the evolution of land prices in order to liquidate their decreasingly productive lands. Ranchers facing economic stress due to highly degraded pastures are on average 54.5% less capitalized than others (p-value=0.015). If farmers are small (area<50 ha)[35], the percentage goes up to 63.8% (p-value=0.049), whereas for bigger farmers (area>=50 ha) pasture degradation is not associated with less capitalization (p-value=0.25). It is unclear whether farmers are less capitalized because their pastures are highly degraded or the other way around, but irrespective of the causation pattern it can be said that less capitalized farmers are less able to cope with situations of stress, and the smallest ranchers are even more vulnerable.

In sum, the role of land markets on intermediating the relation between intensification and migration boils down to the following. Land prices are strongly influenced by productivity. A one standard-deviation increase in productivity is associated with a 7.3% increase in the price of pastureland (table 4.9). The same proportional increase in the productivity level of the farm's neighbours implies a higher 19.7% pastureland price. Highly degraded pastures, on the other hand, are associated with a 19.8% lower pastureland price. Hence, a farmer with degraded pastures and falling productivity will see his pastureland price decline; if his neighbouring farmers are intensifying then the value of his land will be pushed upwards, and it will be rational for him to sell out before

[35] The median total farm area in the sample is 50.4 ha.

the negative effect of his declining productivity offsets the positive effect of the neighbours' intensification.

Table 4.9. OLS regression of value of pastureland (R$) on productivity (R$/ha/year). Dependent variable: ln (value of pastureland)

	Frontier	Transition and consolidated
ln (productivity)	0.0567*	0.0907***
ln (average neighbours' productivity)[1]	0.1707*	0.1298*
Mean distance to markets (Km)	-0.000376	-0.00719***
Degraded pastures	-0.187	-0.129*
Constant	0.408*	0.967***
Observations	40	134
R-squared	0.203	0.382
Adj. R-squared	0.112	0.362

[1]Calculated by multiplying a spatial weights matrix W by the variable productivity. The spatial matrix defines neighbouring municipalities as those located within a distance band that is calculated to give all farms at least one neighbour.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Robust t-statistics in parentheses.

The graph in figure 4.6 below illustrates well the intensification and frontier migration story. Transition areas are where farmers are being pushed to shifting production systems from traditional to intensive. In more evolved, consolidated areas the intensification process has settled in and part of the farmers who were less able to cope with the new situation were already crowded out. Local land values are positively associated with a higher propensity to sell out and migrate, especially in transition areas. Land values appreciate less where pastures are degraded (appendix C4), so farmers facing biophysical constraints can expect that their land will lose value relative to the average. Hence a farmer with degraded pastures who faces high average local land prices should expect the optimum time to sell to be approaching.

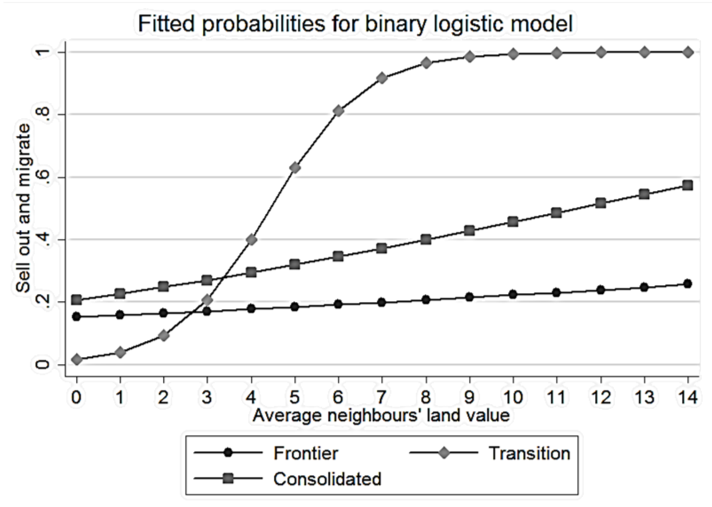

Figure 4.6. Propensity to sell out and migrate according to region and average local land value, controlling for own land value

Moreover, the propensity to sell out and migrate is positively associated with discount rate and degraded pastures, and negatively associated with age and number of previous migrations. Those who are older and have migrated more are less willing to continue moving, whatever their land size and location. But they are also more productive, all else constant. If farmers who migrate more are more successful, even controlling for education, time in the plot and soil aptitude (appendix C5), then there is a strong case that farmers build up capabilities as they migrate.

In this section I have advanced a sequence of causal mechanisms linking intensification to frontier migration. I argued that intensification is a result of land scarcity, which is kindled by an institutional framework that imposes a cost on deforestation, and by biophysical constraints leading to soil degradation. Not all farms, however, embark on an intensification process. A group of technological laggards eventually see their land prices rise as other ranchers intensify. As the land price differential with frontier areas widens, *productively oriented* farmers have an increasing incentive to out migrate.

How sensible is it to assume that farmers are following a productive logic when they take land use decisions? A competing view would suggest that speculative farmers choose not to intensify as they see good prospects in becoming rentiers, or 'idle farmers'. Can productive farmers be distinguished from speculators? I have collected information that allow for that.

4.3. Speculative versus productive behaviour

The land speculation literature offers two key predictions for land use dynamics in frontier regions. First, pecuniary motivations preponderate in explaining settlers' decisions, and the economy resembles an asset market, where land is used as a store of value and transactions aim at capital gains, more than a goods market, where land is used as an agricultural input in a production function (Almeida and Campari, 1995; Assunção, 2008; Barbier, 2011). Second, given the absence of a dominating class of productive farmers who would take risks and invest in farming technologies, frontier settlements tend to see short-lived economic booms followed by long-term busts where population levels decrease and soils remain overexploited and degraded (Bowman et al., 2012; Celentano et al., 2012; Rodrigues et al., 2009).

The latter prediction is disproved by recent evidence, as I have shown before and discuss further in Chapter 6. However, the proposition that agents are largely driven by pecuniary motivations has had little scrutiny, in part due to the inherent difficulty of capturing 'motivations'. The goal of the present section is thus to use farm-level data to look for specific features of the land speculation hypothesis. In particular, I look for evidence of speculative behaviour by confronting farmers' opportunity costs[36] of capital with their propensity to sell out their plots and migrate to a frontier. While an intrinsically productive motivation is difficult to single out from survey data as farmers can give biased responses regarding their propensity to migrate, there is no reason to believe that they did so as it is not one of the topics that raise flags—as opposed to questions on deforestation history, for example.

[36] The best return a factor of production can get in an alternative investment. For example, the opportunity cost of a daily agricultural labourer can be proxied by the minimum salary—the wage paid to most low-skilled workers in urban areas.

Land speculator or productive farmer?

The land speculation literature demarcates speculative behaviour by comparing output with opportunity costs. In a well-functioning market, productive farmers are not expected to sustain situations where output is lower than opportunity costs. Speculative farmers are instead predicted to sustain such situations if the prospects of financial gains are positive. Speculative behaviour would thus be identifiable by one key feature: farmers operating below opportunity costs keep the land when they expect to be able to sell for a higher price at a later date, but sell out if prices are not expected to rise sufficiently. Such behaviour would lead to a situation of "agricultural involution" (Almeida and Campari, 1995), "idle farming" (Assunção, 2008) or simply speculative farming (Bowman et al., 2012). However, the evidence from Rondônia does not fully support the land speculation theory.

Before looking at the data, two qualifications must be made to the measures of agricultural output and opportunity costs. First, opportunity costs are overestimated when transaction costs are omitted. Malfunctioning land markets impose a transaction cost on sales, so even if a farmer expects to be able to sell his plot for a given market price there is a long way between the decision and the realization of sale. Land markets in the Amazon and in Latin America more broadly are recognized as particularly imperfect (Heath and Binswager, 1998; Buchmann, 2006). If transaction costs are properly accounted for then opportunity costs should fall. More importantly, malfunctioning financial markets imply that once a farmer sells out he cannot safely store his wealth in a financial asset. This may not be true for all, but the vast majority of farmers in the Amazon are uneducated and have restricted knowledge of financial instruments, so either they are incapable of managing financial wealth or they feel so. This is another component of transaction costs.

To be sure, cattle is often used as a form of liquid asset ('living stock') that allows farmers to smooth incomes (Siegmund-Schultze et al., 2007), which reinforces the non-agricultural aspect of land possession. Hence, it is indeed the case that land and cattle work partially as a store of value—but this is true for any form of capital asset. The question is not whether land is used as a store of value; rather, it is whether the pecuniary gain motive dominates land use decisions. The latter is an important question because rural economies that maximize financial gain instead of profit may get trapped into sub-optimal equilibria.

The second qualification is that agricultural output underestimates the total land-related output. Land possession has a number of intangible benefits that must be considered along with agricultural output. The most evident non-agricultural benefit from landholding is the abode (Sills and Caviglia-Harris, 2009). This is relevant because, as Bell (2011) has pointed out, farmers with low economic resilience tend to increase their supply of off-farm labour to gain resilience. Hence, if there exists an agricultural labour market at a reasonable distance from the plot, then off-farm wages must be seen as a form of land-related output.

Furthermore, peasants in the Amazon attach a number of non-monetary benefits to the land. For example, Sartre (2003) makes a thorough sociological discussion of intangible benefits from landholding. He argues that land property plays a key role in the reproduction of peasant lifestyle, which is in turn a central motivator for land use decisions. While Sartre's claim that non-economic logics outweigh economic rationality in explaining peasant land use may be overstated, the rich evidence he gathers on tradition-related normative factors shaping the economic behaviour of peasants in agricultural frontiers is appealing.

With overestimated opportunity costs and underestimated output, it can be presumed that part of the farmers who would be categorized as 'speculators' for keeping lands that yield lower output than their opportunity costs are instead operating on a perfectly rational economic logic, based on detailed knowledge of transaction costs and non-agricultural (and non-speculative) benefits of landholding. Indeed, close to two thirds of the farmers I surveyed operate below opportunity costs as conventionally measured (table 4.11 below). Surely, transaction costs and intangible benefits will not account for all that gap. How to explain such a large share of farmers operating below opportunity costs?

The expectation of land price growth in Rondônia is high: on average +10% per year. Farmers operating below opportunity costs also expect high land valorisation: +8.84% per year (p-value = 0.098). This rate is above inflation and above the gross rate of interest in a saving's account (6%), so farmers guided by speculative motivations should be willing to keep the land idle in order to realize capital gains. Yet the data suggests exactly the opposite: those operating below opportunity costs are 43% more likely (p-value = 0.057) to be willing to sell out and migrate to a frontier area, and more so if the expectation of land valorisation is controlled for.

To shed light on this issue, I look for evidence of an alternative explanation based on the Boserupian tenet that as rural settlements evolve the intensification process requires proportionately higher labour inputs. Farmers optimizing labour productivity are attracted by the possibility of migrating to new lands where the marginal product can be higher. This is especially true in the context of degrading soils, where higher labour requirements and capital inputs are needed for fertility recovery. Recent data from three municipalities in Rondônia (Bell, 2011) corroborate Boserup's idea that more intensive systems have lower output per man-day of work per hectare, so poorly capitalized farmers should prefer the more extensive forms of land use. Farmers in areas of older colonization would thus be expected to show a distinctively different behaviour from what is predicted by the land speculation literature: they would try to optimize the use of productive inputs such as labour and soil.

Hence, it is possible to pinpoint farmers with productive motivations: they should show signs of being led out of older settlements due to (a) degrading soils and (b) high labour costs. If the Boserupian story is robust, then these factors must show an association with propensity to sell and migrate—the 'productive effect'.

Empirics of speculative behaviour

I follow Assunção (2008) in formally demarcating speculative versus productive behaviour. In his model both productive and unproductive farmers extract utility from land possession in the form of store of value ($p_t T_t$) as well as from land appreciation ($\Delta p_{t+1} T_t$). However, only productive farmers extract utility from agricultural production ($q-w_t$). Unproductive farmers adopt an extractive production (e) strategy which does not depend on labour. This is a crucial assumption as it is the single feature that differentiates the two types of farmers. To account for the hypothesis I am testing here I add one further assumption by making agricultural output dependent on pasture quality (s_t), as below:

Table 4.10. Determinants of wealth formation by type of farmer

Type of farmer	Expected wealth	Demarcating criteria
Productive	$a_t + (q(s_t) - w_t)T_t + p_tT_t + \Delta p_{t+1}T_t$	Respond to *s* and *w*: 'productive effect'
Unproductive	$a_t + eT_t + p_tT_t + \Delta p_{t+1}T_t$	Respond to *p* only: 'speculative effect'

Notes: *t* = time period; *a* = initial wealth; *q* = agricultural output per hectare; *s* = pasture quality; *w* = wages paid per hectare; *T* = total land area; *p* = land price; *e* = extractive output per hectare

The demarcating criteria above say that unproductive farmers can be distinguished by responding only to land prices in their land use decisions. To test for that I have asked farmers whether they intend to sell out their plot and migrate to a frontier region. The data show no statistically significant association between expected price growth (Δp_{t+1}) and settlement age, so speculative farmers cannot expect to be better-off in frontier areas. Speculative farmers operating below opportunity costs should therefore respond to an expected rise in land prices by keeping their land in idle farming, as there is no gain from migrating. However, they might still be interested in selling out if land prices are not rising. Crucially, signals related to pasture quality and to labour costs should not influence speculative agents' decisions.

Productive farmers, on the other hand, may rationally expect to find better conditions by migrating to a frontier area. Since labour requirements (w) and pasture degradation (s) are positively associated with settlement age, productive farmers should respond by an increased likelihood of migrating to frontier areas—the productive effect.

I calculate returns to labour and to capital (taking land value as a proxy for total capital) and compare them to the respective opportunity costs (table 4.11). The opportunity cost of labour is the annual minimum salary (R$ 8,814) while the opportunity cost of capital is the gross annual rate of return to the savings account (6%). A farmer whose output is lower than the average off-farm wage level is likely to increase his supply of off-farm labour. A speculative farmer whose returns to capital cannot cover the savings account's return is said to be better-off by keeping the land idle if land prices are on the rise.

(4.1) $retl_i = \frac{VP_f}{L_f}$, where *retli* are returns to labour at farm i, *VPi* is the total value of cattle production, and *Li* is total labour employed.

(4.2) $retc_f = \frac{VP_f}{T_f}$, where retci are returns to capital at farm i, *VPi* is the total value of cattle production, and *Ti* is the total value of land assets.

Almost two thirds (62%) of farm labourers for which the variable returns to labour is non-missing operate below opportunity costs. This number is an upper bound since only bovine cattle-related output is measured. To check for the quality of the measure I compare the average on-farm return to labour of those farmers who do not work off-farm (R$ 20,609) to that of those who do (R$ 8,403). These results follow the expected pattern, as off-farm labourers are expected to have a lower on-farm output, so the data does capture the predicted behaviour.

Table 4.11. Returns to labour and capital and opportunity costs

	Returns to labour (*retl*)		Returns to capital (*retc*)	
Category[1]	1	2	3	4
Mean	R$ 48,779	R$ 2,134	23.4%	2.2%
Opportunity cost threshold	>= R$ 8,814	< R$ 8,814	>= 6%	< 6%
Share of respondents	38.0%	62.0%	38.1%	61.89%
Expected yearly land price growth	+9.23%	+9.86%	+11.38%	+8.84%
Propensity to sell out land and migrate	26.2%	34.5%	23.9%	34.2%

[1]There is a 51% overlap between the categories in returns to labour and in returns to capital.

The land speculation theory predicts that speculative farmers in group 4 of table 4.11 should keep their lands if they envisage financial gains, and sell otherwise. To investigate this I have asked farmers whether they are willing to sell out their plots and migrate to a frontier area in the next 3 years. It is certainly not the case that all farmers who have expressed the intention to sell out will in fact do so when faced with the choice, but in the absence of panel data measuring actual land transactions this can be a reasonable approximation. To check for the association between the categorical response variable 'intention to sell' and returns to capital as well as expected land price growth I use a binary logistic model[37]. The equation is the following:

$$(4.3) \quad \log\big(Odds(isell_i)\big) = \alpha + \beta_1 ocost_i + \beta_2 Eprice_i + \beta_3 ocost_i * Eprice_i + \beta_4 labour/ha_i + \beta_5 degraded_i$$

Where *isell*$_i$ is intention to sell out for farmer i, *ocost* is a dummy variable for farmers operating below the 6% opportunity cost of capital threshold, *Eprice* is expected percent land price growth, *labour/ha* is the amount of labour input per hectare, and *degraded* is a dummy for degraded pastures. The data are synthesized in table 4.12:

Table 4.12. Variable definitions

Variable	Time period	*N*	Mean	Standard deviation	Range
Intends to sell out and migrate (*isell*)[1]	Next 3 years	384	0.304	0.46	0/1
Expected land price growth (*Eprice*)	Next 3 years	248	0.364	0.6	[-2.16; +6.6]
Operates below opportunity costs (*ocost*)[2]	Previous year	307	0.62	0.49	0/1
Labour units per hectare	Previous year	346	0.07	0.13	[0; +1,66]
Degraded pasture (*degraded*)[3]	Previous 3 years	378	0.28	0.45	0/1

[1]The original variable includes three categories, "yes", "no" and "maybe". The variable used here assumes value 1 for "yes" and 0 otherwise.

[2]Equal to 1 if returns to capital < 6%, 0 otherwise.

[3]The original variable measures pasture quality variation in the previous 3 years, and was rated on a 7-point scale from -3 (much worse) to +3 (much better). The variable used here assumes value 1 for responses equal to -2 or -3 and 0 otherwise.

The null hypothesis of interest is that $OR_4 = OR_5 = 0$ and $OR_3 < 1$ (where OR are odds ratios): that farmers display speculative behaviour, as in table 4.10. An odds ratio of less than 1 indicates that the variable has a negative association with the odds of a positive outcome. OR_3 tests for the association between expected land price growth and the dependent variable when farmers are operating below opportunity costs. Hence a negative effect of β_3 indicates that farmers keep their land when prices are going up. The

[37] Uses a Maximum Likelihood Estimation Method. The fitted probabilities are calculated as: $\hat{P}(isell_i = 1) = \frac{1}{1+\exp\left[-\left(\hat{\alpha}+\hat{\beta}_1 ocost_i+\hat{\beta}_2 Eprice_i+\hat{\beta}_3 ocost_i * Eprice_i+\hat{\beta}_4 \frac{labour}{ha}_i+\hat{\beta}_5 degraded_i\right)\right]}$

alternative hypothesis is that $OR_4 > 1$ and $OR_5 > 1$: that farmers display productive behaviour.

Discussion of results

I start by discussing identification problems. Two main concerns may be raised. The first is that the hypothesis being tested is dynamic by nature, and the lack of time variation in the data makes causal analysis very difficult. While this is true, reasonable conclusions can still be made from the simple descriptive model I propose above. In particular, survey questions were framed in such a way that farmers were asked to recall information from up to three years earlier (a reasonably short time frame to minimize errors), so the data I use does effectively have a time component, although subject to memory error.

The second concern is about reverse causality. Looking back at model (3), the only variable on the right-hand side of the equation which is not predetermined (in the sense just explained) with respect to the response variable is *Eprice*, but it is also the one variable that is not likely to be subject to reverse causality as it is unlikely that farmers will adapt their land price expectations to their intentions to sell out and migrate. The other explanatory variables could be subject to reverse causality if farmers who do intend to sell out and migrate adapt their labour use, pasture quality and level of output accordingly. If this were the case, however, the variable productivity would need to show an association with propensity to sell out, but the data show no evidence of such association (p-value=0.803).

The regression output in table 4.13 shows that the interaction term has no association with propensity to migrate when labour and pasture degradation are omitted (column 1), but it does have an association (although weakly significant) when these are added (column 5). A Likelihood Ratio test for the joint significance of β_4 and β_5 strongly rejects the null hypothesis (p-value = 0.0004), so a purely speculative effect is rejected. However, the coefficient of β_3 is statistically significant and in line with the hypothesis of a speculative effect. Moreover, a test for the joint significance of β_3, β_4 and β_5 also rejects the null, suggesting that both productive and speculative factors explain the intention to sell out and migrate to a frontier.

Table 4.13. Output of binary logistic regression
Dependent binary variable: intends to sell out farm

	(1)	(2)	(3)	(4)	(5)
	Odds ratios				
Below opp. cost of capital (*ocost*, β_1)	2.291***	1.713**	1.609*	1.478	2.137**
Expected land price growth (*Eprice*, β_2)	1.832*	1.486*	—	1.500*	1.892**
*ocost***Eprice* (β_3)	0.426	—	—		0.324*
Labour / hectare (β_4)	—	—	—	114.3***	148.5***
Degraded pasture (*degraded*, β_5)	—	—	—	1.964**	1.976**
Constant	0.271***	0.298***	0.358***	0.193***	0.171***
Observations	225	225	225	225	225
Likelihood Ratio test (p-value)	0.0403	0.0511	0.0569	0.00176	0.00692

*** p<0.01, ** p<0.05, * p<0.1; robust z-statistics.

While farmers' land use decisions do seem to respond to land price signals, they respond in a manner that is in line with a labour productivity optimization strategy, not with a purely speculative strategy. To see if the response to land prices is stronger than the response to productive inputs I plot the fitted values of model 5 in figure 4.7. The graph on the left shows that propensity to sell out increases with labour employed per hectare, in line with the alternative hypothesis. Similarly, farmers expecting high land appreciation are less likely to sell out and migrate if operating below opportunity costs (arrow A, the 'speculation effect'), whereas those who expect land prices to decrease express a higher propensity to migrate when operating below opportunity costs. The graph on the right shows the effect of pasture degradation on the response variable. The arrow B indicates the 'productive effect' that has to do with migrating to the frontier in search of more fertile lands. The arrow C indicates the other productive effect, having to do with migrating to the frontier in order to optimize labour marginal productivity. It is clear that the productive effects are more important that the speculation effect.

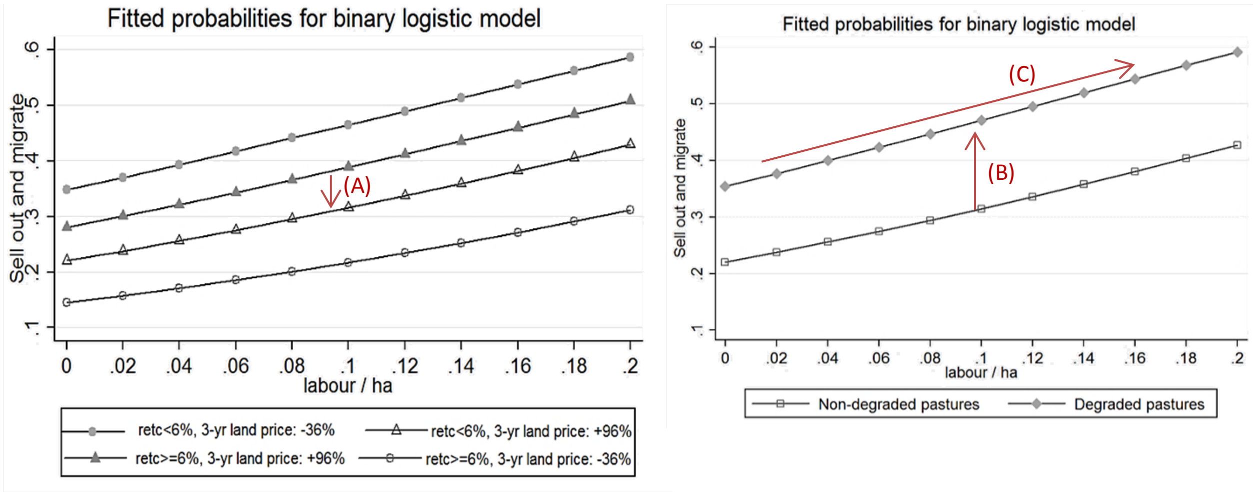

Figure 4.7. Declared intention to sell out and migrate, labour per hectare, returns to capital and expected land appreciation. The dependent variable (*isell*) assumes value 1 when farmers expressed the intention to sell out their plots in the coming 3 years and 0 when they answered "maybe" or "no". *retc* = returns to capital. 6% = opportunity cost threshold. The variable degraded pastures assumes the value 1 when farmers rated their pasture's quality -2 or -3 on the scale [-3; 3]. The values fixed for the variables 3-year land price growth are respectively the mean minus and plus one standard deviation. The range fixed for labour/ha includes the minimum (zero), the mean (0.07) and the mean plus one standard-deviation (0.2).

The literature review on the technological treadmill (Chapter 1) led to the supposition that laggard farmers faced with degrading pasturelands and rising land prices would become either rural rentiers or frontier migrants. In this section I distinguish a 'productive' effect from a 'speculative' effect and find that productive behaviour is more rather than less important than speculative behaviour to explain land use and migration decisions among farmers surveyed in Rondônia. While the evidence suggests that farmers behave according to *both* productive and speculative motivations, I show that the productive effect is more important than the speculative effect. This in turn suggests that a Boserupian framework is more appropriate to explain land use decisions in the Amazon than ideas of speculative behaviour. The displacement of farmers from older settlements to new frontiers may thus be understood as a rational, productive strategy, confirming the potential validity of the model of indirect land use effect developed in the last section.

4.4. Conclusion

In 1974 the Food and Agricultural Organization's global food price index was 37.8% higher than in 1972. In real terms that was the highest level reached by the index (since 1961), surely due to the first oil shock. But prices were back to the previous level already by 1977. The food price boom of the 2000s, on the other hand, has lasted twice as long and still there are no signs of prices getting back to their pre-boom level. The overall index rose by 61.4% in real terms since 2002, with every subcategory—meat, dairy, cereals, oils and sugar—having grown almost monotonically in the period. Meat prices went up 41.7%, the lowest rise but still a gigantic one. With this scenario in mind, and with growing preoccupations regarding climate change and protection of biodiversity, policymakers are challenged to implement agricultural policies that not only increase production but also save forests. This leaves no choice other than yield-increasing technologies, or what is known as land use intensification.

The Brazilian Amazon is a central case not only because of its scale but also because it has become a leading player and an experimentation field for forest-related environmental policies. From the various land uses that compete with forests in the Amazon, planted pastures for beef and dairy production are by far the most important. It is due to such recognition that most conservation projects today have intensification of cattle ranching as one key target. Yet producing more livestock in the same area is not a sure solution to deforestation. The possibility of a so-called rebound effect whereby more intensive forms of land use displace traditional, low-input agriculture to forest margins and keep deforestation going is not easily out-ruled.

At the macro scale, a land use rebound effect depends on how much commodity prices are affected by shifts in production and to what extent demand shifts in response. An initial technological shock that saves land by causing more to be produced in the same area is likely to decrease prices, all else constant. Depending on the elasticity of demand, consumers may respond by consuming nominally more than before, pressing supply to increase even more up to the point where the marginal cost of intensification reaches the marginal cost of horizontal expansion and more lands are incorporated into production.

Explaining processes at the micro level is a rather different enterprise. Individual farmers are price takers and demand shifts are by and large exogenous to most changes in production functions. An indirect land use effect must therefore be explained on different grounds. If productive rather than speculative motivations inform land use decisions, then it is essential to look at the profitability of alternative land uses and how land markets allow the most profitable land uses to crowd out the others. These considerations are in line with a von Thünean approach, and have been captured by various models that study cattle ranching displacement by the expansion of intensive soya / sugarcane and optimal levels of payment for avoided deforestation in a climate change framework. Three important elements have been disregarded, and that is where this thesis adds to the literature.

First, displacement of traditional cattle ranching by intensive cattle ranching is a recent phenomenon and one that has not been systematically studied. Second, the role of pasture degradation as a driver of intensification and at the same time of frontier migration has been overlooked. Third, heterogeneity among farmers in terms of capacity to respond to barriers to horizontal expansion and intensify has also been overlooked as a key explanatory variable for land use dynamics in the Amazon. The central contribution of this chapter is to pin down the causal mechanisms that lead up to an indirect land use effect, to frame them in terms of verifiable conditions and to use survey data to look for those conditions.

A process of land use intensification in the Brazilian Amazon has been established by others using inter-temporal data. The survey data I put together on cattle ranching in the State of Rondônia confirms that trend. If settlements in different stages of the colonization process (frontier, transition and consolidated) can be regarded as snapshots of a single, unfolding development process separated only by age and idiosyncratic factors, as I argue they can, then it is clear that land use intensification in cattle ranching is happening over time. Three factors can explain the intensification process: higher costs to deforestation due to enforcement of environmental legislation; higher costs to buying or leasing land due to rising land prices; and a biophysical process of soil degradation that decreases stocking capacity of pastures and forces farmers to adopt technologies to recover degraded pastures.

Enforcement of the environmental legislation is an important deterrent to horizontal expansion of agricultural land. Since the late 1990s the Brazilian government has made substantial efforts to convince farmers that the command-and-control legislation to protect forests will be enforced, and the results are evident in the narratives of farmers that I interviewed between 2011 and 2013. There is a large consensus that failing to comply with the law results in unbearable costs, while at the same time farmers recognize that when they first migrated to Rondônia enforcement was nonexistant. I show, however, that perceived enforcement varies according to settlement age, and farmers in frontier areas report a lower degree of enforcement. I also document that land prices are 4 times higher in consolidated than in frontier areas, and that they are expected to rise by 10% every year on average (inflation rate is between 6% and 7%), so horizontal expansion becomes increasingly expensive also due to rising land prices.

Most importantly, planted pastures are expected to exhaust the natural fertility of soils after 10 to 15 years of continuous use if measures to administer fertility are not taken. Liming and fertilizing (chemically or organically) are the basis of an intensification process, but other technologies such as pest control and rotational grazing are also part of the standard productivity-enhancing technological package. Farmers who are unable to curb the degradation process see a rapid decline in pasture stocking capacity. I report that controlling for soil aptitude, 44% of all pastures in transition areas are on a condition of high degradation, while in consolidated areas the percentage is 19%. Because the degradation curve is steep, farmers need to take action relatively quickly once they notice the problem if costs are to remain feasible. A group of elite farmers does manage to embark on the intensification process before degradation becomes serious, but many are unable to do so due to capital restrictions.

The fact that degrading pastures pose an extra restriction on production functions and forces farmers to shift from a traditional to an intensive production system has not been accounted for in the land use literature. Yet it is central not only in explaining the timing of adoption of intensification technologies, but also to understand why frontier migration can be caused by the intensification process.

Three conditions are *necessary* for a land use rebound effect. First, a frontier where land prices are near-zero must exist. I use qualitative evidence from fieldwork in various frontier settlements in Rondônia to show that even if the pattern of colonization of new areas has changed from state-led to private-led, with new settlements being less numerous than what they were in the 1990s, there still exist new frontiers where lands with full natural fertility can be purchased for a fraction of the cost in consolidated areas. I also argue that the popping up of spontaneous settlements in forest margins, but not its subsequent occupation, can be approximated as an exogenous process to older settlements. Thus, if frontiers exist and if farmers are aware of them—as I show they are, then farmers faced with increasing restrictions to traditional cattle ranching may decide to migrate to a new settlement where forest protection is less enforced, land prices are lower and fertility is higher.

The second condition is that there must be a land market that functions well enough for lands to be allocated to their most profitable use. If farmers who lag behind in transition areas can transfer their assets to new frontiers, where conditions are more favourable for traditional forms of cattle ranching, then the most marginalized farmers will consider liquidating their lands in order to migrate to new frontiers. I present evidence that land rental markets increase their spread as settlements evolve, which improves allocative efficiency thus allowing farmers to respond to declining marginal labour productivity by out-migrating.

In a Boserupian framework, land and labour productivity are inversely related. This is essential to explaining land use change in the Amazon, where labour is scarce and land is increasingly so. Farmers who shift from fallowing systems to intensive forms of land use need to employ more labour per unit output, all else constant. I show that this is indeed the case in Rondônia, and that propensity to sell out and migrate to frontier areas is positively associated with average labour productivity. Since labour requirements in traditional ranching systems are lower, farmers weigh the cost of staying against the benefit of migrating. Land markets and competition in transition and consolidated areas thus spur an indirect land use effect whereby more productive farmers take up the place of less productive ones, who then take up the remaining place at the frontier.

The third necessary condition for a rebound effect is that a group of technological laggards coexist with elite farmers in areas where barriers to horizontal expansion are becoming insurmountable. If this is the case, then demand for depleted pastures will be created from successful cattle ranchers who have reached their technological limit at given input prices and need to incorporate new lands to expand production. I show that heterogeneity between farmers is indeed at its highest in transition areas, where the gap in pasture degradation, technological inputs and farm size is the widest. In consolidated areas the technological and farm size gaps narrow while pasture degradation wanes and land productivity is boosted.

Farmers take land use decisions—notably frontier migration—to maximize labour productivity. This is how the Boserupian framework can be compressed. If they are instead driven by speculative motivations where asset valorisation is the main objective, then the framework I advance is invalid. I develop an analytical framework and collect data that allow me to disentangle a productive from a speculative effect. I measure farmers' willingness to sell out their plots and migrate to a frontier, and check whether that can be explained by a model of purely speculative behaviour where farmers who cannot cover opportunity costs respond to the expectation of rising land prices by keeping their lands. The evidence rejects the hypothesis of a purely speculative behaviour, but it does point out to a combination of productive and speculative motivations. In addition, I show that the productive effect is stronger than the speculative effect, confirming that the presumption of productive behaviour is realistic.

Frontier settlements start off with low degrees of income inequality. Pioneers are by definition those agents whose opportunity costs are so low that the precarious social and economic environment of the frontier is the best they can aim for. As settlements evolve, farmers differentiate according to previously held assets, such as skills and capital, but also to varying initial conditions, such as soil quality and the geographic pattern of emerging local markets. Small differences in initial endowments amplify over time to consolidate a degree of inequality that approaches the national level. By the time barriers to horizontal expansion become as important as land degradation, farmers in the weakest part of the inequality curve start to see migration as an option to increase their economic resilience. This is where the indirect land use effect materializes.

While in this chapter I have studied in detail land use intensification in the Amazon and how, at the micro scale, it can be associated with deforestation in forest margins, I have not provided a test for the land use rebound effect. The mechanisms that underlie an indirect land use effect in the case I study are intrinsically space and time-lagged, so a test of the complete causality chain cannot be implemented with cross-sectional data. In the next chapter I use panel data at the municipality level to provide a first such test.

Part Three

Secondary research

Testing the rebound effect and the boom-bust hypotheses

In the following two chapters I use econometrics to test two key hypotheses in the land use literature. The chapters are organized as self-standing pieces, with their own literature reviews, data sections and methodological considerations. In this part of the thesis I am particularly concerned with assessing the consistency of the results, which produces a number of robustness check tables that make for a heftier reading. I try to alleviate this by placing less relevant tables in the Appendices, but extra patience is still advised.

The main data is at the municipality level and comes from various sources, including IBGE, Embrapa, IPEA, the Ministry of Environment, and others. I use data starting from the 1996 agricultural census, which partially circumvents the problem of changing boundaries in municipalities (Federal legislation has almost totally prevented the creation of new municipalities from 1996 onwards). As an extra measure of caution, I drop municipalities whose total area has changed by more than 5% between 2000 and 2005, as measured by IBGE. I also generate two new variables on farm gate beef prices and legal reserve requirements, with procedures detailed in appendix D1.

In Chapter 5 I develop a spatial econometric specification to look for evidence of a spatially indirect and time-lagged effect of productivity of cattle ranching in consolidated areas on deforestation in frontier municipalities. I run a number of robustness checks that confirm the main result of a land-sparing effect of productivity. The results suggest that the conditions for a rebound effect that I advanced in Chapter 2 have not been met. I further discuss the reasons for this in the conclusion to the thesis.

In Chapter 6 I test the hypothesis that booms in deforestation lead to busts in welfare. I use the Human Development Index (HDI) as the dependent variable and deforestation as the independent variable. I analyse alternative sources of data, ranging from cross-sectional to time-series to long-term case studies, and find consistent evidence allowing for a rejection of an association between deforestation and welfare.

Chapter 5

Eating beef or saving the Amazon: does livestock intensification increase deforestation?[38]

How to feed a population that is growing towards 8 billion while protecting forests and biodiversity? To this question many have pointed land use intensification as the only possible answer, including a recent policy document by political and academic heavy-weights such as Pascal Lamy, Jean-Claude Trichet, Nicholas Stern, Amartya Sen and others (Oxford Martin Commission, 2013). But this optimistic view is disputed by a growing number of scholars. While in principle producing more food in the same area may logically seem to cause demand for land to decrease, in practice, because of second-round effects, the opposite can be the case. With a time lag, using land more intensively in certain areas may positively affect demand for land in forest margins, inducing more deforestation in the long run. The mechanism should be made cleared in the remained of this chapter, but it has to do with the change in rents that stems from intensification in consolidated areas and the way it affects migration to the frontier.

A theoretical case can be built for an indirect land use effect of cattle ranching intensification on deforestation in the Brazilian Amazon (Vale and Andrade, 2013). Out-migration of farmers from consolidated areas can be related to changes in land productivity of cattle, with pasture degradation and land markets playing a crucial role in pushing marginalized farmers to move to areas where soils are naturally fertile and average land prices are low. If the micro-level mechanisms depicted in Chapter 4 conduce to a sufficiently high level of rural-rural migration, then a characteristic increase in deforestation should be evident in frontier municipalities. Rather, if the land-sparing effect is the predominant force, then deforestation at the frontier should be correspondingly reduced.

[38] The empirical procedures adopted in this chapter have benefitted from comments and suggestions by Henrique Neder, to whom I am greatly thankful. Any errors remain mine.

In this chapter I look for signs of a rebound effect—intensification shooting back and causing more deforestation—at the aggregate, municipality scale. I adopt a new empirical strategy to look at time and space-dynamic effects of land use intensification in the cattle ranching sector, building upon the model by Arima et al. (2011), which tests the hypothesis that expansion of soya in consolidated areas affects deforestation in frontier areas. I use municipality-level census data from a 16-year period in which the livestock sector saw important increases in yields in the Amazon to provide the first empirical assessment of the relationship between productivity growth in consolidated areas and changes in deforestation in frontier locations. I find robust evidence that the increase in productivity was associated with a substantial decrease in deforestation.

The essence of the land-sparing hypothesis is that by being able to increase output by resorting to mostly vertical expansion, farmers in consolidated areas reduce the overall demand for new land in frontier locations. This optimistic idea is sometimes called a 'Bourlaug hypothesis', for the American biologist Norman Bourlaug who is best known as the father of the green revolution. The supposition that increasing yields is the fundamental land-saving mechanism is countered by advocates of the so-called 'Boserup hypothesis'. They state that processes of intensification and extensification are intrinsically related, and while in more densely populated locations productivity of land may be pushed upwards, horizontal expansion into marginal lands is unlikely to cease, as rational farmers unable to cope with the intensification process will look for areas where land abundance allows them to stick to a less labour-intensive production system.

The alternative theory is also referred to as the 'Jevons's paradox' or the 'rebound effect' hypothesis. It states that productivity gains in the use of a natural resource may be overcompensated by second round price and income effects[39]. The classic example is petrol consumption for transportation: all else equal, more efficient automobiles might be expected to save fuel at the aggregate as people would be able to drive the same amount of miles with less petrol. However, as driving a mile becomes less expensive, drivers may automatically adjust to driving more miles, depending on their preference structures. Or else, the lower demand for fuel may push prices down and incomes up, which can

[39] Gillingham et al. (2013) and Villoria et al. (2014) provide the most up-to-date assessment of the seminal insight by Stanley Jevons in his 1865 book *The Coal Question*.

eventually feedback on consumption. The resulting net effect could still be a savings, but might well be a more than elastic rise in miles driven, incurring in a negative savings of fuel. The key question is thus how elastic the demand is with respect to prices.

A similar reasoning is often applied to deforestation, as more efficient agricultural and livestock technologies can feedback on demand and overcompensate short term gains (Angelsen and Kaimowitz, 2001; Lambin and Meyfrodt, 2011). For example, Rudel et al. (2009) compiled data on crop yields and land use across the world and found evidence against the hypothesis of crop productivity gains saving land. Whereas a rebound effect—increased land use following a productivity gain—would require a time lag to operate, the alternative, land-sparing effect—lower total land use following a productivity gain—should in principle manifest within a shorter time span. Between 1990 and 2005, only in two of nine world regions did land use decrease at the same time as crop yields increased, suggesting that intensification may have indeed backfired on extensive land use.

But the parallel between the Jevon's paradox, which was specifically geared towards energy consumption, and land use change has a major limitation. While the adoption of energy-efficient technologies by consumers is rather straightforward and depends largely on a simple cost/benefit calculation, agricultural technologies are subject to all kinds of adoption biases that lead to below optimal adoption (Duflo et al., 2011) and situations of technological lock-in (Possas et al., 1996). Since technological dissemination is far from granted in agriculture, it is unclear that technology-driven efficiency gains can have the impact necessary for a rebound effect to materialize.

5.1. Cattle displacement and productivity gains

Cattle livestock plays a pivotal role in global environmental change: it accounted for as much as 18% of anthropogenic greenhouse emissions and 63% of reactive Nitrogen mobilization by the year 2000 (Pelletier and Tyedmers, 2010). Being the key driver of land use change in the Amazon, in recent years different policy initiatives have been implemented in the region with a view to enhance conservation efforts by inducing cattle ranching intensification—thus implicitly assuming the validity of the land-sparing hypothesis[40]. While some authors have found evidence of an indirect land use effect from consolidated to frontier areas in the Amazon for the specific cases of soya (Arima et al., 2011; Brown et al., 2005; Macedo et al., 2012) and sugar-cane (Sa, Palmer and Di Falco, 2012), the land-sparing hypothesis has had minor scrutiny when it comes to cattle ranching (as evidenced by Cohn et al., 2011).

A pattern similar to a rebound effect has been observed in some cases within the agricultural sector, both in Latin America and elsewhere (Angelsen and Kaimowitz, 2001; Ceddia et al., 2013). When it comes to cattle in the Brazilian Amazon, however, the evidence is ambiguous. Though a land-sparing effect cannot be ruled out as beef production has grown by 50% from 2004 to 2010 at the same time as deforestation felt by 75% (figure 5.1), recent evidence put together by Barretto et al. (2013) point to the opposite direction. Looking at the correlation between land use intensity and deforestation at the country scale (with data extracted from satellite pictures), they find that pasture intensification occurs predominantly in consolidated areas in tandem with a broader process of agricultural land use intensification. Moreover, pasturelands decrease in consolidated areas while increasing in frontier areas, with a chronology that resembles an indirect displacement effect associated with the intensification process.

[40] See Trivedi et al. (2012) and Strassburg et al. (2012) for the standard land sparing assumption from the point of view of funding parties. Based on those premises a "*low carbon agriculture and avoided deforestation to reduce poverty in Brazil*" programme is being funded by UK Department for Environment, Food and Rural Affairs to incentivize farmers to invest in cattle ranching intensification technologies in various States in Brazil. The Dutch government has also committed funds to a pilot project on sustainable livestock farming to be implemented in the Brazilian Amazon (GTPS, 2012). The Brazilian government has created lines of subsidized credit for a 'low carbon agriculture programme' that includes recovering degraded pastures; the government's agricultural research and extension agencies have also created their own cattle intensification programmes: Embrapa *Boas Práticas Agropecuárias*, and Emater *Programa Balde Cheio*.

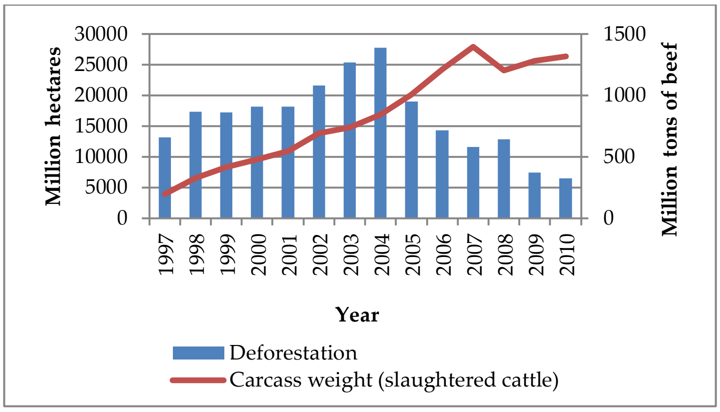

Figure 5.1. Deforestation and carcass weight of slaughtered cattle in the Brazilian Legal Amazon, 1997-2010.

Sources: National Institute for Space Research (INPE) and Brazilian Geography and Statistics Institute (IBGE)

The thin literature that explores causal mechanisms in a multivariate framework has merged livestock with agricultural crops. Using a general equilibrium model, Cattaneo (2002) concluded that in the short term technological intensification in consolidated areas would reduce deforestation, but in the long run, with factor mobility, capital and labour would inevitably migrate to the frontier and cause further clearings, thus increasing deforestation. A potentially complementary conclusion was reached by Marchand (2012), who used cross-sectional census tract data to estimate the technical efficiency of "representative farmers", and found a nonlinear effect of productivity on deforestation. Farmers at the bottom and top of the productivity distribution deforested more than those with intermediary productivity levels. The majority of farmers lay on the ascendant slope, so the combination of higher than average productivity and higher than average deforestation was predominant. These two pieces of evidence reinforce the idea that productivity is not univocally associated with land sparing.

Livestock farming normally occupies marginal lands, with high-yield cropping systems occupying the best soils. The Brazilian Amazon, however, is a hotspot of cattle expansion where livestock competes with other uses, often in good soils (Mann et al., 2014); farmers switch to cattle as soon as they can because it is less labour-intensive and because it provides a form of savings. Cattle expansion in the Amazon used to be mostly horizontal, as there were no constraints to clearing new lands, but the situation has changed over the last two decades[41]:

Table 5.1. Productivity of cattle ranching (R$ / ha / year), 1996-2006

Region	Municipalities[a]	Mean Δ productivity (96-06)	Standard deviation	Standard error	Median Δ productivity (96-06)
Pre-frontier	180	41.4%**	1.73	0.13	6.85%
Frontier	102	52.7%**	1.70	0.17	-1.35%
Consolidated	253	70.9%***	2.60	0.16	23.29%
Total	535	57.50%	2.18	0.09	15.29%

Source: Agricultural Censuses, IBGE.

[a]221 municipalities dropped due to missing data.

These results show an average productivity gain whose magnitude had not been evidenced in previous studies, that have focused on the density rate only. To be kept in mind nonetheless is that the distributions include municipalities that have seen a productivity decline. Moreover, the difference between the mean and the median shows that the distributions are schewed to the right and that the averages may be contaminated by outliers. Indeed, when seven observations that lie outside a three standard deviation window from the mean are dropped, the mean falls to 38.41%, while the median remains almost unchanged at 14.59%. This only shows that summarizing a schewed distribution in one number is a difficult task, but also that in any case an important productivity gain has been observed in ten years.

One factor that has contributed to the drop in deforestation shown in figure 5.1 is policy. The Federal government has since 2004 enacted an 'Action Plan to Prevent and Control Deforestation in the Amazon' (PPCDAm) that greatly increased the level of enforcement of the environmental legislation. The two phases of the plan included actions such as the restructuring of the enforcement agency and the use of satellite technology to detect deforestation with minimum delay, the creation of 20 Mil ha of conservation units, and

[41] See Lapola et al. (2014) for a recent empirical assessment of the intensification process.

the blacklisting of highly deforesting municipalities to better target the enforcement effort (Arima et al., 2004). This policy lever is a key factor that needs to be controlled for if the effect of productivity on deforestation is to be correctly identified.

What happens to deforestation when cattle expands vertically, by intensification? As the literature has quite clearly suggested, it is possible that land is spared, but a chain of indirect causation may spur further deforestation. This would of course not be the case if virtually all farmers would increase production by land use intensification only, while it would definitely be the case if all farmers would keep productivity constant and expand production horizontally. The real world question is what happens when some combination of intensification and traditional ranching is used to increase supply—if vertical and horizontal expansions occur simultaneously, which one dominates?

5.2. Methods and data

I provide a first test to the hypothesis that land use intensification in consolidated areas pushes low-productivity cattle ranching to the frontier and causes more deforestation. The process I analyse is dynamic both in space and time, so the empirical specification is based on spatially and time-lagged measures of the changes in productivity and deforestation. The main model is estimated over frontier municipalities only (between 64 and 72 municipalities, depending on the number of observations dropped due to missing data), with information on key control variables in consolidated areas being captured through a spatial weighting matrix.

I first adapt the reduced form model by Arima et al. (2011) and run a first difference specification of the growth in deforestation (2007 to 2012 as well as other time frames) on the growth in productivity (1996 and 2006). By taking a first difference on both sides, this model eliminates potential sources of bias coming from entity and time-fixed omitted variables correlated with the levels of the dependent variable as well as the treatment (table 5.2 below). Variables purposefully left out are those that reflect the very process that links intensification to deforestation, such as migration (so-called *intervening variables*).

Based on a panel with two time periods, the resulting econometric specification is effectively a cross-section of differences, thus with the same properties as a regular cross-sectional Ordinary Least Squares model (for example, the error terms may be heteroscedastic but not autocorrelated, as there is no time subscript to the error term). The model yields results for cattle that are comparable to Arima et al.'s results for soya: that there is a rebound effect. Crucially, however, this specification is based on a strict exogeneity assumption: that the error term is uncorrelated with the explanatory variables for all time periods. This assumption, known as *strict exogeneity*, is necessary for the standard first difference estimator to be consistent. A simple way to test for this assumption in a model with two time periods is simply to include the levels of the explanatory variables in the model – if they are significant, the assumption is invalid.

Controlling for fixed effects in the levels of deforestation is important inasmuch as the levels of deforestation affect the growth rate of deforestation. However, the key question is how much the *growth* in productivity in consolidated areas affects the *change* in deforestation at the frontier. Intuitively, productivity growth depends on initial levels of productivity: municipalities where productivity is higher to start with should display lower growth rates. The same applies to the other controls and even to the dependent variable itself, so the levels are in principle important additional controls.

Another way of justifying the inclusion of the levels is to see that the deforestation dynamic path is affected by factors other than the levels of deforestation. For instance, institutional characteristics in the different Federal States may *directly* affect the change in deforestation; the initial level of productivity in consolidated areas is in itself a determinant of the migration process (other than the growth in productivity), hence a relevant control in itself; the initial level of deforestation at the frontier may also affect migration, so it is another a relevant control.

To account for the dynamic nature of the cattle indirect land use effect, I improve the model by adding controls that capture fixed effects in growth rates. This procedure has been employed in a similar context by Weinhold and Reis (2008), whom I follow closely in constructing my empirical specification. When this is done, the results from model 1 are reversed. A strong land-sparing effect is now evident, with a series of robustness checks and one placebo test confirming the result. In particular, I find that intensification in consolidated municipalities is associated with lower deforestation in neighbouring frontier as well as consolidated municipalities, and no outcome in pre-frontier areas. Increasing the growth in productivity by one standard-deviation (from its median level) is associated with a drop in the change in frontier deforestation of approximately 30% of one standard-deviation. The impact on deforestation in consolidated areas is lower in magnitude but equally statistically significant. This would suggest that, in line with a Bourlaug hypothesis, policies aimed at increasing land yields in cattle ranching are likely to achieve positive environmental outcomes.

Reduced-form models and description of variables

The reduced form equation in (5.1) is a modified version of the model in Arima et al. (2011). Their model uses a spatial econometric specification that accounts for time variant, spatially indirect effects of soya expansion on deforestation. By using a weights matrix that disentangles the effects of intensification in consolidated areas from local cattle dynamics within the frontier, Equation (5.1) attempts to test the hypothesis that intensive cattle expansion into degraded pastures in areas of older colonization ends up pushing traditional cattle ranching to the agricultural frontier, hence producing greater deforestation.

Table 5.2. Variable definitions, descriptive statistics and sources

Variable	Unit	Years	Obs.	Mean (1996)	Relative change[1]	St. Dev.	Source
Deforested area (d*ef*)	Km^2	1997; 2000-2012	589	669.3[a]	2.31[b]	21.83[b]	INPE
prod: land productivity of cattle (*output/pasture*)	R$ / ha / year	1996; 2006	618	0.51	27.87	98.52	IBGE
output: total value of livestock production (bovine, bubaline and other types of grass eating stock animals)	R$ 10^3	1996; 2006	625	6,597.6	0.84	3.36	IBGE
Total *pasture* area, natural and planted	ha	1996; 2006	622	81,531	1.30	11.75	IBGE
Gate *price* of beef[2]	R$	1996; 2006	756	24.2	0.064	$2.86*10^{-6}$	IPEA, IMEA, Seagri, own calculations
Total *cattle* herd	heads	1996; 2006	619	56,855	1.06	4.77	IBGE
Share of land with full land title (*tit*)	%	1996; 2006	623	91.29	0.09	1.13	IBGE
State protected areas (*pr.areas*)	%	1996; 2006	750	2.06	1.19	13.28	Ministry of Environment
Mandatory legal reserve (*LR*)[2]	%	1997; 2006	589	71.5[a]	-0.09[b]	0.14[b]	Forest Code Law, own calculations
Total environmental *fines* / municipality's agricultural output	%	1996; 2006	619	1.90	23.16	124.36	Ministry of Environment, IBGE

Notes: INPE = National Space Research Institute; IBGE = National Bureau of Statistics; IPEA = Applied Economics Research Institute; IMEA = Mato Grosso Institute of Agricultural Economics; Seagri = Secretary of Agriculture, São Paulo; currency in constant 2000 R$.

[1]Unless indicated otherwise, change between 1996 and 2006: $(\bar{x}_{06} - \bar{x}_{96})/\bar{x}_{96}$, where x is is the variable in question.

[2]See appendix D1 for calculation details.

[a]Year = 1997. [b]Base year = 1997.

$$(5.1) \qquad \ln(\Delta \boldsymbol{def}_{i,f,07-12}) = a_t + \boldsymbol{\beta}\Delta \boldsymbol{W_1 prod}_{i,c,96-06} + c\Delta W_1 price_{i,c,96-06} + d\Delta W_2 cattle_{i,f,96-06} + e\Delta tit_{i,f,96-06} + f\Delta fines_{i,f,96-06} + g\Delta prareas_{i,f,96-06} + h\Delta LR_{i,f,96-06} + \Delta\epsilon_{i,f,07-12}$$

The subscripts *i* and *j* denote municipalities; *f* and *c* denote frontier and consolidated areas. The link between municipalities *i* and all other (*n-1*) municipalities is established by a weights matrix *W*. I create two spatial weights matrices, one based on an Euclidean distance band (W_1) and another that computes the average five nearest neighbours (W_2). The distance matrix links municipalities *i* to their neighbours *j* in consolidated areas subject to a maximum threshold distance (*m*) chosen to allocate at least one neighbour to every frontier municipality (see details in appendix D2). I apply the distance matrix to the variables productivity and farm gate beef prices to obtain a clean measure of productivity of cattle ranching in consolidated areas[42], and apply the 5-neighbours matrix to cattle herd at the frontier to control for local dynamics of cattle. The resulting variables are spatially lagged, average values of productivity, beef prices and cattle herds:

(5.2) $W_1 prod_{i,f,96} = \sum_{j \neq i}^{n} (w_{1,ij} * prod_{j,c,96})$, where

$$w_{1,ij} = \begin{cases} 1/k \text{ if j is one of } k \text{ nearest neighbours within distance } m \\ 0 \text{ otherwise} \end{cases}$$

(5.3) $W_2 cattle_{i,f,06} = \sum_{j \neq i}^{n} (w_{2,ij} * cattle_{j,f,06})$, where

$$w_{2,ij} = \begin{cases} 1/5 \text{ if j is one of 5 nearest neighbours} \\ 0 \text{ otherwise} \end{cases}$$

The weighting schemes above are row-standardized, so the resulting spatial lagged variables are weighted averages of the neighbouring municipalities. The use of Euclidean distance as the criterion to establish proximity is justified by the von-Thünean assumption that farmers using traditional methods (low productivity) will locate further away from the areas where intensive agriculture develops, with the key link between rents in separate locations being distance to markets. Ranchers seeking to maximize profits by selling out where land prices are rising and buying new lands in frontier areas will try to minimize distance in order to reduce the costs of moving their herds and households. The assumption that proximity is best captured by Euclidean distance is standard in the spatial econometrics literature, yet an arguably better approach would be to study land use-related migratory patterns and construct a measure of proximity based on migration data, for example. This is an improvement that I intend to implement in the future by using migration data.

---

[42] I check for robustness by using an inverse distance weighting scheme, where instead of giving equal weight to each neighbouring municipality a weight equal to the inverse of the Euclidean distance is given. The results are approximately unchanged: the magnitude of the coefficients is larger, but the effect kicks in with a longer time lag (see discussion below). I also use an expanded distance weights band that includes neighbouring municipalities in all clusters: pre-frontier, frontier and consolidated. This alternative specification tests for a more general neighbourhood effect of intensification on deforestation, and the results are compatible with those presented.

The dependent variable, $\ln(\Delta def_{i,f})$, is the change in deforestation between 2007 and 2012 in frontier municipalities. I use 2007 as the baseline because it allows for a one year interval after the treatment (growth in productivity), but I also present robustness checks with other baseline years. The deforestation distribution is skewed to the right, with a high incidence of zero values as well as outliers, so I take the log of the change to improve the model's fit. However, by logging the dependent variable the zero values are dropped, which can bias the results. I run a binary logistic regression to check for the association between the zero values and the treatment. The dependent variable takes value 1 if the change in deforestation equals zero and zero otherwise, and the right-hand side variables are the same as in the main model. The results show no statistically significant association, so logging the dependent variable should generate any bias.

The independent variable and the covariates are all for the inter-census years of 1996 to 2006. The variable measuring the intensification process is $\Delta W_1 prod_{i,f}$, the growth in productivity in the average neighbouring consolidated municipality. Covariates are the following: farm gate beef prices in consolidated areas ($\Delta W_1 price_{i,f}$), containing information on transportation costs to clear the productivity measure out of local specificities; cattle herd in neighbouring frontier municipalities ($\Delta W_2 cattle_{i,f}$), to distinguish local dynamics of cattle expansion within the frontier from the land use process of interest, caused by dynamics in consolidated areas; property rights in frontier areas ($\Delta tit_{i,f}$, a measure of land titling), a key factor that could be influencing both changes in productivity and in deforestation; enforcement of environmental legislation ($\Delta fines_{i,f}$, the total value of environmental fines as a share of total agricultural output), state protected areas ($\Delta prareas_{i,f}$), and the environmental law itself in frontier municipalities ($\Delta LR_{i,f}$, the average share of farms that by law have to be kept forested as a 'legal reserve') (see table 5.2 for full variable definitions). ϵ is the error term. Changes are calculated after spatially-lagging the variables.

The specification in (5.4) follows Weinhold and Reis (2008) in adding the levels of the control variables, the initial level of deforestation as well as State dummies (DS_i) to account for fixed effects in the growth rate of deforestation. In case the initial levels are not relevant or have been fully accounted for by fixed effects in levels, the additional controls (in bold) should be jointly non-significant and the β coefficient should be correspondingly unchanged.

(5.4) $\ln(\Delta def_{i,f,07-12}) = a_t + \boldsymbol{DS_i} + \boldsymbol{\alpha \ln(def_{i,f,07})} + \beta \Delta W_1 prod_{i,c,96-06} + \boldsymbol{\beta_1 W_1 prod_{i,c,96}} + c\Delta W_1 price_{i,c,96-06} + \boldsymbol{c_1 W_1 price_{i,c,96}} + d\Delta W_2 cattle_{i,f,96-06} + \boldsymbol{d_1 W_2 cattle_{i,f,96}} + e\Delta tit_{i,f,96-06} + \boldsymbol{e_1 tit_{i,f,96}} + f\Delta fines_{i,f,96-06} + \boldsymbol{f_1 fines_{i,f,96}} + g\Delta prareas_{i,f,96-06} + \boldsymbol{g_1 prareas_{i,f,96}} + h\Delta LR_{i,f,96-06} + \boldsymbol{h_1 LR_{i,f,96}} + \Delta\epsilon_{i,f,07-12}$

Identification and spatial clustering

If models (5.1) and (5.4) were not subject to endogeneity bias, the β coefficients would give the causal indirect effect of land productivity on deforestation and the control variables would assure the conditional independence assumption. The specification I employ approximates the ideal world of full identification by dissociating (lagging) the independent variables from the outcome both spatially and temporally. The problem of simultaneity is thus minimized as the independent variables are time-lagged. Moreover, other types of endogenous causation (any potentially omitted variables) would need to bias the model by simultaneously affecting land productivity in consolidated areas and deforestation at the frontier. This would be less likely to happen, but the specifications also control for fixed endogenous determinants—such as legal constraints or climatic and environmental conditions—affecting the levels of (models 1 and 2) and the change in deforestation (model 2). Finally, measurement error in deforestation leads to downward bias in a fixed effects specification (Griliches and Hausman, 1986).

I cluster municipalities into 3 groups: pre-frontier, frontier and consolidated (see figure 5.2 below). Pre-frontier is where a settlement process has not been sparked. Because limited immigration of people and cattle is expected to flow to these municipalities, this cluster works as a counterfactual to the intensification / deforestation process—the statistical coefficients (β) for the indirect land use effect variables are expected to be non-significant, while those for local processes (d) are expected to be significant. Frontier municipalities are where there is a boom in deforestation. Consolidated areas are where settlements are older and deforestation activity lower. The categories are based on deforestation data from the years 2000 to 2004. Pre-frontier municipalities are where deforestation extent (stock) and activity (flow) were low, frontiers are where deforestation extent was low but activity high, and consolidated where deforestation extent was high and activity low.

I follow Rodrigues et al. (2009) and Celentano et al. (2012) in using information on past values of the dependent variable to classify municipalities. Since there is no overlap between the period used for the classification and the time frame used for the outcome variable, this does not configure selection on the dependent variable. I use two alternative measures of deforestation to classify municipalities and obtain comparable results[43]. I also use two alternative classification rules, again with the same results (appendix D3). Moreover, I find a significant overall effect even when I ignore the classification and run the model for all municipalities.

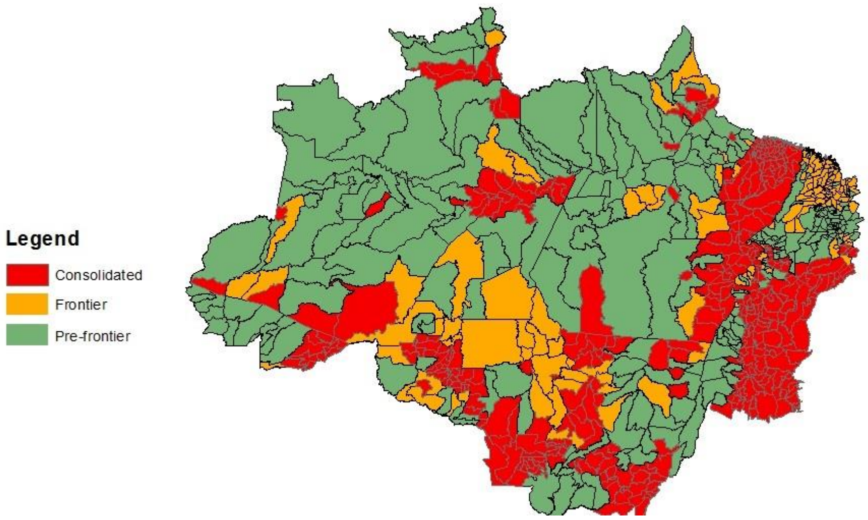

Figure 5.2. Classification of municipalities into clusters of pre-frontier, frontier and consolidated areas

[43] The deforestation measure provided by INPE only covers forested areas, so I divide the variable deforestation by the total forest cover of each municipality before creating the groups. I use two alternative measures of forested area, one by Embrapa and one by the Ministry of the Environment, thus obtaining two alternative deforestation measures. In all cases, however, each of these classification schemes may result in apparent inconsistencies, for example a given municipality that is known as a frontier location being classified as pre-frontier. This is an unavoidable consequence of creating relatively arbitrary rules to classify a high number of municipalities.

I use a panel dataset with 756 municipalities in the Brazilian 'Legal Amazon'[44]. The dataset comprises the two last Brazilian agricultural censuses, 1995/1996 and 2006, including the variables described in table 5.2. There are two reasons for not using data on previous time periods. First, boundaries have changed a lot until 1997 so going back in time means losing spatial definition as one is forced to aggregate today's municipalities into 'minimum comparable areas'[45]. To be sure, there is nothing intrinsically wrong with trading spatial definition against time variation, but in the particular case of this study there would be a lot to lose and very little to gain: going back in time means blurring out the difference between consolidated and frontier areas as the older municipality boundaries include most of today's consolidated areas. Secondly, the intensification process that I am depicting is a phenomenon of the late 1990s, and the internal context of the Amazon was structurally very different prior to 1994, so there would be little to gain by going back in time.

One confounding factor that may pose identification problems to the coefficients in productivity is the anti-deforestation policy discussed above (PPCDAm). There are three reasons, however, why the models in this chapter should not suffer from omitted variable bias due to PPCDAm. First, to the extent that the policy is in part an Amazon-wide effort that affects all municipalities equally, it is controlled for by a time dummy. Second, the policy has also targeted specific municipalities differently starting in 2008, and this is captured by municipality-fixed effects in the regressions that are run for periods starting in 2008. Third, in the main specification, which starts in 2007, the municipality blacklisting policy goes to error term, yet it can only bias the productivity coefficient if it simultaneously affects deforestation in targeted frontier municipalities (which is does, according to Arima et al., 2014) and productivity in consolidated areas. The fact the coefficients remain significant and with comparable magnitudes for time frames starting in 2004, 2007, or 2010 (tables 5.6 and 5.9 below) suggests no relevant bias from the policy.

Finally, the existence time trends in cattle cycles may be a source of measurement error for the productivity variable, which, if systematic, can cause coefficients to be inconsistent. As

[44] Out of 756 municipalities, 661 have deforestation data for generating group classification, 618 have productivity data for both 1996 and 2006, and 535 have both.

[45] To reduce measurement error, I drop municipalities whose areas (as published by IBGE) have changed more than 5% between 2000 and 2005.

long as farmers respond strategically to shifts in relative prices of different cattle outputs, the regression should control for those cattle cycles. In the specifications presented below there are three ways in which this source of measurement error is accounted for. First, the intercept of the model captures a general time trend applying to all municipalities. Second, the change in farm gate beef prices accounts for additional spatial and time variation in prices that could correlate with productivity. Third, the fixed effects in growth rates control for any remaining cattle cycle-related factor from the first time period that may be affecting the changes.

5.3. Results

Deforestation is a phenomenon of frontier locations where a process of primitive accumulation takes place by turning idle lands into economic assets. This is consistent with a von-Thünean framework where activities that yield lower rents are pushed to the marginal lands whereas intensive production stays close to central markets. In this chapter I am testing the idea that the process of intensification guarantees the reproduction of the frontier and thus of the deforestation dynamics. The results of model 1, where I restrain from controlling for potential fixed effects in the growth rate of deforestation, are consistent with a Boserupian induced intensification framework where farmers migrate to forest margins to maximize the marginal product of labour, as the rapport between land prices and soil fertility is more convenient there. However, when I properly account for initial levels of deforestation, productivity and other controls directly affecting the change in deforestation, I find stronger and more robust evidence in favour of the competing theory of a benign, land-sparing effect of intensification.

Model 1

The results from model (5.1) support the hypothesis that intensification in consolidated areas causes increased deforestation. The estimated effect, however, is relatively small, with an extra standard deviation growth in productivity (all else constant, an increase of R$ 7,400,000 in output from 1996 to 2006) being associated with a 0.14 standard deviation supplementary growth in deforestation at the frontier (26.68 Km^2 additional deforestation).

The graphs in figure 5.3 help to start appreciating the pattern that comes out of the data. Municipalities in frontier areas that are neighbours to municipalities in consolidated areas where productivity has grown between 1996 and 2006 have seen an increased number of cattle purchases. This applies to both quantity and value, as well as growth of cattle herd. At the same time, intensification in consolidated areas has a strong negative association with cattle purchases within consolidated areas, suggesting that productivity is positively associated with cattle herd growth in frontier but not in consolidated areas. In pre-frontier areas, no statistically significant association is found, which is expected since those areas are exogenous to the colonization process that has triggered most livestock and agricultural expansion in the Amazon. Given that cattle is raised at lower stocking rates in frontier areas, these results are consistent with the rebound effect hypothesis as cattle herd growth in those locations is expected to imply horizontal expansion.

Table 5.3 indicates that productivity ($\Delta W_1 prod$) had no statistically significant association with frontier deforestation before 2001 (columns 1-3), but that since then the positive coefficient became significant and the model's fit improved (adjusted-R^2 rose from 0.47 to 0.64, columns 4-7), in line with the rebound effect hypothesis. It also shows that the model passes a placebo test, as there's a low model fit and no statistically significant association for the period 97-00 (column 1). Table 5.4 then shows that the association is robust to including the relevant covariates discussed in section 5.2, as well as to controlling for baseline year to account for a global shift in the deforestation pattern. Finally, table 5.5 shows that the statistically significant association only holds for frontier municipalities, with all other areas yielding non-significant results.

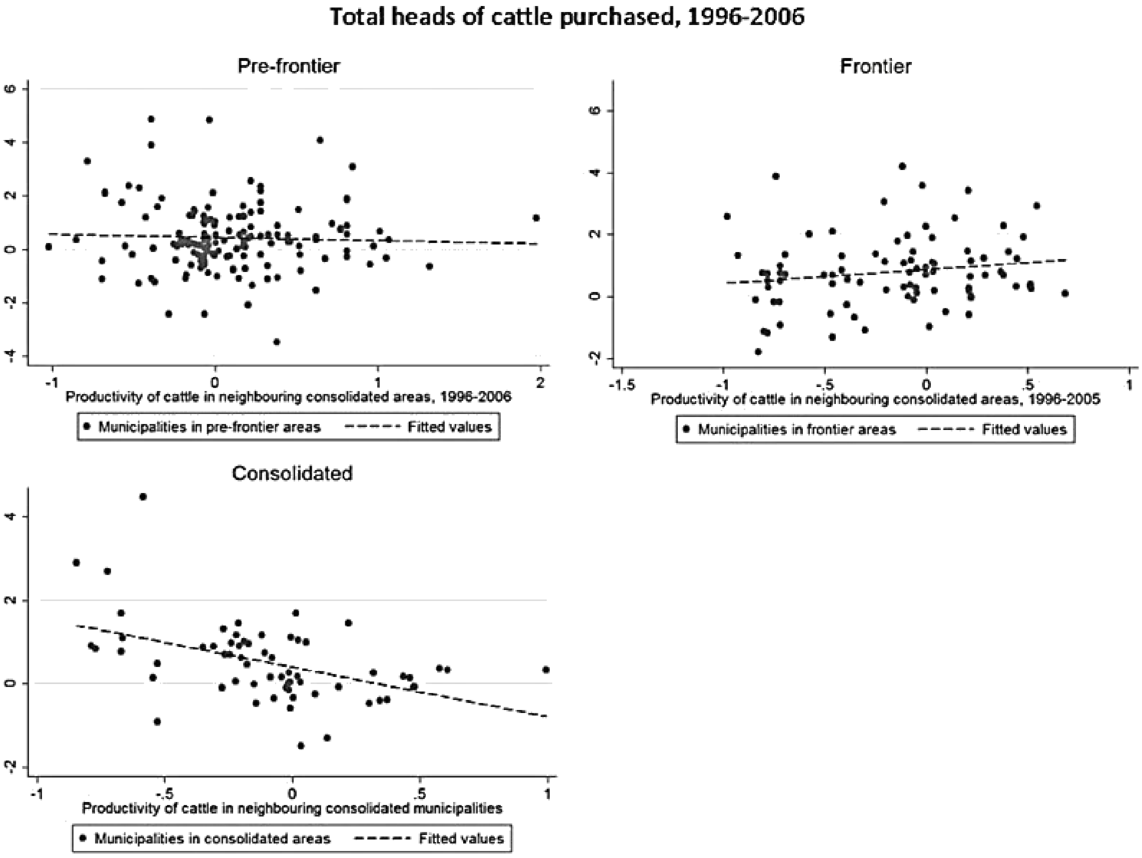

Figure 5.3. Movement of cattle towards the frontier, 1996-2006

Table 5.3. First difference regression of deforestation on productivity of cattle (OLS), different time frames
Dependent variable: natural logarithm of change in deforestation, frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time frame	97-00	97-12	00-12	01-12	04-12	07-12	10-12
ΔW_1*prod*	0.524	0.311	0.369	1.834***	1.540***	0.820*	1.328***
ΔW_1*price*	3.499	1.300	1.154	1.998	3.527***	2.297	3.232**
ΔW_2*cattle*	2.04e-05***	1.68e-05***	1.61e-05***	1.58e-05***	1.59e-05***	1.59e-05***	1.78e-05***
Δ*LR*	4.376	11.98***	15.28***	14.78***	16.09***	16.53***	16.58***
Δ*title*	0.00310	0.00716	0.00734	0.00137	-0.00327	-0.00321	0.00377
Δ*pr.areas*	-0.132	-3.262**	-3.758**	-3.458**	-3.111**	-2.452*	-0.958
Δ*fines*	-0.0338	-0.130	-0.133	0.0308	-0.0149	-0.0237	-0.0332
Year	-1.933	3.663*	3.663*	1.629	-1.614	-0.717	-3.809*
Observations	64	64	64	64	64	64	65
R-squared	0.438	0.531	0.534	0.683	0.715	0.633	0.717
Adj. R-squared	0.357	0.463	0.467	0.637	0.673	0.579	0.676

Note: the reduced number of observations (64) is due to these regressions being estimated over frontier municipalities only. The information on consolidated municipalities is captured by the spatial weights matrix W_1.

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics

From table 5.4 it is evident that the variable farm gate beef price has a modestly positive impact on the coefficient of productivity (columns 1-2). Local cattle herd dynamics in frontier areas significantly decrease the coefficient of productivity (columns 2-3), confirming that the effect of the intensification process needs to be separated from a more localized frontier dynamics effect (as suggested by Arima et al., 2011). The year control shows a negligible impact on regression coefficients (columns 6-7). The environment-related variables have a small downward impact on the coefficient of productivity. For example, taken together, the legal reserve legislation, environmental fines, and the creation of protected areas seem to decrease the attractiveness of a frontier municipality for intensification-related deforestation (columns 5-7).

Table 5.4. Robustness check. First difference regression of deforestation on productivity of cattle (OLS)
Dependent variable: natural logarithm of change in deforestation (2007-2012), frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\Delta W_1 prod$	1.675***	1.871***	0.390	0.397	1.046**	0.991**	0.979**
$\Delta W_1 price$	—	2.905	0.422	0.411	2.100	2.630	1.984***
$\Delta W_2 cattle$	—	—	2.60e-05***	2.61e-05***	2.17e-05***	2.37e-05***	2.37e-05***
ΔLR	—	—	—	—	17.39***	17.46***	17.19***
$\Delta title$	—	—	—	-0.00159	-0.00206	-0.00220	-0.00215
$\Delta pr.areas$	—	—	—	—	—	0.737	0.301
$\Delta fines$	—	—	—	2.009	—	-0.143	-0.140
Year	3.749***	-0.649	2.003	—	-0.133	-1.003	—
Observations	65	65	65	65	65	65	65
R-squared	0.157	0.186	0.454	0.454	0.543	0.547	0.901
Adj. R-squared	0.143	0.159	0.427	0.418	0.504	0.492	0.889

Note: the reduced number of observations (65) is due to these regressions being estimated over frontier municipalities only. The information on consolidated municipalities is captured by the spatial weights matrix W_1.

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Table 5.5 presents the results of using the full variation in the data to look at the effect of intensification in consolidated areas on deforestation in pre-frontier, frontier and consolidated municipalities. The variable productivity is interacted with the clusters to capture the specific associations within each cluster. For example, the second row of the table indicates that the growth in productivity in consolidated areas has a positive coefficient but no statistically significant association with deforestation in pre-frontier areas. This result is in line with interpreting pre-frontier areas as a counterfactual to the settlement-intensification-migration-deforestation process. The coefficient on change in productivity for frontier areas, as in the previous tables, is statistically significant at the 1% level and in the range +1.5 to +1.74. Finally, the coefficient for consolidated areas is negative but non-significant, suggesting that deforestation is either not impacted or decreased in neighbouring consolidated municipalities as a result of intensification.

Table 5.5. Robustness check. First difference regression of deforestation on productivity of cattle (OLS), different clusters of municipalities Dep. variable: natural logarithm of change in deforestation (2007-2012)

	(1)	(2)	(3)
ΔW_1*prod*	-0.172	-0.223	-0.376**
ΔW_1*prod*pre-frontier*	0.372	0.139	0.203
ΔW_1*prod*frontier*	1.738***	1.459***	1.686***
ΔW_1*prod*consolidated*	-1.284	-1.685	-1.582
ΔW_1*price*	-2.014**	-0.444	1.579***
Year	5.606***	3.121**	—
All other controls	No	Yes	Yes
Observations	362	362	362
R-squared	0.058	0.408	0.848
Adj. R-squared	0.0369	0.384	0.824

*** p<0.01, ** p<0.05, * p<0.1 Robust t-statistics.

The results from model 1 suggest that a given intensification shock in consolidated areas may or may not have a land-sparing effect within consolidated areas, but the effect on frontier areas would be more deforestation. These conclusions, however, are reverted in model 2.

Model 2

Controlling for fixed effects in growth rates affects the conclusion to a major extent, with the evidence of a land-sparing effect being as robust as that of a rebound effect in model 1, but with a stronger association (in the opposite direction) and statistically significant at lower levels. Keeping the 1996 level of productivity in consolidated areas at its median value, an additional growth in productivity of one standard deviation (all else constant, an increase of R$ 7,400,000 in output from 1996 to 2006) is associated with a 0.36 standard deviation reduction in the growth rate of deforestation in frontier municipalities (66.8 Km^2 less deforestation).

I start by showing, in table 5.6, that a statistically significant association is not found for the placebo test (column 1), nor for periods starting before 2001 (columns 1-3); starting in 2001 the association becomes significant at the 1% level, and the model fit (adjusted-R^2) rises from 0.50 to 0.75 (columns 4-7). The coefficients are consistently negative, suggesting a land-sparing effect with a magnitude in the range of -3.8 and -5.3. The most interesting piece of evidence in table 5.6 is an apparent trade-off between the effects of the growth in local cattle herds within the frontier and the change in productivity in the more distant, consolidated municipalities. Up until 2000 (columns 1-3), the change in deforestation was significantly and positively associated with the growth in local cattle herds, but not with the growth in productivity in consolidated municipalities. In the subsequent period, the pattern was inverted.

Table 5.6. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates), different time frames. Dependent variable: natural logarithm of change in deforestation, frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time frame	97-00	97-12	00-12	01-12	04-12	07-12	10-12
$\Delta W_1 prod$	-3.861	-2.341	-2.202	-5.279**	-3.819***	-3.935***	-4.303***
$W_1 prod_{96}$	-2.219	-1.866*	-1.918**	-3.950***	-2.955***	-2.795***	-3.570***
$\Delta W_1 price$	37,202	20,797	17,325	8,326	7,292	8,450	4,685
$W_1 price_{96}$	-2,377	-1,329	-1,107	-532.7	-466.2	-540.2	-299.9
$\Delta W_2 cattle$	2.56e-05**	1.62e-05**	1.53e-05**	-4.80e-06	-1.51e-06	9.95e-07	-3.48e-06
$W_2 cattle_{96}$	-1.81e-05*	-1.06e-05	-1.38e-05**	-1.98e-06	-6.14e-06	-9.50e-06	-7.99e-06
ΔLR	4.723	10.71***	13.55***	8.573	12.18**	12.68***	10.91**
LR_{96}	–	–	–	–	–	–	–
$\Delta title$	0.0152*	0.0151	0.0135	0.00303	0.000130	0.000284	0.00673
$title_{96}$	0.0727***	0.0325	0.0215	0.0292	0.0232	0.0260	0.0233
$\Delta pr.areas$	-0.136	-0.604	-1.365	-12.41**	-11.48**	-9.655*	-13.45***
$pr.areas_{96}$	-6.810	4.051	6.810	15.57***	15.60***	13.90**	18.74***
$\Delta fines$	-0.549**	-0.357**	-0.329**	0.133	0.0627	0.00508	0.0899
$fines_{96}$	13.01***	1.475	-0.492	7.964	1.807	3.911	-1.545
State dummies	yes	yes	yes	yes	yes	yes	yes
Init. defor. level	yes	yes	yes	yes	yes	yes	yes
Year	24.69	18.19*	17.37*	28.71***	18.88***	16.92***	14.57***
Observations	64	64	64	64	64	64	65
R-squared	0.694	0.682	0.665	0.831	0.835	0.790	0.871
Adj. R-squared	0.541	0.524	0.498	0.746	0.752	0.685	0.803

Note: the reduced number of observations (64) is due to these regressions being estimated over frontier municipalities only. The information on consolidated municipalities is captured by the spatial weights matrix W_1.

*** p<0.01, ** p<0.05, * p<0.1 Robust t-statistics.

Productivity now explains frontier deforestation at the expense of local cattle dynamics (columns 4-7). While the relation between deforestation and local cattle herds is not the focus here, the fact that the coefficient on productivity becomes significant when the one on cattle becomes non-significant suggests that, with a time lag, the impact of the intensification process grows sufficiently strong to dominate the relation with deforestation over local cattle dynamics. This can be seen as evidence that the model is well specified. In fact, in controlling for growth of local cattle herds municipalities within the frontier I am assuming that such growth is not caused by intensification in consolidated areas, otherwise I would be washing away part of the process I am trying to uncover. Yet my assumption is likely to be too strong as any migration process coming from consolidated municipalities through cattle will arguably affect not only frontier municipalities, but also their immediate neighbours. Therefore, by controlling for local herd dynamics I am being overcautious and partially spurring away the effect of interest (appendix D4, columns 1 and 2).

If a triple association between productivity, local cattle herd and deforestation should be expected, then the trade-off that comes out in table 5.6 suggests that the information in the variable productivity becomes sufficient to account for the full correlation pattern from 2001. Interestingly, this trade-off did not appear in model 1 (see table 5.3). Why does it manifest in model 2? The reason is the inclusion of the State dummies and initial levels of the control variables (appendix D5). I report F-tests of the joint signification of the fixed effects and they are always highly significant, suggesting that model 2 should be preferred over model 1. The estimated land-sparing effect is robust to excluding most variables from model 2 (appendix D4). The coefficient on productivity remains negative in all cases, and only when the State dummies and most initial level controls are removed (table 5.7, columns 3-4) does it become non-significant at the 10% level. However, these results are somewhat sensitive to the sample size, as I show in columns 5-6:

Table 5.7. Robustness check. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates). Dependent variable: natural logarithm of change in deforestation (2007-2012), frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta W_1 prod$	-3.724***	-3.723**	-0.910	-0.933	-2.579*	-2.066
$W_1 prod_{96}$	-2.774***	-2.995**	-1.227	-1.539	-2.148**	-2.314**
$\Delta W_1 price$	15,390	14,469	22,460***	2.890	22,989***	2.342
$W_1 price_{96}$	-983.3	-924.6	-1,435***	—	-1,468***	—
$\Delta W_2 cattle$	9.68e-06	1.81e-05	3.52e-05***	2.80e-05***	3.34e-05***	2.76e-05***
$W_2 cattle_{96}$	-1.10e-05	-1.72e-05	-2.74e-05**	-1.26e-05*	-2.45e-05***	-1.12e-05*
ΔLR	15.11***	17.15***	—	19.69***	—	19.32***
LR_{96}	—	—	10.52***	—	9.339***	—
$\Delta title$	0.000668	0.00121	0.00690	-0.00122	0.00713	-0.00395
$title_{96}$	0.0239	0.0331	0.0349	—	0.0414**	—
$\Delta pr.areas$	-1.954	-8.819	0.877	1.765	1.492	2.746
$pr.areas_{96}$	5.480	15.19**	4.030**	—	3.953*	—
$\Delta fines$	-0.0932	-0.239	-0.517**	-0.216	-0.464***	-0.204*
$fines_{96}$	2.516	2.009	-0.951	—	1.364	—
State dummies	yes	yes	no	no	no	no
Init. defor. level (2007)	yes	no	no	no	no	no
Year	11.41	13.84**	0.390	-0.557	3.664	0.277
Observations	65	65	65	65	72	72
R-squared	0.778	0.747	0.665	0.597	0.690	0.619
Adj. R-squared	0.662	0.632	0.579	0.532	0.621	0.563

Note: the reduced number of observations (between 65 and 72) is due to these regressions being estimated over frontier municipalities only. The information on consolidated municipalities is captured by the spatial weights matrix W_1.

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Table 5.8 presents the results of model 2 for each of the three spatial clusters as well as for the full sample. The coefficient on productivity is negative and statistically significant for frontier as well as consolidated municipalities, but non-significant for pre-frontier areas, as expected. The overall effect is thus a net land savings, as in column 1. I analyse the effect of productivity on deforestation in consolidated areas, and find that the coefficients start to be consistently negative and significant from the year 2003 (table 5.9). This suggests that the intensification process has an indirect impact on frontier deforestation even before (year 2001) it impacts deforestation in the closer, consolidated municipalities (year 2003). Table 5.9 also shows that, as should be expected, cattle herd dynamics in frontier locations have no impact on deforestation in consolidated areas (however, the opposite is true under model 1).

Table 5.8. Robustness check. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates), different clusters of municipalities. Dependent variable: natural logarithm of change in deforestation (2007-2012)

	(1)	(2)	(3)	(4)
Municipalities	All	Pre-frontier	Frontier	Consolidated
ΔW_1*prod*	-0.720***	-0.155	-5.475***	-1.785***
W_1*prod*$_{96}$	-0.736***	-0.168	-3.964***	-1.696***
ΔW_2*cattle*	5.66e-06*	1.28e-05**	9.42e-06	-9.47e-07
W_2*cattle*$_{96}$	-4.21e-06	-3.71e-06	-1.11e-05	-5.62e-06
Full set of covariates	yes	yes	yes	yes
Init. levels	yes	yes	yes	yes
State dummies	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observations	362	118	72	172
R-squared	0.607	0.683	0.783	0.733
Adj. R-squared	0.579	0.601	0.679	0.689

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Table 5.9. Robustness check. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates), different time frames. Dependent variable: natural logarithm of change in deforestation, consolidated municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Time frame	97-12	02-12	03-12	04-12	06-12	07-12	08-12	10-12
ΔW_1*prod*	-0.509	-0.431	-0.999**	-1.067**	-1.283**	-1.503**	-1.989***	-1.696**
W_1*prod*$_{96}$	-0.740	-0.779*	-1.158***	-1.177***	-1.256**	-1.473***	-1.932***	-1.821***
ΔW_2*cattle*	-9.47e-07	-1.21e-06	-7.93e-07	9.28e-08	-1.49e-07	-1.76e-06	-1.26e-06	-2.30e-06
W_2*cattle*$_{96}$	1.45e-06	-3.58e-06	-5.71e-06*	-5.52e-06*	-3.72e-06	-4.14e-06	-7.06e-06*	-3.91e-06
Full set of covariates	yes	yes	yes	yes	yes	yes	yes	yes
Init. levels	yes	yes	yes	yes	yes	yes	yes	yes
State dummies	yes	yes	yes	yes	yes	yes	yes	yes
Year	yes	yes	yes	yes	yes	yes	yes	yes
Observations	159	159	159	159	159	159	159	163
R-squared	0.724	0.788	0.798	0.780	0.760	0.733	0.690	0.691
Adj. R-sq.	0.675	0.750	0.762	0.740	0.717	0.686	0.634	0.637

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

The comparison between models 1 and 2 is clearly in favour of the latter. While both pass a placebo test that looks at the impact of growth in productivity between 1996 and 2006 on deforestation between 1997 and 2000, model 2 includes control variables that make theoretical sense, are jointly significant according to an F-test, and produce results that are in line with theory, particularly with regards to the roles of local cattle herd dynamics versus intensification in consolidated municipalities. Moreover, model 1 gives a counterintuitive result when estimated over consolidated municipalities: the coefficient on cattle herd dynamics in frontier locations is consistently positive and significant, suggesting a spatial effect that runs from frontiers to consolidated areas, counter to what should be expected and to the results from model 2.

Controlling for the initial level of productivity causes the coefficient on productivity growth to change signs. The State dummies increase the significance of the negative coefficient, while all other initial levels have only a minor impact on the results. This suggests that the results in model 1 are biased by the omission of the initial level of productivity, and that the mechanism linking intensification to frontier deforestation depends on initial levels. The initial level of productivity is negatively correlated with both the change in deforestation and productivity growth, so its omission led to an upward bias. All in all, the evidence presented under model 2 points to a strong land-sparing effect caused by intensification in consolidated areas. The effect on deforestation in frontier areas is already strong, but I find that deforestation in consolidated municipalities is also reduced.

5.4. Conclusion

Two competing predictions for the effect of land use intensification on deforestation have been proposed in the literature: an optimistic hypothesis that more productive land uses will spare land for nature, and a less optimistic scenario that suggests a displacement effect from localities closer to markets towards forest margins. Evidence allowing for the discrimination between these alternative hypotheses has been thin so far, especially in what relates to cattle ranching. Given the relevance of livestock raising for land use change across the world, this chapter analyses the outcomes of the intensification process in the Brazilian Amazon.

Intensification of cattle ranching takes place mostly in consolidated areas, where markets have deepened and the initial, pioneering phase of the colonization process gave way to a more established society and economy. The main factor that explains the process of land use intensification is enforcement of a command-and-control legislation that places a high toll on land clearings, thus incentivizing farmers to adopt land-sparing technologies. Any stimulus to use land more productively, however, becomes weaker as distance from markets increase, due to lower enforcement of the law as well as high transportation costs curtailing profits. Deforestation due to horizontal agricultural expansion is therefore more likely in frontier locations.

I use data from a 16-year period to test for an indirect land use effect of cattle ranching on deforestation in the Amazon. I categorize municipalities into pre-frontier, frontier and consolidated clusters and look for an association between productivity of cattle in consolidated areas and deforestation in frontier locations. I employ Euclidean distance weights matrices to establish the link between frontier municipalities and their neighbouring municipalities in consolidated areas. Based on a conventional von Thünean approach, an intensification shock in consolidated areas is expected to have a stronger effect on spatially closer frontier municipalities, and a much weaker effect on locations further away. Under this assumption, I run a first-difference model to look for evidence a rebound effect.

I start by adapting the spatial econometric model by Arima et al. (2011) to the case of livestock intensification. Using appropriate controls that include information from frontier municipalities, such as protected areas and property rights, as well as factors from consolidated areas, such as farm gate beef prices, the model suggests a small positive effect of productivity of cattle ranching on deforestation, in line with the rebound effect hypothesis. The results would indicate that changes in productivity in consolidated locations are positively associated with migration of cattle to frontier areas and negatively associated with migration of cattle to consolidated areas. Furthermore, the regression results produce a consistently positive and statistically significant coefficient on the intensification variable.

A key contribution of this chapter is to improve the empirical analysis by adapting the framework in Weinhold and Reis (2008) to the indirect land use effect problem being tested here. I add State fixed effects and initial levels affecting the growth rate of deforestation, thus producing a more coherent framework to test the inherently dynamic hypothesis of a rebound effect. The inclusion of fixed effects directly affecting the growth rate is justified by the presumption that the standard fixed effects in levels is likely to leave out omitted variable bias coming from, for example, the initial level of productivity in consolidated areas affecting the growth rate of deforestation at the frontier through a channel other than the levels of deforestation. I test for the joint significance of the additional controls by running F-tests and the results are in favour of keeping the variables. Moreover, their inclusion changes the results drastically, suggesting that the assumed role of fixed effects in growth rates is indeed important.

The conclusions from the initial model are now reverted and the evidence points consistently to a substantial land-sparing effect of land use intensification. I run a placebo test by estimating the impact of the change in productivity from 1996 to 2006 on the change in deforestation from 1997 to 2000. The resulting coefficient on productivity is not statistically significant, as expected. I run the model for different time frames of the growth in deforestation, starting from 1997 to 2012 until 2010 to 2012, and the effect of productivity starts to be significant from the year 2001, consistent with the idea that there is a time lag. Moreover, there is a clear trade-off between the indirect land use effect coming from distant consolidated areas and the effect of cattle herd growth in the nearest five frontier municipalities. The latter variable becomes non-significant exactly in 2001, suggesting that the effect of productivity becomes sufficiently strong to dominate the indirect effect-related covariance structure.

I run robustness checks to test for the sensitivity to control variables, and the results are consistently robust to dropping control variables in different combinations. I also implement a second placebo test by running the model for pre-frontier municipalities, where the intensification process is expected to have no impact, and the result is as expected. Lastly, I look for more generalizable versions of the model by running it for deforestation in consolidated municipalities, and find that there is an equally robust and statistically significant land-sparing effect, only with a lower magnitude and with a longer time lag (the coefficient starts to be significant in the year 2003).

How strong are the econometric results to allow for a rejection of the rebound effect hypothesis? The identification of the regression coefficients relies on two assumptions. First, that the classification of municipalities into frontier and consolidated locations is exogenous conditional on the control. While different classification schemes have been implemented with equivalent results, this is likely to be a strong a hypothesis that should require further scrutiny. it would be important to try alternative ways of classifying frontiers and consolidated areas. One possibility would be to use the fact that frontier areas tend to see a rapid growth in the area planted with rice, while the consolidation process sees a trade-off between rice and pasture, to distinguish frontiers from consolidated areas. Using rice instead of deforestation would address any remaining concern of selection on the dependent variable.

Second, there can be no omitted variable bias (other than the potential selection bias just discussed) operating through the spatial and time lags assumed for the indirect land use effect. This assumption is more likely to be valid as it is difficult to think of time-varying factors simultaneously affecting productivity in consolidated (1996 to 2006) areas and deforestation in frontier locations (2007 to 2012). In this respect, another improvement would be to use inter-municipality migration data to construct the spatial weights matrix, as the Euclidean distance-based approach may be too crude a way of capturing the spatial pattern of migration.

With those caveats, the overall robustness of the results is a firm suggestion that a land-sparing effect should be taken seriously. Moreover, since the measure of deforestation I use does not capture reforestation or forest regrowth, the possibility of lands previously cleared being abandoned and thus taken for a reduction in deforestation is ruled out.

The provisional conclusion is that productivity growth in consolidated areas can save forests. How does this happen? While the exact mechanism of a land-sparing effect remains unclear, some suppositions can be advanced (a more elaborate discussion of the potential channels is provided in the conclusion of the thesis). The results indicate that the intensification process in consolidated areas first reduces deforestation at the frontier, then reduces deforestation in consolidated areas. This timing suggests that farmers in consolidated areas are initially prevented from out-migrating, reducing deforestation in frontier areas since 2001, but keeping the deforestation pattern unchanged in consolidated areas until 2003, when farmers eventually revert to intensification or migrate to urban areas.

Cattle ranchers in the Amazon are to a large extent price takers, who respond to mostly exogenous output price signals. Once they switch from a traditional production function that relies heavily on horizontal expansion to a more intensive production function, demand for land will decrease at the same time as demand for other production factors (including labour) will increase. An important parcel of farmers, however, are left out of the intensification process, and given the effect that it has on land prices, part of those laggard farmers will at some point resort to out-migration, either to urban areas or to frontiers. The effect on deforestation then depends on the pattern of the resulting migration. For example, the out-migration process can be segmented at the household level, with some members of the family going to the frontier while others head to urban or peri-urban areas. This segmentation may lead to a different pattern of land use at the frontier, but further research is needed to uncover the mechanism linking the intensification process to a land-saving effect at the frontier.

Chapter 6

The flip side of the Environmental Kuznets Curve: do booms in deforestation lead to busts in development?[46]

The Russian economist Simon Kuznets would have been surprised to learn that in the 21st Century his name is attached to discussions of environmental degradation. He was the main scholar behind the creation of the national accounts and the subsequent establishment of economic growth as a key indicator of welfare, in the immediate post-war period. His interest for economic growth was such that he went on to develop the highly controversial hypothesis that per capita GDP growth would initially spur higher levels of inequality, but that continuous economic development would eventually cause inequality to peak and decline—the well-known 'Kuznets curve' (Kuznets, 1955).

If Kuznets' model were to be accepted as a valid general description of the dynamics of inequality, then policymakers would be warranted in aiming at economic growth and expecting inequality to fall. However, a much more nuanced view of the process of inequality reduction is now prevalent over Kuznets' deterministic approach (see, for example, Acemoglu and Robinson, 2002). The result is that instead of targeting growth and expecting equality to follow, policy is increasingly directed at the specific target of reducing inequality.

Likewise, policy is ever more directed at environmental targets as stand-alone goals. Therefore, the question whether environmental degradation stabilizes and fades back when a certain threshold of economic welfare is reached is of upmost importance. Advanced by Grossman and Krueger (1991) and subjected to intense scrutiny in the late 1990s and early 2000s, the Environmental Kuznets Curve (EKC) hypothesis states that environmental degradation follows an inverted U-shape trajectory as per capita GDP

[46] A different version of this chapter has been co-authored with Diana Weinhold and Eustáquio José Reis and published as a Grantham Institute Working paper (Weinhold et al., 2012). More recently, a revised version of the joint work was submitted for publication (Weinhold et al., 2014). Many of the ideas here have benefitted from discussions with the two co-authors, to whom I am thankful, and from the process of editing the mentioned papers. Any error should remain solely mine.

grows. The possibility of an EKC relationship has been examined for various environmental outcomes, including Sulphur and Carbon emissions and concentrations (Stern, 2004), but also for forest loss (Barbier, 2004), with mixed results. On the other hand, if explicit welfare targets (such as GDP growth) are given priority over environmental outcomes, then it is equally important to ask the reversed question, that is, what environmental target is expected to lead to a given development outcome?

This chapter analyses the possible causal nexus between booms in deforestation and busts in development. A handful of theoretical and empirical studies have exploited the so-called 'boom-bust hypothesis' for the specific case of the Brazilian Amazon, with mixed results. The thesis that deforestation causes welfare to follow an inverted U-shaped relationship was first put forward by Schneider et al. (2002). They showed that, if solely based on logging and cattle ranching in humid zones, welfare would see a first phase of rapid growth as deforestation rises, only to suffer a severe decline and enter a stable period of depression when a given tipping point of clearance is reached and overshot. The idea was subsequently extended by Celetano and Verissimo (2007) and empirically substantiated—if only for the bivariate case—by Rodrigues et al. (2009). A more thorough empirical contribution by Celentano et al. (2012) further advanced the analysis by looking at a cross-sectional multivariate (partial) relation and trying to account for spatial unobservables.

If welfare outcomes are to be affected by deforestation, then a reversed version of the EKC should be envisaged. Among the first to examine this issue, Edward Barbier (2004) ran a cross-country regression for tropical countries and Latin America using panel data for the period 1961-94, and found evidence in favour of a boom-bust effect of agricultural expansion on per capita income. The theory behind his model is clearly grounded on the resource curse hypothesis, which states that the exploitation of abundant natural resources often prevents other, more important economic sectors from growing. On the other hand, studies looking at a within-country boom and bust pattern of development (in the Amazon) lack clarity with respect to the mechanisms through which deforestation is expected to affect welfare. At the empirical level, those studies also fail to account for relevant region-wide spatial confounding factors and to provide time-series backing for the inherently dynamic boom-bust hypothesis. Neither do in-depth case studies from across the Amazon show any evidence of a boom-bust pattern of development. Hence the need for a more thorough assessment of the fundamentals behind the boom-bust theory.

I contribute to the discussion of a causal role of deforestation on welfare in four ways. First, I review the existing literature to identify the key potential channels of causation, and use the findings to substantiate an empirical test of the boom-bust hypothesis. Second, I provide evidence on the role played by region-wide unobservable spatial patterns of causation and how these undermine the cross-sectional association that had been identified by previous studies. Third, I assemble a new dataset using data on the 2010 Brazilian Census and recently published municipal HDI figures to look at the problem from a time-series perspective, and find that little evidence can be identified of a causal effect of deforestation on welfare. Fourth, I synthesize in-depth case studies from the States of Pará, Rondônia and Amapá that generated long term evidence allowing for a detailed, site-specific assessment of the boom-bust theory, and find that over time, welfare tends to improve, not bust, as deforestation continues. I conclude by discussing the reasons why my results contradict what was previously found by others, and contextualize the conclusion in terms of discussions of resource curse and hollow frontier.

6.1. How are booms in deforestation linked to busts in welfare?

The idea that deforestation in Amazonia cannot lead to a sustained improvement of wellbeing for local populations dates back to at least the French Geographer Pierre Gourou's (1953) thorough assessment of the numerous challenges that tropical countries face in order to develop. Arguments as varied as the deleterious role played by heat, the excess of rain, soil fragility, amongst others, have been advanced—especially since the beginning of the military government-led internal colonization programmes in the 1960s—to sustain the idea that the particularly fragile environment of humid tropical forests would not be adapted to sustain the types of economic activity that are seen in every developed region (Fearnside, 1986).

The contemporary work on boom-bust patterns of development in the Amazon derives from the tradition above. In this section, I provide an assessment of the mechanisms of causation that have been advanced by recent studies on the boom-bust hypothesis. After a short description of the methods and results of each paper, I list and evaluate the proposed channels of causation, filtering down the arguments to two central ideas. I then use the resulting insights to provide a simple model that describes two channels of potential causation of cumulative deforestation on development by distinguishing direct from indirect welfare outcomes of ecosystem services.

The ground-breaking model by Schneider et al. (2002) was aimed at predicting the outcomes of predatory vis-à-vis sustainable economic activities in the humid parts of the Amazon. They put together a simulation of a "typical Amazonian county" (1 million hectares of dense forest) that either starts out with two economic sectors, predatory logging and cattle ranching, or opts for a sustainable logging sector only. In the first case, extensive cattle ranching progressively occupies the area that is left behind by loggers, until the stocks of timber are fully depleted on year 21, when the county's economy becomes uniquely based on low-productivity livestock production. As opposed to this, in the second simulation, where logging follows pre-established criteria of forest management—harvests have to respect the minimum rotation cycle of 30 years, among others, the economy grows 30% less than in the boom-bust scenario in the first thirteen years, but income is maintained indefinitely at that level.

Two channels of causation can be identified. First, depletion of timber stocks leading to a bust in development. This mechanism is the basis for any boom-bust argument, and it relies on two strong assumptions: that no institutions will emerge that encourage sustainable forest management, and that no other economic sectors will develop to replace logging as the engine of the economy. The second mechanism is extensive cattle ranching leading to an overexploitation crisis. The assumptions in this case are that the activity only generates insignificant levels of welfare and that it is unable to intensify. These, however, are not necessary outcomes of deforestation, as I have shown above.

The work of Schneider and colleagues was successful in showing that no economy can be sustainable when based solely on extensive cattle ranching and predatory logging. However, an economy with such characteristics is virtually nonexistent even in Amazonia. The assumption that no other sector will ever emerge is too restrictive (as the Mazagão and Ouro Preto cases summarized in section 6.3.3 show), as is the assumption that cattle land use systems will remain extensive. Moreover, a proper assessment of the outcomes of two competing sets of economic activities should allow them to interact, so that the fittest can dominate the other, rather than modelling each one in isolation.

In an attempt to establish empirical ground for a more refined version of the theory, Celentano and Veríssimo (2007) made a comprehensive descriptive exploration of the boom-bust idea. They classified municipalities into groups of forested, under pressure and deforested, and computed different indicators of socioeconomic wellbeing for each group, such as GDP per capita, HDI, urban and rural violence, child and slave labour, among others. They conclude that forested municipalities have more sustainable economies where wellbeing indicators are not necessarily higher than in booming areas, but do show a stable long-term behaviour; municipalities under pressure have the highest rates of economic growth but the worst social indicators; and deforested municipalities have the lowest growth and worse social indicators than forested areas.

However, simple correlations are not enough to establish causality. For example, the fact that forested municipalities have a lower incidence of slave labour does not necessarily imply that lower deforestation leads to better labour practices—the observed correlation can be spurious.

The first causal mechanism put forth by the authors is that economic activities based on forests would create more employment and welfare than activities based on cleared land, so continuous deforestation would deplete the economic basis of development. This, however, has been shown to be a questionable assumption (Andersen et al., 2002, Ch. 5). A second channel would be that cumulative deforestation could have a negative, indirect effect on welfare conditional on agricultural potential. For example, if humid areas have poor agricultural potential (low soil fertility, high incidence of plagues), deforestation in these areas could lead to short-lived economic booms. I will further explore this mechanism in the next sections.

The most prominent attempt to empirically substantiate the boom-bust theory for the Brazilian Amazon was made by Rodrigues et al. (2009), who focused on one wellbeing indicator, HDI, and created seven categories of municipalities according to levels of deforestation extent (until 2000) and activity (variation between 1997 and 2000). Category A included localities with a very low cleared area (less than 5%) that were roughly inactive in deforestation (less than 0.5% growth in three years); Category B included those with less than 25% cleared area and between 0.5% and 5% deforestation activity; and so on, until category G, with more than 90% cleared area and less than 0.5% deforestation activity. The authors computed median HDI values for each group and plotted them on a graph with deforestation extent on the horizontal axis and HDI on the vertical.

The resulting curve (figure 6.1), made of the junction of seven points, has a concave shape indicating that municipalities in the agricultural frontier (high deforestation activity) tend to see a boom in development, while post-frontier areas (highly deforested) face lower levels of absolute HDI. The visual pattern is robust to the adoption of different boundaries to group municipalities. The shape of the curve is also roughly maintained when the three components of HDI, income, education, and longevity, as well as the gross value of production of timber, cattle and crops, are plotted against deforestation extent.

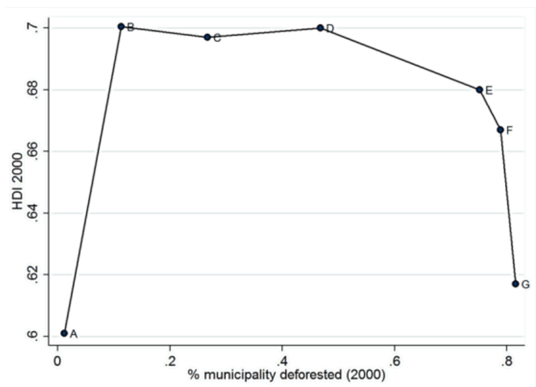

Figure 6.1. Empirical representation of the boom-and-bust hypothesis, reproduced using the methods and data of Rodrigues et al. (2009)

While it is challenging to draw conclusions from such a limited exercise, the possible conclusion would be that when all the relevant omitted variables are kept constant across municipalities, the level of deforestation that maximizes wellbeing at the minimum level of forest clearance is, on average, 11%. However, there is no evidence that when a municipality overshoots that point, say to 80%, it ends up with a net loss of wellbeing; nor is there evidence that increasing the forested area causes a municipality to 'un-develop'. In fact, if anything the data would be showing that the optimum level has increased over time, since for 1997 it was approximately 8.3%.

Two chains of causation were proposed by the authors. First, the exhaustion of the natural resources that supported the initial boom would lead to a bust—the same idea as in Schneider et al. (2002). Second, soil degradation would be an important reason behind the peaking and busting welfare, possibly through its key role on agricultural output. If there is some fixed characteristic in soils that make them unfit for agriculture, deforestation should interact with this fixed characteristic to curtail agricultural development and thus welfare.

Finally, the paper by Celentano et al. (2012) expands the approach by Rodrigues et al. by implementing a multivariate econometric analysis based on cross-sectional data. They run a spatial econometric specification that includes a spatial lag of the dependent variable as well as a spatial structure for the error term, and add a number of controls including rain and agricultural potential. Their conclusion is a less general version of the boom-bust hypothesis. They find evidence in support of a partial boom-bust, where deforestation has an inverted-U shape relation with welfare *conditional on a set of control variables*. They also find evidence of a cubic relationship, whereby at very high levels of deforestation welfare might go up again. The methods and results of this paper will be further explored in section 6.3.1 below.

The causal mechanism suggested by Celentano et al. is similar to the resource curse theory. It states that the large amount of rents paid to one dominant activity tend to suppress other economic sectors as well as leading to corruption, weak institutions and lack of investment in human capital. A resource curse in the Amazon would be characterized by "forest mining", where "*harvest of the high value timber from mature forest* *generates temporarily high profits and employment but leaves behind a less productive forest and appears not to generate sufficient human or other productive capital to sustain the local economy*" (p. 861). The mechanism here is again linked to persistent unsustainable logging coupled with the absence of other sectors that can mature and sustain a growing population.

6.2. A simple model of deforestation and welfare

Three key ideas come out of the literature above. First, a resource curse mechanism could unfold to make any agricultural exploitation activity doomed to failure. This mechanism would be operating on two fronts, one institutional and one economic. On the institutional front, the rents generated in the boom would be wasted rather than channelled to productive uses, and the rules that regulate the use of forests would remain weak and lead to overexploitation. On the economic front, the dominance of the booming activity would create a situation in which resources are centralized in the booming sector and do not make their way to other sectors in the economy. The result would be overexploitation leading to a bust with no other relevant sector in the economy making up for the busting activity.

The resource curse mechanism is an important theoretical background to the analysis I undertake here, and my results certainly shed light on the discussion, but my empirical specification does not try to capture in any explicit way institutional channels or general-equilibrium, inter-sectoral dynamic effects. I instead focus on the effect that deforestation may have on welfare through two channels: the provision of ecosystem services and agricultural output.

The second mechanism is the role of environmental externalities and, more specifically, ecosystem services such as pollination, nutrient cycling, and pest regulation. The absence of forests affects the provision of ecosystem services. This channel affects welfare through agriculture, irrespective of the level of other variables. A third channel would instead capture the hypothesis that where ecosystems are initially fragile—poor soils and too much rain—the impact of cumulative deforestation on ecosystem services and thence on agricultural output would exhibit a strong boom-bust trajectory, while areas with higher agricultural potential would be able to benefit from deforestation in a more sustained way. In this case there would be an indirect effect of ecosystem services on output, intermediated by initial conditions of fertility and rain—what I call 'agricultural potential'.

To integrate these ideas into a simple model that can later be assessed empirically, I start by making welfare (as measured by poverty, per capita GDP, or HDI) a function of agricultural output, institutions and other economic activities, as in Equation (6.1). This emphasizes the role of agricultural output in intermediating the effect of deforestation on welfare, as well as the possibility of a resource curse deterring institutional development and economic diversification.

$$(6.1) \qquad Welfare = f_1(\boldsymbol{agricultural\ output}, institutions, other\ economic\ activities)$$

Agricultural output is a function of cleared area (deforestation), fixed ecological conditions such as fertility and rain (agricultural potential), and changing techno-managerial circumstances (technology):

$$(6.2) \qquad Agricultural\ output = f_2(\boldsymbol{deforestation}, \boldsymbol{agricultural\ potential}, \boldsymbol{technology})$$

Moreover, the functional form f_2 must include both (a) a direct effect of cumulative deforestation (through a variety of unobserved ecosystem services) on agricultural output, and (b) an indirect impact of cumulative deforestation on agriculture that depends on the initial level of agricultural potential and on technological dynamics. For instance, areas with very high precipitation would be subject to a more substantial deleterious effect of deforestation as the depletion of ecosystem services would more easily undermine ecosystem resilience (and thus agricultural output). Likewise, areas with higher investment in technologies that increase ecosystem resilience—and agricultural potential—would see lower impacts of deforestation on welfare as farmers would have some control over the supply of fertility and other relevant agricultural inputs. In short, (a) implies an individual effect of deforestation on welfare that does not depend on the level of any other variable, whereas (b) implies different slopes for different levels of agricultural potential.

Lastly, an impact of deforestation on welfare that does not depend on agricultural output can also be envisaged. In this case, provision of ecosystem services that affect quality of living, such as weather regulation, biodiversity (option value), and environmental amenities (existence value), would have a direct effect on welfare, as in Equation (6.3).

(6.3) $Welfare = f_1(agricultural\ output, institutions, other\ economic\ activities, \boldsymbol{deforestation})$

The resulting model is a synthesis of the mechanisms explored above, including (1) the role of agricultural output on welfare as well as the possibility of a resource curse, (2) the indirect role of deforestation through agricultural output as well as through agricultural potential, and (3) the direct impact of deforestation on welfare. In the next section I use time-series data to provide the first dynamic test of the boom-bust hypothesis, and the equation in (6.4) is the primary empirical specification I employ (presented now to establish the link with the theoretical model, but with a more detailed discussion in section 6.3.2). The coefficients β give the partial effect of deforestation on welfare, ρ gives an indirect effect of deforestation through initial conditions of agricultural potential, δ gives indirect effect of deforestation through changes in technology, and X is a set of control variables including population density and immigration. Variables that intermediate the association between deforestation and welfare, such as agricultural output and human capital, are purposefully omitted to leave way for the causal mechanism to show up.

(6.4) $$welf_{i,t} = a_i + T_t + \beta' def_{i,t}^{\omega} + \rho'\left(def_{i,t}^{\omega} * agrpot_i\right) + \delta'(def_{i,t}^{\omega} * tract_{i,t}) + \pi' X_{i,t} + \varepsilon_{i,t}$$

Where the subscripts i and t indicate municipality and year, *welf* is either HDI or per capital GDP, a are municipality fixed effects such as distance to markets, T is a time fixed effect, *def* is deforestation, *agrpot* is agricultural potential, *tract* is number of tractors (a proxy for agricultural technologies), X is a vector of control variables including agricultural potential, tractors, immigration, and population density (a proxy for settlement age), and ε is the error term.

I now turn to an assessment of the boom-bust hypothesis based on three sets of evidence. I initially use cross-sectional data to scrutinize the static models by Rodrigues et al. (2009) and Celentano et al. (2012). The analysis of the cross-sectional evidence provides a fine-grained assessment of the empirical results in the existing literature and discusses their limitations. I then provide a more appropriate analysis of the dynamics implicit in the boom-bust theory by using time-series data on a 14-year period and resorting to the simple theoretical model developed in the present section. Finally, I document published evidence on four case-studies in the Brazilian Amazon that allow for a more detailed assessment of the long term dynamics of deforestation and development.

6.3. Assessing the boom-bust hypothesis

The results presented in this section are based on municipality-level data for the Brazilian Amazon from official sources, including the National Institute for Spaceship Research (INPE), the Brazilian Institute of Geography and Statistics (IBGE), and the Applied Economic Research Institute (IPEA), as detailed in table 6.1. The main dependent variable I use is the Municipal Human Development Index, whose values for the year 2010 were released by the United Nations Development Programme (UNDP) in August 2013; to the best of my knowledge, this is the first study to look at the change in HDI from 2000 to 2010 in the context of deforestation. The methodology for the calculation of the HDI has been updated[47] and the 2013 figures include the values for 2010 as well as recalculated values for 2000 that allow for time and space comparability.

Table 6.1. Variable descriptions, definitions and sources

Variable name and description	Mean (2000)	Years	Definition	Source
Municipal Human Development Index (*HDI*)	0.66	2000, 2010	Index of education, longevity and income	UNDP
GDP, R$ (per capita) (*gdppc*)	2,921.90	1996, 1999-2010	(=GDP/population)	IBGE
Agricultural output, R$ (per capita) (*agrout*)	0.23	1996, 2000, 2007, 2010	(=agricultural output/population)	IBGE
Average revenue, R$ (*rev*)	353.25	2000, 2010	—	IBGE
Deforested area (percent) (*def*)	0.33	1997, 2000-2010	(=cleared area/areakm2)	INPE
Deforested area outside conservation units (percent) (*defout*)	0.47	1997	(=cleared area/areakm2)	Celentano et al. (2012)
Total population (*pop*)	26,647.15	1996, 2000, 2007, 2010	—	IBGE
Area of municipality, km_2 (*area*)	6,658.80	1995,1998, 2000, 2010	—	IBGE
Average year temperature, ^{o}C (*temp*)	26.17	Historical	—	IPEAData
Average year rainfall, mm/month (*rain*)	162.44	Historical	—	IPEAData
Soil fertility index (*fert*)	3.49	1995	(from 1 to 8, where 1 = lowest)	Embrapa
Literacy rate (*educ*)	0.75	1996, 2000, 2010	—	Ministry of Education, IBGE
Tractors per Mha agricultural area (*tract*)	0.55	1995, 2006	(=tractors in rural household/total area rural households)	IBGE
Immigration rate (persons born outside the State) (*immig*)	0.24	2000, 2010	(= persons born outside state/population)	IBGE
Population density (per km2) (*pdensity*)	19.44	1996, 2000, 2007, 2010	(=pop/areakm2)	IBGE
Transport costs from municipal seat to São Paulo, R$ (*tcost*)	3,338.80	1995	—	IPEAData
Controls in Celentano et al. (2012)'s model	—	—	—	Celentano et al. (2012)

Notes: UNDP = United Nations Development Programme; IBGE = National Bureau of Statistics; INPE = National Space Research Institute; IPEA = Applied Economics Research Institute; Embrapa = Brazilian Enterprise for Agricultural Research. Currency in constant 2000 R$.

[47] Two changes have been implemented: first, the formula for the education component of HDI has changed as of 2010, and the new formula has been applied to the old series; second, the data for the years before 2010 was put in the 2010 municipality grid using census tract-level data.

6.3.1. Cross-sectional evidence

I start by reproducing the original findings by Rodrigues et al. (2009) using both their restricted sample (N=286) and the full sample of municipalities in the Brazilian Amazon (N=756). I then use visual interpretation to look for patterns of spatial clustering of the data that could bias the bivariate results.

The simplest econometric specification attempts to explain the variation in HDI by using data on deforestation, with both level and quadratic terms:

$$HDI_i = \alpha + \beta def_i + \gamma def_i^2 + \varepsilon_i \quad (6.5)$$

The results are presented in table 6.2. Starting from columns 1-3 (the original sample used by Rodrigues et al.), it can be seen that a model without the quadratic term does not fit the data (F-statistic very low), and that when present the quadratic term is negative (for a concave curve) and significant in both specifications, using deforestation either in 1997 or in 2000. Columns 4-6 then show that in the full sample all specifications are significant, but column 5, where level and quadratic terms are included for deforestation in 1997, shows the best fit. The comparison between the full sample and the original sample also indicates that the results are systematically weaker when all municipalities are taken into consideration. Indeed, the slope of the curve is reduced by one third (comparing the coefficients on the quadratic terms in columns 5 and 2), making the concavity much less accentuated. Moreover, the specification with the complete sample is significant without a quadratic term (column 4), although the explanatory power rises substantially when the quadratic is added (columns 5-6).

The bivariate results are thus robust to sampling, but they are also robust to using measures of HDI and deforestation from any two years, as I show in figure 6.2. They remain, however, cross sectional correlations. For the cross-sectional pattern to be interpreted as indicative of a typical dynamic process within a single municipality, it must be assumed that those regions in high clearing categories (F or G) are good proxies for the future of areas in low-clearing categories (A or B), and that intermediate categories (C, D, and E) are good proxies for the interim conditions in a boom-bust transition. In other words, all municipalities in the sample must be on the same dynamic path. However, the Brazilian Amazon is a highly heterogeneous region with several distinct sub-regions, each with their own unique historic, economic, geographic, and climactic characteristics. To the extent that the variation in any of these characteristics (omitted in a bivariate model) is correlated with HDI and land clearing, spatial heterogeneity could lead to a spurious interpretation of the relationship between deforestation and development.

Table 6.2. Summary of OLS regression results for cross-sectional specification without controls
Dependent variable: Human Development Index (2000)

Sample:	*N*=286 (Rodrigues et al., 2009)			*N*=756 (all municipalities)		
	(1)	(2)	(3)	(4)	(5)	(6)
Deforestation (1997)	-0.038	0.32***	—	0.11***	0.19***	—
Deforestation² (1997)	—	-0.37***	—	—	-0.25***	—
Deforestation (2000)	0.033	—	0.33***	-0.12***	—	0.13***
Deforestation² (2000)	—	—	-0.36***	—	—	-0.17***
F-statistic	0.18	35.64	30.3	10.81	31.02	15.06
Prob > F	0.831	0	0	0	0	0
R-squared	0.002	0.172	0.167	0.024	0.065	0.037
Adj. R-squared	-0.0053	0.166	0.161	0.021	0.062	0.034

*** p<0.01, ** p<0.05, * p<0.1 Robust t-statistics.

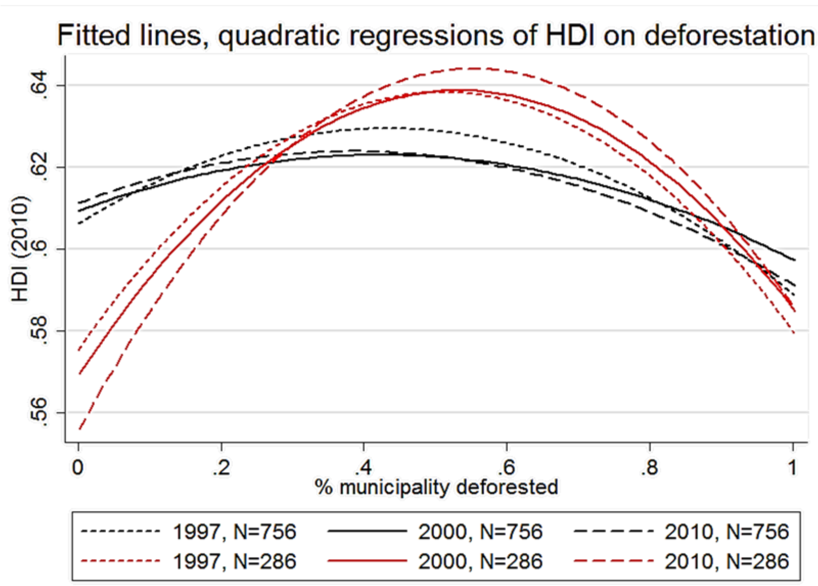

Figure 6.2. Bivariate results for different cross-sectional time frames using full sample (*n*=756) and Rodrigues et al. (2009)'s sample (*n*=286)

To have an initial idea of whether the conclusions from the bivariate analysis are being driven by spurious spatial patterns, I have plotted the HDI values of pre-frontier, frontier, and post-frontier municipalities on a map of the Legal Amazon (figure 6.3). The map on the bottom left-hand side shows that municipalities with low HDI in the pre-frontier category are clustered in the west of the Amazon region, covering most of the State of Amazonas; the map at the top shows that frontier municipalities are dispersed through the so-called deforestation arch, in the southeastern fringe of the region, and most of them indeed have higher than median levels of HDI; and the map at the right-hand side shows that post-frontier municipalities can be divided into a group with median to high levels of HDI, which is dispersed in different clusters in four States out of roughly seven analysed, and a numerous group of municipalities with very low HDI that is almost totally concentrated in the Northeastern State of Maranhão.

The idea is to check whether the municipalities in each phase of the boom-bust cycle (pre-boom, boom, and bust) are spatially well distributed across the region, or if they are instead clustered in specific areas, and the unambiguous conclusion is that localized phenomena are playing an important role. The 'map-observations' in figure 6.3 do indeed display a 'boom-bust' pattern, with the coloured municipalities in less cleared areas (category A) displaying low levels (red) of HDI, the coloured municipalities in the middle categories displaying relatively high (green) HDI, and the more cleared municipalities in categories E-G displaying again low levels of HDI.

But figure 6.3 also illustrates the high degree of spatial clustering of these municipalities. The municipalities with low levels of HDI in category A are almost exclusively clustered in the far western edge of the Amazonas State, and, more strikingly, the municipalities responsible for the 'bust' part of the relationship—those with low levels of HDI in categories E,F and G—are tightly clustered in the historically poor Northeastern region in and around the State of Maranhão. Figure 6.4 zooms in on the group of post-frontier municipalities with very high deforestation ('G' category) to show that those with low-HDI are all clustered together in Maranhão.

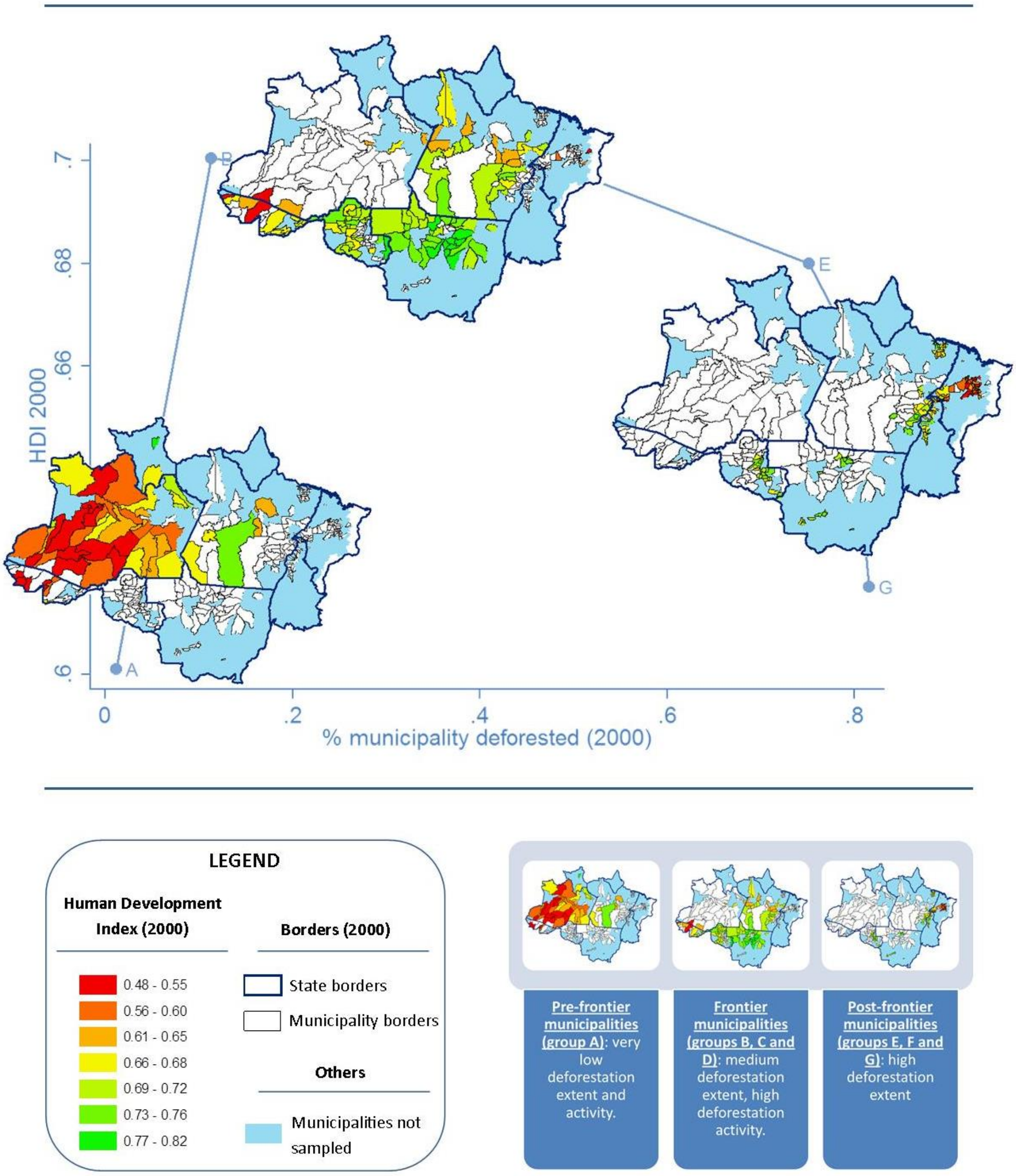

Figure 6.3. Spatial clusters of HDI and deforestation in the Brazilian Amazon.

Sources: INPE, UNDP. Municipalities are divided into three groups based on the categories and data in Rodrigues et al. (2009), then mapped out and colour-coded by level of HDI

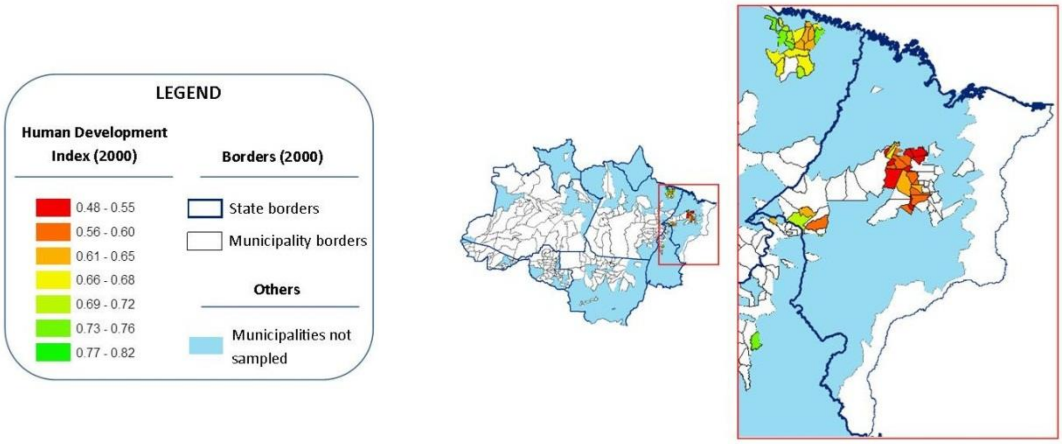

Figure 6.4. Post-Frontier municipalities (group G of Rodrigues et al., 2009).

Sources: INPE, UNDP

The categories pre and post-frontier coincide with clusters of lower than median development in western and eastern Amazonia, whereas frontier municipalities are much more dispersed over the region. This suggests that the boom-bust pattern may be an extrapolation for localized phenomena rather than a global Amazonian phenomenon. In fact, the States of Amazonas and Maranhão have the most important clusters of low HDI not only in Amazonia but in the whole country, which suggests that there may be other factors to explain their lower than average performance. For example, lack of road infrastructure is one of the most important predictors of low deforestation in Amazonas, and it also explains the lower than average HDI observed in that State (see, for example, Andersen et al., 2002, Ch. 6). Poverty in Maranhão, on the other hand, is a phenomenon that has to do with the dynamics of the Northeastern region much more than it has to do with any specificity of Amazonia (see Andersen et al.(2002, pp. 21-33) for a detailed discussion).

I illustrate the latter point in table 6.3, which presents the average relative percentile rank of rural and urban median household income and poverty among municipalities in Amazonas and Maranhão compared to all other municipalities in Legal Amazonia in both 1980 and 2000. The figures show that while municipalities in Amazonas have fallen behind as large numbers of poor internal migrants have moved to the region, the relative poverty of Maranhão has remained virtually stagnant over the entire period. In other words, there is no sign of a 'bust' in Maranhão; municipalities there have consistently ranked near the bottom in human development over time.

Table 6.3: Share of municipalities (%) below key poverty and income thresholds within Legal Amazonia (percent that rank below)

	Amazonas		Maranhão	
Year	1980	2000	1980	2000
Rural poverty rate	0.46	0.94	0.73	0.68
Urban poverty rate	0.38	0.60	0.71	0.69
Rural median household income	0.63	0.19	0.26	0.32
Urban median household income	0.61	0.41	0.30	0.31

Source: Diana Weinhold (Weinhold et al., 2012) with data from IPEA.

The bivariate relationship advanced by Rodrigues et al. is an unconditional one. It suggests that the boom-bust pattern holds irrespective of any other factor. However, a simple spatial analysis refutes the generalized version of the boom-bust model, showing that the results are instead driven by localized phenomena. Because the clusters seem to be State-specific, this spatial pattern would be in principle ideally captured by State dummy variables, which would control for State-specific characteristics and the difference between States.

The multivariate case

Taking the above insights about region-wide patterns of spatial causation, I now consider the partial boom-bust pattern evidenced by Celentano et al. (2012). Their model is an adaptation of Equation (6.5) for the multivariate case, where they look at the association between deforestation and welfare conditional on a set of control variables, including a spatial structure for the dependent variable and error term. Their cross-sectional results would confirm a more restricted version of the boom-bust hypothesis by showing a robust quadratic effect of deforestation on HDI, both in the standard OLS framework and in the spatial specification. Their spatial econometric model is the following:

$$welf_i = \alpha + \rho W welf_i + \beta def_i + \gamma def_i^2 + \delta def_i^3 + \pi' X_i + (W\epsilon_i + \varepsilon_i) \quad (6.6)$$

Where W is an inverse-distance spatial weights matrix, ϵ is the part of the error-term structure which is assumed to be spatially auto-correlated, and ε is the idiosyncratic term. The model acknowledges the potentially biasing role of spatial clustering and tackles the problem with an approach known as 'general spatial model', where both a lag of the dependent variable and an assumed structure for the error term, which accounts for clustering in the unobservable variables, are included (see Gibbons and Overman (2012) for a detailed discussion of this model). By doing this, their model assumes that welfare in municipality i is affected by conditions in municipality i but also by welfare in the neighbouring municipalities. This is a problematic strategy as it introduces an extra source of endogeneity which cannot be dealt with by purely econometric means (see Anselin (2002) for a full critique of this procedure).

The spatial pattern that has biased the bivariate results, however, is unlikely to be captured by the weighting scheme in W, as the Amazonas and Maranhão clusters are located in two extremes of the Amazon region, so the inverse-distance procedure will prevent them from being considered neighbours and hence will miss the most important spatial pattern. For this reason a proper specification should also include State dummies that account for the differences between any two States.

Table 6.4 presents results of Equation (6.5) for two welfare indicators, per capita GDP and HDI. In both cases, it is clear that cumulative deforestation is strongly associated with welfare whenever individual effects of States are disregarded. However, if controls that account for unobservable effects of single States are accounted for, any partial association between deforestation and HDI at the cross-section is eliminated (coefficients of the deforestation variables become non-significant). This is true both for standard OLS specifications and for Maximum Likelihood spatial models, attesting that the spatial structure that is incorporated into Equation (6.6) is not able to capture the region-wide effect of clusters of low deforestation-low development in Amazonas and high deforestation-low development in Maranhão. The results are robust to the inclusion of an interaction term between deforestation and agricultural potential to account for the indirect effect specified in Equation (6.5), as well as to using the full sample of Amazon municipalities.

Table 6.4. OLS and General Spatial models of deforestation on HDI using Celentano et al. (2012)'s sample and specification

	Human Development Index (2000)				Per Capital GDP (2000)			
	OLS		ML (Lag Y + Error)		OLS		ML (Lag Y + Error)	
Deforestation (1997)	0.336***	0.0315	0.171***	0.085*	1957.6***	-80.72	700.69***	44.52
Deforestation^2 (1997)	-0.842***	-0.102	-0.450***	-0.161	-4950.7***	-373.37	-2223.8***	-574.98
Deforestation^3 (1997)	0.531***	0.0818	0.307***	0.108	3032.7***	398.07	1561.6***	519.18
Spatial lag of Y (W_Y)	—	—	0.866***	0.695***	—	—	0.882***	0.518***
Controls	yes	yes	yes	yes	yes	yes	yes	yes
State dummies	no	yes	no	yes	no	yes	no	yes
Constant	0.740***	0.763***	0.122***	0.284***	1406.2***	1361.2***	433.66***	908.57***
Observations	399	399	399	399	399	399	399	399
AIC	-1184	-1421	-1389	-1485	5853	5582	5597	5564
Adj. R-squared	0.301	0.619	_	_	0.294	0.647	—	—
Pseudo R-squared	—	—	0.608	0.696	—	—	0.653	0.681

Notes: Controls (same as in Celentano et al., 2012): agricultural potential, rain, presence of mining activities, paved roads, population density, rural population, distance to State capital and Amazon River. Sample (same as in Celentano et al., 2012): municipalities whose original vegetation cover was less than 50% Amazon forest were dropped, as well as four State capitals and four municipalities with no welfare data. AIC = Akaike Information Criterion: similar to a Log-Likelihood comparison of nested models, this stastic is used for the comparison of non-nested models, lower values indicating the preferred specification.

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

A major problem with Celentano et al.'s model is that they correct the deforestation measure to exclude protected areas. While I calculate the variable deforestation as $def = \frac{def_{PA}+def_{NPA}}{area_{PA}+area_{NPA}}$, where NPA is non-protected area and PA is protected area, Celentano et al. remove the terms with the subscript PA. This is problematic because it takes municipalities that have the typical features of highly forested areas (a forest economy and high provision of ecosystem services) for high clearers. For example, the municipality of Guajará-Mirim, in Rondônia, is a typical highly forested municipality, where only 5% of the area had been cleared by the year 2000. The village and the agricultural areas in this municipality are surrounded by vast dense forests, and to this day it remains a highly forested municipality. However, since a big part of the 95% forested area were protected areas, Celentano et al.'s measure of deforestation in Guajará-Mirim for the year 2000 was an astonishing 56%, well above the mean for all municipalities of 40%.

A similar example is the municipality Centro Novo do Maranhão, where the conventional measure of deforestation amounted to 30% in the year 2000, but Celentano et al.'s measure was 94%. On average, the deforestation measure is increased by 19.35% of one standard-deviation due to the exclusion of protected areas. Not surprisingly, the procedure adopted by Celentano et al. virtually doubles the size of the coefficients on deforestation, and makes them remain significant even with State controls, contrary to what I find with the normal measure of deforestation. This is so because municipalities such as Guajará-Mirim, where forest cover is high but the economy still quite small, are instead taken for highly forested municipalities where the economy is busting.

A cross-sectional specification that correctly accounts for spatial patterns, therefore, fails to find evidence of a partial boom-bust relationship. I now turn to look for dynamic boom-bust patterns using panel data.

6.3.2. Time-series evidence

I start by providing a simple test of the implications of the boom-bust hypothesis. Municipalities in Group G of Rodrigues et al. (2009) had at least 90% of their areas cleared in 2000; since then they could not have returned to a frontier or pre-frontier condition, so if the boom-bust hypothesis holds, those municipalities should have seen a bust in development in the subsequent years. According to the theory, municipalities that were in the highest deforestation group should have developed at a slower pace than the rest. To test for that, I compare GDP per capita at the municipality level between the years 2000 and 2007. For the boom-bust theory to hold, municipalities in Group G would need to have seen a very low, or at least lower than median growth in GDP per capita during that period. Results are presented in table 6.5.

Median per capita GDP in post-frontier municipalities grew almost 50% above the national median, slightly more than the Legal Amazon's median, and a little less than the median of groups A to G (but roughly the same when averages are computed instead of medians). This result contradicts the central prediction of the boom-bust theory, that "*relative development levels* (…) *decline as the frontier advances*" (Rodrigues et al., 2009, p.

1435), and that "*standard of living improve*[s] (…) *at below* [national] *average rates as deforestation progresses*" (p. 1436).

Table 6.5. Implications of boom-and-bust theory and empirical evidence

Group	Implication of theory for rate of development	Median variation of per capita GDP, 2000 - 2007	Average variation of per capita GDP, 2000 - 2007
A (pre-frontier)	No specific implication. Municipalities in this group could have migrated to any other group in seven years.	31.50%	33%
B to F (pre to post-frontier)	Anything; this is a diverse group of municipalities that could either be at the boom phase, with higher than median rates of development, or at the post-frontier phase, with lower than median rates of development.	40.70%	49.20%
G (post-frontier)	**Theory implies lower than median rates of development.**	**36.90%**	**45.20%**
All Brazil	_	25.5% *	31.6% *
All Legal Amazon	_	35.80%	47.90%
A to G	_	39%	45.80%

Source: Brazilian statistical agency (IBGE).

*Based on estimates of population for municipalities with more than 170,000 inhabitants.

I further explore the time-series data for clues of the inverted U-shaped relation between cumulative deforestation and welfare found in Rodrigues et al.. For the boom-bust hypothesis to be correct, there would need to be (i) at least some municipalities that boom and then bust, (ii) these localities should be faring worse than the national average, and (iii) there would need to be at least some suggestion that those municipalities saw a boom-bust due to deforestation. To check for that, I classify 621 Amazonian municipalities with recorded data on GDP per capita from 1996 to 2010 according to weak definitions of 'boom', 'bust' and 'high clearance', and look for any association between boom-bust and high levels of deforestation.

a) A discernible boom is defined as per capita GDP growth higher than in 75% of sampled municipalities between 1996 and any year before 2002 (inclusive).

b) A discernible bust is defined as per capital GDP growth lower than in 75% of sampled municipalities between 1999 and any year before 2010 (inclusive).

c) I define high clearance as being among the top 40% clearers in 1997.

From the 220 municipalities that had both a discernible boom and a bust, only 4 fared worse than Brazil (in terms of per capita GDP growth) in the full period, with 1 having had negative per capita GDP growth (figure 6.5). From the 4 boom-bust municipalities that fared worse than Brazil, none was among the high clearers: one had zero deforestation in 1997 (Bagre), two were on the 28th percentile of the deforestation distribution, and one was on the 57th percentile (Brasil Novo).

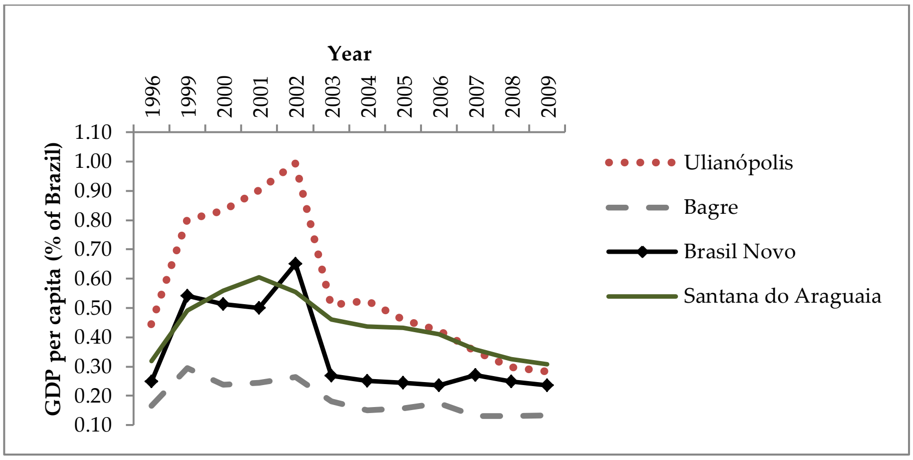

Figure 6.5. Municipalities in Brazilian Amazon with boom and bust in per capita GDP that fared worse than the Brazilian average, 1996 - 2010

Lastly, I face the problem the other way around, looking for the high clearers first then checking what happened to them in terms of per capita GDP and agricultural output. If deforestation is related to a boom and bust situation at all, then agricultural output is likely to be the channel of causation. Yet no high clearing municipality saw a discernible boom and bust in per capita agricultural output; indeed, the lowest per capita agricultural output growth between 1996 and 2007 for all municipalities was +34.9%. Moreover, only two high clearers saw a discernible boom-bust in per capita GDP: Ulianópolis and Santana do Araguaia. Their per capita agricultural output change was +238.5% and +162% respectively. Both groups of municipalities fared better than Brazil in the 14 years captured by the data.

A simple description of the data shows no unconditional effect of deforestation on welfare in the Amazon region. While only four municipalities out of 622 had a discernible boom-bust and fared worse than Brazil in the 1996-2010 period, none of them was a top 40% clearer. Moreover, no less than 147 boom-busters actually grew more than Brazil in terms of per capita GDP. This suggests that even if deforestation causes degradation of ecosystems and a reduction of ecosystem services, there seems to be no clear impact on welfare. Yet one must leave room for a partial effect of deforestation in the time-series. Even if there is not a global bust in highly deforested municipalities, partial causality of deforestation on welfare may still be hidden by other forces. A final test would be to try and purge out those confounding factors and see if a partial effect of deforestation on welfare comes out.

The multivariate case

I employ a first difference procedure to estimate Equation (6.4) with panel data while controlling for time and municipality fixed effects in the level of welfare. The resulting specification (Eq. 6.7) accounts for any time invariant characteristics of municipalities that may be correlated with the levels of deforestation and welfare. The right-hand side variables are time lagged (with the exception of immigration) to decrease the possibility of reverse causality. For example, I use the change in deforestation between 1997 and 2009 and the change in number of tractors between 1996 and 2006:

$$(6.7)\ \Delta welf_{i,t} = \Delta T_t + \beta' \Delta def_{i,t}^{\omega} + \rho' \left(\Delta def_{i,t}^{\omega} * agrpot_i\right) + \delta' (\Delta def_{i,t}^{\omega} * \Delta tract_{i,t}) + \pi' \Delta X_{i,t} + \Delta \varepsilon_{i,t}$$

β, ρ and δ test the hypotheses of a direct effect of deforestation on welfare, an indirect effect through agricultural potential, and an indirect effect through technology, respectively. *Welf* is either HDI, per capita GDP, or per capital agricultural output, T is a time dummy that controls for factors such as international commodity prices, ω is the quadratic exponential of the variable deforestation, X is a matrix of control variables including adoption of agricultural technologies (tractors), immigration rate, and population density (a proxy for settlement history[48]), and $agrpot_i = \{rain_i + fert_i\}$ is agricultural potential, including historic measures of precipitation and natural fertility of soils.

The results are in table 6.6. Starting from the control variables, immigration has a positive sign indicating that increasing the amount of residents born outside the State tends to be associated with higher welfare. Change in number of tractors is also positively associated with change in HDI. Change in population density, on the other hand, has a negative sign, suggesting that older frontiers develop saturation effects that reduce welfare, all else constant. For example, depletion of soil fertility may be a process linking population density to welfare. The coefficients on deforestation indicate a statistically significant association with welfare, both directly and indirectly. In fact, the results are significant only when the indirect effects (interactions with agricultural potential and tractors) are considered. The total effect of deforestation on welfare, though, is positive (figure 6.6).

Table 6.6. Fixed effects regressions of HDI on deforestation (1997-2009)
Dependent variable: change in HDI (2000 - 2010)

	(1)	(2)	(3)	(4)	(5)
Δ Deforestation (Δdef)	1.24e-06	9.64e-05***	8.16e-05***	2.82e-06	8.12e-05***
Δ Deforestation² (Δdef²)	9.57e-11	-4.49e-08***	-4.05e-08***	8.64e-11	-3.98e-08***
Δdef x rain	—	-4.32e-07***	-3.57e-07***	—	-3.52e-07***
Δdef² x rain	—	2.16e-10***	1.92e-10***	—	1.88e-10***
Δdef x fertility	—	-2.88e-06	-2.14e-06	—	-2.12e-06
Δdef² x fertility	—	1.45e-09***	1.43e-09***	—	1.42e-09***
Δdef x Δtractors	—	-2.58e-05**	-1.74e-05	—	-2.03e-05***
Δdef² x Δtractors	—	1.43e-09	-6.98e-10	—	—
Δ Immigration	—	—	0.000777***	0.000728**	0.000769***
Δ Tractors (96-06)	—	0.00552	0.00661	0.00115	0.00730***
Δ Pop. Density (96-06)	—	—	-0.000321***	-0.000343***	-0.000317***
Year.2010	0.159***	0.157***	0.160***	0.161***	0.160***
Observations	444	444	444	444	444
R-squared	0.015	0.068	0.113	0.068	0.113
Adj. R-squared	0.00876	0.0465	0.0880	0.0557	0.0900

Note: municipalities whose boundaries changed more than 5% between 2000 and 2010 were dropped, as well as those with no data for at least one of the variables in the model for at least one year.

*** p<0.01, ** p<0.05, * p<0.1; robust t-statistics.

[48] Settlement history is a particularly important confounding factor inasmuch as older frontiers tend to see saturation effects that are correlated with deforestation. For example, reduction of soil fertility arises naturally after a few decades of agricultural activity, and it tends to be correlated with a municipality becoming a high clearer.

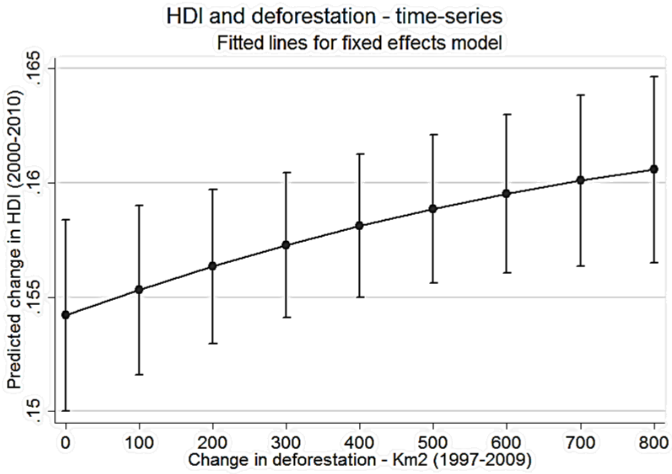

Figure 6.6. Estimated association between change in deforestation (1997-2009) and change in HDI (2000-2010)

The results from a simple fixed effects specification, however, could be biased by the omission of initial levels of deforestation and the control variables. Similar to model 1 in Chapter 5, Equation (6.7) does not control for fixed effects in the growth rate of welfare, such as characteristics from a given State that may be correlated with both the change in deforestation and in welfare. It was clear from the analysis of cross-sectional data that a spatial pattern linking the States of Maranhão and Amazonas is crucial to explain the variation of HDI across space. The Celentano et al. model also showed that accounting for a spatial structure in the data significantly reduces the coefficients on deforestation. Those results were valid for the levels of HDI, but they could be as valid for the change. I therefore follow Weinhold and Reis (2008) in adding controls for the initial levels of the independent variables ($X_{i,t1}$) as well as for State fixed effects (DS_i):

(6.8) $$\Delta welf_{i,t} = DS_i + \Delta t_t + \varphi def_{i,97}^{-1} + \beta' \Delta def_{i,t}^{\omega} + \boldsymbol{\tau}'\left(\Delta \boldsymbol{def}_{i,t}^{\omega} * \boldsymbol{def}_{i,97}^{-1}\right) + \boldsymbol{\rho}'\left(\Delta \boldsymbol{def}_{i,t}^{\omega} * \boldsymbol{agrpot}_i\right) + \boldsymbol{\delta}'\left(\Delta \boldsymbol{def}_{i,t}^{\omega} * \Delta \boldsymbol{tract}_{i,t}\right) + \vartheta' X_{i,t1} + \pi' \Delta X_{i,t} + \Delta \varepsilon_{i,t}$$

This specification departs from the fixed effects in growth rates model in Chapter 5 in one crucial way: I now focus on the *inverse* of the initial level of deforestation ($def_{i,97}^{-1}$) as well as its interaction with the change in deforestation ($\Delta def_{i,t}^{\omega} * def_{i,97}^{-1}$). The reason is the following. In dynamic terms, municipalities at the beginning of the boom-bust cycle are predicted to show low total deforestation and growing deforestation activity, along with a positive rate of welfare growth. Municipalities at the opposite extreme of the boom-bust curve are instead predicted to have a high initial level of deforestation and low growth in deforestation, along with a negative welfare growth. Hence, the change and the level of deforestation are predicted to be jointly but inversely correlated with welfare. The key variable to test the boom-bust theory, therefore, is the *ratio* between the rate and the initial level of deforestation (with the parameter τ in Eq. 6.8). The other parameters of interest, ρ and δ, are the same as before.

Table 6.7 presents the results for the dependent variables HDI, per capital GDP and per capital agricultural output. The τ coefficients, on the top two lines, are consistently non-statistically significant, indicating lack of evidence of a boom-bust pattern. Table 6.8 presents a robustness test in which I use a different time frame for the independent variable. In this case, the GDP and the agricultural output models have statistically significant coefficients in the no-controls specifications (columns 3 and 5). When the controls and fixed effects are added, the coefficients become non-significant, showing that the controls are indeed important confounding factors, especially the State dummies.

Table 6.7. Fixed effects in growth rates regressions of HDI, per capita GDP and per capita agricultural output (2000-2010) on deforestation (1997-2009)

Dependent variable:	Δ HDI		ln (Δ GDPpc)		ln (Δ Agr.Outp.pc)	
	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta def / def_{97}$	-0.000152	-0.000200	-0.0721*	-0.0586	-0.0516	-0.0303
$\Delta def^2 / def_{97}$	-2.85e-08	-1.02e-08	1.32e-05	1.07e-05	4.92e-05	2.12e-05
Δ Deforestation (Δdef)	9.55e-06***	9.00e-06**	0.000417***	0.000386**	0.000444	0.000558*
1 / $Deforestation_{97}$ ($1/def_{97}$)	0.000799**	0.000891*	0.0801***	0.0733***	0.164***	0.135***
Δ $Deforestation^2$ (Δdef^2)	-5.70e-10**	-5.48e-10**	-5.27e-08	-4.90e-08	-1.08e-07*	-1.14e-07*
Set of control variables	no	yes	no	yes	no	yes
Init. levels	no	no	no	no	no	no
State controls	yes	yes	yes	yes	yes	yes
Year.2010	0.179***	0.180***	7.359***	7.233***	-1.997***	-2.143***
Observations	349	349	327	327	196	196
R-squared	0.302	0.314	0.395	0.409	0.368	0.415
Adj. R-squared	0.273	0.279	0.368	0.377	0.319	0.359

Table 6.8. Robustness test. Fixed effects in growth rates regressions of HDI, per capita GDP and per capita agricultural GDP (2000-2010) on deforestation (1997-2004)

Dependent variable:	Δ HDI		ln (Δ GDPpc)		ln (Δ Agr.Outp.pc)	
	(1)	(2)	(3)	(4)	(5)	(6)
Δdef / def₉₇	0.000393	-6.88e-05	-0.150***	-0.0304	-0.327***	0.0576
Δdef² / def₉₇	-9.07e-08	-2.22e-08	2.86e-05***	3.93e-06	0.000175**	-2.73e-05
Δ Deforestation (Δdef)	3.08e-06	4.41e-06	0.000449***	0.000208	0.000839**	0.000313
1 / Deforestation97 (1/def97)	0.00168***	0.000571	0.106***	0.0641***	0.184***	0.114***
Δ Deforestation² (Δdef²)	-0	-1.50e-10	-7.32e-08**	-2.42e-08	-2.32e-07***	-6.67e-08
Set of control variables	no	yes	no	yes	no	yes
Init. levels	no	yes	no	yes	no	yes
State controls	no	yes	no	yes	no	yes
Year.2010	0.156***	0.178***	7.007***	6.850***	-2.071***	-2.798***
Observations	349	349	327	327	196	196
R-squared	0.028	0.349	0.063	0.441	0.078	0.466
Adj. R-squared	0.0105	0.310	0.0459	0.405	0.0483	0.406

Notes for tables 6.7 & 6.8: municipalities whose boundaries changed more than 5% between 2000 and 2010 were dropped, as well as those with no data for at least one of the variables in the model for at least one year. The GDP and agricultural output regressions lost respectively 22 and 149 observations due to zero values in the logged dependent variable. The results are unchanged when the dependent variable is not logged.

*** p<0.01, ** p<0.05, * p<0.1; robust t-statistics.

Focusing on HDI, table 6.9 presents another round of robustness checks, showing that the boom-bust coefficients remain non-significant whatever controls are added or removed. The panel evidence thus seems to confirm the conclusions from the previous sections.

Table 6.9. Robustness test. Fixed effects in growth rates regression of HDI on deforestation (1997-2009). Dependent variable: change in HDI (2000 - 2010)

	(1)	(2)	(3)	(4)	(5)
Δdef / def₉₇	0.000234	-0.000197	-0.000565	-0.000629	-0.000276
Δdef² / def₉₇	-1.19e-07	-7.47e-08	6.60e-09	4.02e-08	-3.85e-08
Δ Deforestation (Δdef)	4.50e-06	6.22e-06	1.41e-05***	1.34e-05***	6.85e-06
1 / Deforestation97 (1/def97)	0.00170***	0.00136**	0.000833**	0.000930**	0.000599
Δ Deforestation² (Δdef²)	-1.69e-10	-2.31e-10	-1.39e-09**	-1.34e-09**	-4.61e-10
Set of control variables	no	yes	no	yes	yes
Init. levels	no	no	no	no	yes
State controls	no	no	yes	yes	yes
Year.2010	0.156***	0.158***	0.179***	0.180***	0.179***
Observations	349	349	349	349	349
R-squared	0.027	0.063	0.304	0.316	0.350
Adj. R-squared	0.00956	0.0378	0.275	0.280	0.310

I then analyse the interaction between deforestation and agricultural potential to check for indirect channels of causation. Table 6.10 presents the results for the variable rain, showing that the coefficients on the interaction between deforestation and rain remain non-statistically significant across almost all specifications. Table 6.11 shows similar results for soil fertility, confirming that deforestation is not associated with HDI through agricultural potential.

Table 6.10. Fixed effects in growth rates regression of HDI on deforestation (1997-2009) and rain. Dependent variable: change in HDI (2000 - 2010)

	(1)	(2)	(3)	(4)	(5)	(6)
Δdef x rain	1.69e-07	1.72e-07*	1.69e-07*	1.69e-07*	3.00e-07*	1.61e-07*
Rain	-0.000256***	-0.000106	-0.000103	-0.000112*	-0.000137*	3.17e-05
Δdef^2 x rain	—	—	—	—	-5.49e-11	—
Δ Deforestation (Δdef)	-2.62e-05	-2.48e-05	-2.43e-05	-2.01e-05	-4.18e-05	-1.97e-05
1 / $Deforestation_{97}$ ($1/def_{97}$)	—	—	0.000601	0.000622	0.000586	0.000417
Δ $Deforestation^2$ (Δdef^2)	—	—	—	-5.73e-10**	8.84e-09	—
Δdef x fertility	—	—	—	—	—	-2.59e-07
Δdef x Δtractors	—	—	—	—	—	-1.60e-05***
Set of control variables	no	no	no	no	no	yes
Init. levels	no	no	no	no	no	yes
State controls	no	yes	yes	yes	yes	yes
Year.2010	0.198***	0.195***	0.194***	0.195***	0.199***	0.169***
Observations	349	349	349	349	349	349
R-squared	0.082	0.302	0.302	0.310	0.312	0.398
Adj. R-squared	0.0711	0.277	0.275	0.281	0.281	0.357

Note to tables 6.9 and 6.10: municipalities whose boundaries changed more than 5% between 2000 and 2010 were dropped, as well as those with no data for at least one of the variables in the model for at least one year.

*** p<0.01, ** p<0.05, * p<0.1; robust t-statistics.

Finally, I test the hypothesis that deforestation affects welfare conditional on use of technologies. The coefficients in the first line of table 6.12 give the effect of deforestation conditional on the change in number of tractors in each municipality. The coefficients are consistently statistically significant, with a negative sign. When the coefficients of the different deforestation variables are accounted for, the net effect of deforestation conditional on number of tractors indicates that in municipalities where technological growth was the highest, positive changes in deforestation were associated with lower growth in HDI. Technological development would thus make deforestation less welfare-friendly, contrary to what would be expected. I check the robustness of these findings by running the same model for agricultural output (table 6.13). In this case, agricultural technologies have a consistently statistically significant association with deforestation and welfare, but now with a positive sign. The marginal effect is now also in line with what would be expected: where use of tractors increased, more deforestation was associated with higher growth in per capital agricultural output.

Table 6.11. Fixed effects in growth rates regression of HDI on deforestation (1997-2009) and soil fertility. Dependent variable: change in HDI (2000 - 2010)

	(1)	(2)	(3)	(4)
Δdef x fertility	-2.26e-06*	-1.21e-06	-2.59e-06	-2.59e-07
Fertility	0.00290***	0.00259**	0.00277**	0.00233**
Δdef^2 x fertility	—	—	4.27e-10	—
Δ Deforestation (Δdef)	1.49e-05***	1.34e-05**	2.06e-05	-1.97e-05
1 / $Deforestation_{97}$ ($1/def_{97}$)	—	0.000899**	0.000922***	0.000417
Δ $Deforestation^2$ (Δdef^2)	—	-4.39e-10	-2.60e-09	—
Δdef x rain	—	—	—	1.61e-07*
Δdef x Δtractors	—	—	—	-1.60e-05***
Set of control variables	no	no	no	yes
Init. levels	no	no	no	yes
State controls	yes	yes	yes	yes
Year.2010	0.172***	0.172***	0.172***	0.169***
Observations	349	349	349	349
R-squared	0.309	0.314	0.314	0.398
Adj. R-squared	0.284	0.285	0.283	0.357

*** p<0.01, ** p<0.05, * p<0.1; robust t-statistics.

Table 6.12. Fixed effects in growth rates regression of HDI on deforestation (1997-2009) and number of tractors (1996-2006). Dependent variable: change in HDI (2000 - 2010)

	(1)	(2)	(3)	(4)	(5)
Δdef x Δtractors	-1.78e-05***	-1.59e-05***	-1.52e-05	-1.46e-05***	-1.60e-05***
Δ Tractors (96-06)	0.00658	0.00277	0.00267	0.00303	0.00277
$Tractors_{96}$	—	—	—	—	-0.00793***
Δdef^2 x Δtractors	—	—	-1.51e-10	—	—
Δ Deforestation (Δdef)	7.06e-06***	1.46e-05***	1.46e-05***	8.72e-06***	-1.97e-05
1 / $Deforestation_{97}$ ($1/def_{97}$)	—	0.000720*	0.000723*	0.000652	0.000417
Δ $Deforestation^2$ (Δdef^2)	—	-7.58e-10***	-7.41e-10**	—	—
Δdef x fertility	—	—	—	—	-2.59e-07
Δdef x rain	—	—	—	—	1.61e-07*
Set of control variables	no	no	no	yes	yes
Init. levels	no	no	no	no	yes
State controls	no	yes	yes	yes	yes
Year.2010	0.155***	0.179***	0.179***	0.179***	0.169***
Observations	349	349	349	349	349
R-squared	0.069	0.337	0.337	0.336	0.398
Adj. R-squared	0.0579	0.309	0.307	0.306	0.357

Table 6.13. Robustness check. Fixed effects in growth rates regression of per capita agricultural output on deforestation (1997-2009) and number of tractors (1996-2006).
Dependent variable: natural logarithm of change in per capita agricultural output (2000 - 2010)

	(1)	(2)	(3)	(4)	(5)	(6)
Δdef x Δtractors	0.000783**	0.000448	0.000537*	0.00309***	0.00232***	0.00251***
Δ Tractors (96-06)	0.164	0.236	0.155	-0.446	-0.0110	-0.0470
$Tractors_{96}$	—	—	—	—	0.552**	0.520**
Δdef^2 x Δtractors	—	—	—	-5.60e-07***	-4.29e-07***	-4.81e-07***
Δ Deforestation (Δdef)	-0.000171	-0.000106	0.000324	-0.000290	-0.000106	-0.00273***
1 / $Deforestation_{97}$ ($1/def_{97}$)	—	—	0.156***	0.176***	0.142***	0.143***
Δ $Deforestation^2$ (Δdef^2)	—	—	-1.06e-07*	4.30e-08	1.67e-08	-5.20e-08
Δdef x fertility	—	—	—	—	—	-0.000100
Δdef x rain	—	—	—	—	—	1.74e-05***
Set of control variables	no	no	no	no	yes	yes
Init. levels	no	no	no	no	yes	yes
State controls	no	yes	yes	yes	yes	yes
Year.2010	-2.082***	-1.973***	-2.084***	-1.865***	-2.492***	-2.511**
Observations	196	196	196	196	196	196
R-squared	0.054	0.361	0.389	0.421	0.491	0.515
Adj. R-squared	0.0345	0.319	0.342	0.373	0.436	0.451

Notes to tables 6.12 and 6.13: municipalities whose boundaries changed more than 5% between 2000 and 2010 were dropped, as well as those with no data for at least one of the variables in the model for at least one year. 149 observations were dropped due to zero values in the logged dependent variable. The results are unchanged when the dependent variable is not logged.

The results in this section indicate no boom-bust pattern of development in Amazon municipalities between 2000 and 2010. While the results from a simple fixed effects specification would suggest a positive association between deforestation and welfare, a better specified model which also controls for initial levels shows no statistically significant association, either directly or indirectly through agricultural potential. One exception is the intermediary role of technology, which is consistently statistically significant but with an unexpectedly negative sign on HDI.

6.3.3. Case study evidence

Much of the case-study evidence regarding the Amazon is based on cross-sectional data. Long term studies that follow farmers over time are expensive and rare. The lack of inter-temporal variation in the data is particularly troublesome for the boom-bust theory, as it refers to a phenomenon that is intrinsically dynamic by extrapolating from cross-sectional, spatial variation to time variation. In this section I report on evidence from locations in three geographic extremes of the Brazilian Amazon: the eastern State of Pará, the western State of Rondônia, and northern Amapá, where inter-temporal household data has been collected for periods of between 7 and 22 years. I find that at least in these cases the time series evidence does not support a boom-bust theory.

Altamira, Pará

Household data on this municipality has been collected by a group of researchers from Indiana University and Embrapa, the Braziilan agricultural research agency, and includes two waves in the period 1997/1998 to 2005. Induced settlement in Altamira dates back to the early 1970s, when colonizers were attracted by the government—that provided roads and most of the basic socioeconomic infrastructure—with the aim of developing the agricultural potential of the Amazon. Altamira's occupation was similar to that of the rest of the Amazon, and because it started 30 years before the period studied by Guedes et al. (2012), a distinctive bust in welfare would have to be identified for the boom-bust hypothesis to be corroborated. Yet in analysing the evolution of poverty, inequality and per capita income, using both conventional measures and a more sophisticated multidimensional metric, the authors find compellingly optimistic results: in seven years the share of settlers under the absolute poverty line dropped from 60.1% to 36.8%, while the Gini index fell from 0.74 to 0.56. Hence this case provides no evidence of a boom-bust pattern of development.

Ouro Preto do Oeste, Rondônia

Caviglia-Harris and her team have collected four waves of household data from six municipalities in the region of Ouro Preto, Rondônia, between 1996 and 2009. Similar to what was verified in Altamira, the scenario depicted by the authors (Hall and Caviglia-Harris, 2013) is the contrary of what would be expected in a boom-bust situation. They adapt an industrial life-cycle model (from microeconomics) to agriculture in frontier regions to look for signs of a pattern of development in the rural economy that is in line with a process of growth followed by consolidation—the opposite of growth followed by bust. The agricultural life-cycle model predicts that variables such as number of firms, prices and output should show distinctive signs of an economy that outgrows the booming sector, and the authors show that municipalities in the Ouro Preto region have indeed followed that pattern of development—an economy that consolidates and stabilizes—rather than boom-bust. This evidence goes against the hypothesis that a resource curse would prevent resource-rich economies from diversifying.

One criticism that may be raised against the analysis in Ouro Preto (which in English means 'black gold') is that the region is known for having soils with above average fertility, so the case may not say much about the average Amazonian settlement. While this may be true, it does nevertheless confirm that a boom-bust pattern is at most a non-generalizable hypothesis. The data from Machadinho that I present below, however, show no evidence of boom-bust even in a municipality with average / poor soils.

Mazagão, Amapá

An interesting complement to the agricultural life-cycle argument was made by Sears et al. (2007) and Piñedo-Vasquez et al. (2001), who studied the dynamics of the logging industry in a floodplain area of Amapá, in the northern extreme of the Amazon, between 1991 and 1998. The papers provide a detailed account of the history of the timber industry since the 1970s and explain how rural dwellers were able to use the logging skills they learned during booming times to cope with the crisis that followed the exhaustion of the main timber species in the region in the 1980s. The authors document the emergence of a more sustainable form of logging in the 1990s that stemmed from the use of local ecological knowledge along with skills that were acquired through off-farm work during booming times.

The process allowed a new type of logging operation to emerge and for production to increase while timber species were explored in a sustainable manner. Transferable skills were canalized through off-farm labour to create an economy capable of adapting to resource scarcity. This evidence contrasts with the original boom-bust theory (Schneider et al., 2002), which was based on the strong assumption that local economies do not have the means to endogenously recover from logging booms. This evidence too contradicts the hypothesis of a resource curse which would inhibit institutional development and hamper the development of human capital.

Machadinho do Oeste, Rondônia[49]

Data on households in the Machadinho settlement has been collected in 7 waves since 1986 by Embrapa (Mangabeira, 2010). This is a unique dataset that provides fine-grained detail and covers a relatively long period, encompassing the full history of the settlement since the first arrivals in 1986. The Machadinho settlement was designed following an innovative method that adapted the shape of roads and plots to the ecological characteristics of the terrain, including topography and water networks. The organic design has arguably had a positive effect on welfare outcomes as compared to the conventional 'fishbone' approach adopted elsewhere (Batistella and Moran, 2005). Soils, on the other hand, are not particularly fertile in Machadinho compared to the rest of the Amazon (Castro and Singer, 2012).

To provide another test for the boom-bust hypothesis, I look at the evolution of three welfare indicators in Machadinho: per capital agricultural output, average monthly family expenses, and average number of houses per household for three typologies of houses (an indicator of domestic assets). The data does not show evidence of a boom followed by a bust in welfare. While per capita output seems to suggest a steep growth in the first 10 years followed by slower growth (figure 6.7), the data on family expenses indicates a stable welfare gain from 1999 to 2008 (table 6.14). The data on house type shows that the percentage of rural households dwelling in thatched houses felt from 30% to near zero, while those living in masonry houses rose from near zero to almost 20% (figure 6.8). Wooden houses in the Amazon have a short lifespan due to excessive rain and acidic soils, so the still high prevalence of wooden houses is a sign that many rural dwellers still live in relatively basic conditions. Yet the overall picture is clear, and in no case can it be said to indicate a situation of bust.

[49] Part of the data for this case study is periodically published by Embrapa (http://www.machadinho.cnpm.embrapa.br/index.html). The disaggregated data used in this section, however, has been made available for this thesis only.

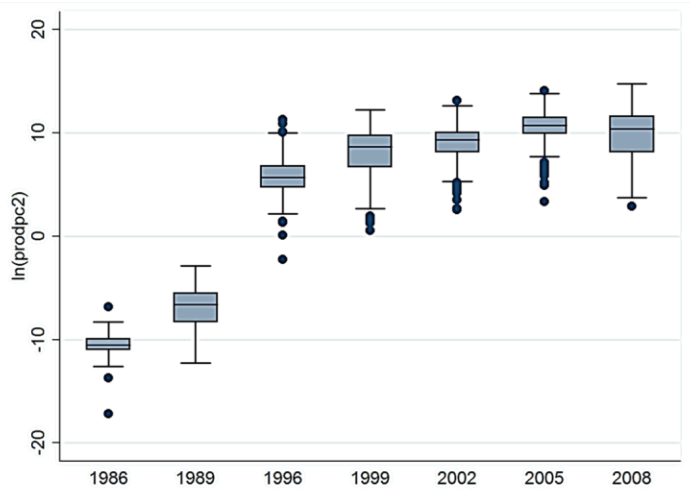

Figure 6.7. Box plots of the value of agricultural production per capita (in logs), Machadinho do Oeste.

Source: Embrapa (Mangabeira, 2010).

Table 6.14. Average monthly family expenses (2012 R$), Machadinho do Oeste

Year	Mean	Std. Dev.	Freq.
1999	91.43	84.38	315
2002	145.25	113.31	315
2005	274.77	261.33	315
2008	312.27	521.44	315

Source: Embrapa (Mangabeira, 2010).

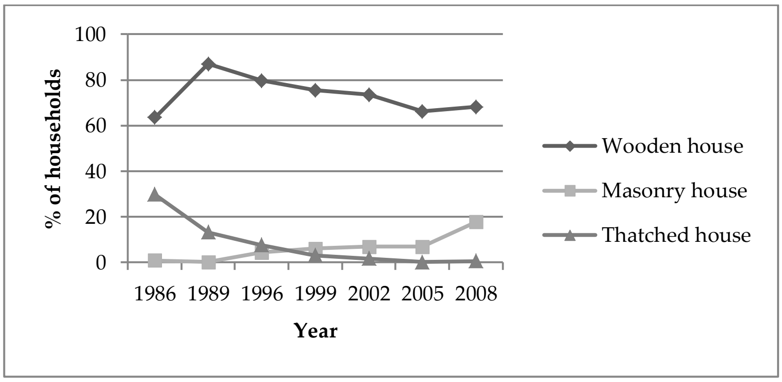

Figure 6.8. Relative frequency of type of dwelling houses, Machadinho do Oeste.

Source: Embrapa (Mangabeira, 2010)

In none of the four cases above does the evidence corroborate a boom-bust hypothesis. While the absence of busts in four single cases cannot prove that a boom and bust cycle will not be observed in the next municipality, the cases I document do disprove a general rule of busting economies following a deforestation process.

6.4. Conclusion

I study the flip side of the Environmental Kuznets Curve hypothesis, that is, the idea that pollution and environmental outcomes may have a causal effect on welfare. Two influential papers have exploited this issue for the case of deforestation by looking at the proposition that forest clearance leads to short-lived economic gains before causing a sustained bust in economic activity. They examined data from the Brazilian Amazon and argued that a boom-bust model may explain the observed cross-sectional variation. I contribute to the discussion in three ways. First, I propose a straightforward theoretical model that links forest cover and ecosystem services to welfare and encapsulates the main channels through which deforestation may affect welfare. Second, I reproduce the cross-sectional results from the existing literature and show that they do not correctly account for spatial correlation. Third, I use new time-series evidence to test the model and look for a discernible time variant pattern in the data.

The results go in the opposite direction of the existing literature. I initially show that the cross-sectional evidence that initially substantiated a boom-bust hypothesis missed an important Amazon-wide pattern of spatial variation that was wrongly taken for a consequence of deforestation. If there is to be an unconditional, inverted-U shaped relation between deforestation and welfare that is valid across the board, then it should be roughly randomly distributed across space. If instead some noticeable clustering pattern is found, then it can be suspected that some omitted factor may be driving the results. By looking at the spatial distribution of deforestation and HDI in the Brazilian Amazon I find that two clusters of low development, in the States of Amazonas and Maranhão, seem to account for an important part of the presumed boom-bust curve. I show that those areas cannot be taken for counterfactuals of the whole region as their welfare situation has specific determinants that are not clearly related to deforestation. To account for the unobserved effects of individual States, I replicate the models in Celentano *el. al.* (2012), including State dummy variables, and find that the apparently robust association between deforestation and HDI vanishes completely.

The results from multivariate regressions using cross-sectional data suggest that, when time-invariant State-specific factors such as climate and history are accounted for, no partial association between deforestation on development can be identified in support of a boom-bust hypothesis. However, any causal effect of the type being studies here would be inherently dynamic, so time-series data needs to be considered for a more solid argument as to the role of deforestation on welfare to be raised.

The theoretical specification I propose focuses on deforestation-related changes in ecosystem services and their role in explaining agricultural output and welfare. I distinguish a channel that directly affects agricultural output from an indirect channel, where the effect on agriculture depends on the initial level of ecological resilience. Fragile ecosystems—for example, where precipitation levels are very high and soil fertility is low—may be less able to sustain economic activity than more resilient ones. On the other hand, human action can shape and manipulate ecological resilience by using technology. This theoretical distinction is captured at the empirical level by an interaction term between deforestation and agricultural potential (a proxy of resilience that includes rain and fertility), and an interaction between deforestation and technology (proxied by number of tractors per agricultural area). I use a panel dataset that covers a 14-year span to look at the association between the change in deforestation and the change in HDI, per capita GDP and per capita agricultural output.

I use a first-difference transformation to run two sets of models, one with standard fixed effects in levels and another that also includes fixed effects in the growth rate of welfare. The standard fixed effects model suggest a robust positive association between the change in deforestation and the change in welfare, controlling for the change in immigration, population density (a proxy for settlement age) and number of tractors (a proxy for technology), when the indirect channels discussed above are considered. If the interaction terms between deforestation and agricultural potential and technology are instead omitted, then the coefficients on deforestation are non-significant, indicating that there would be at most an indirect effect, and that it would be in the opposite direction of the boom-bust hypothesis.

The simpler fixed effects model, however, fails to incorporate the crucial fact that the predictions from the boom-bust theory are based on the initial level of deforestation as much as they are on the growth rate. A proper test must thus control for the level as well as for the change in deforestation. Moreover, since the initial level of deforestation is predicted to be inversely related to the growth in welfare, I construct the independent variable as the ratio between deforestation growth and its initial level. In this second model I also control for the initial levels of the control variables as well as for State dummies, in order to account for the possibility of the spatial pattern found in the cross-section to be affecting the change in welfare.

The results of the fixed effects in growth rates model strongly suggest that the boom-bust hypothesis can be rejected. The test for a direct effect of deforestation on welfare yields consistently non-significant coefficients, either for HDI, per capital GDP or per capital agricultural output. The tests for an indirect effect of deforestation through fertility and rain also yield consistent non-significant results. Only the coefficients on the indirect effect of deforestation through technology remain consistently statistically significant, with the model for agricultural output giving the expected results, that the more technological growth the more deforestation is associated with output growth, but the model for HDI gives results with the opposite sign, showing that this particular effect should merit a more detailed study in the future. All results are robust to different ways of capturing the effect of deforestation—quadratic and cubic terms, different interactions with variables that proxy for ecosystem resilience, different samples of municipalities.

Lastly, I summarize the results of four in-depth case studies across the Amazon that not only contradict the boom-bust hypothesis but also show consistent evidence of a pattern of sustained welfare gain over time. The Altamira case shows sustained welfare gains even after 30 years of colonization in an area in western Amazonia that has no particular reason (biophysical or other) to be successful. The Ouro Preto case shows a similar pattern in eastern Amazonia, even though soil fertility might be taken as part of the explanation. The Machadinho settlement, which is very close to Ouro Preto both in space and timing of colonization, shows sustained welfare gains in the absence of particularly fertile soils. Here again, though, it could be argued that Machadinho is exceptional due to a better settlement design, but this would only suggest that settlements can indeed be designed in a way that is conducive to development. The case of Mazagão, in the northern State of Amapá, confirms that the very process of colonization, through migration and off-farm labour, can generate the bases for an adaptive economy that uses indigenous ecological knowledge to manage scarce resources in a rational way.

The results I obtain using three different sources and types of evidence as well as different methods agree in rejecting the boom-bust hypothesis. These findings speak to broader debates on agricultural frontiers, exploitation of natural resources and development, such as in Barbier (2011). The idea of a boom-and-bust pattern of development is often linked to processes of growth that rely on the extraction of wealth from the primary sector. Theorists aligned to the idea of a resource curse argue that as much as mineral resources can have a deleterious role in long term growth through the artificial appreciation of exchange rates, other forms of natural endowments such as forests can also lead to a situation of Dutch disease.

For example, Barbier (2004) looks at the reversed Environmental Kuznets Curve for forests and finds evidence at the cross-country level that conversion of forests for use in agriculture lead to a boom-bust pattern of development, particularly in Latin America. The standard explanation for such a situation is that resource-dependent economies tend create perverse incentives that lead to corruption, under-investment in public goods such as education, and a level of concentration of production factors in the booming activity that prevents other sectors from developing. Resource-rich economies would therefore be endogenously fragile and susceptible to crises.

Some of the findings in the previous chapters of this thesis, however, suggest that a resource curse theory does not apply to the Brazilian Amazon. For example, the generalized evidence that 'consolidated' municipalities—where the settlement process has stabilized and deforestation has reached high levels—have seen a process of land use intensification in the cattle ranching as well as in the cropping sector can hardly fit ideas of a cursed, busting economy, or a 'hollow frontier'. Rather, what I argue in Chapter 4 is that the very ecological process of soil degradation is one of the factors pushing farmers to resort to more intensive land use practices. This, along with other factors such as a strong command-and-control anti-deforestation legislation, has caused many farmers to go down the path of vertical rather than horizontal expansion of production, which in turn has been shown by Hall and Caviglia-Harris (2013) to have generated economic synergies that contradict a Dutch disease hypothesis.

The main contribution of this chapter is therefore to challenge the idea that deforestation can be a policy variable for welfare outcomes—what I have labelled the flip side of the Environmental Kuznets curve. While the common wisdom tends to attribute a very relevant role for deforestation in shaping economic wellbeing, I show that almost no evidence can in fact be singled out to support that claim. Further elaborations of the analysis might look more directly at the role of technology as an intermediating factor between deforestation and welfare, or at specific ecosystem services that depend on forests, such as weather and pest regulation, and how they relate to deforestation on one side and to welfare on the other.

Conclusion

Land use intensification in the Amazon is not a flying cow. Traditionally an activity that occupies marginal lands and that remains technologically backward as compared to agriculture, cattle ranching has seen an average productivity rise of 57.5% in 10 years after 1996. The process has been fuelled by increasing land scarcity generated by both endogenous and exogenous factors, and it has been paralleled by a 79% drop in deforestation from 2004 to 2013. Land use intensification in cattle ranching is a new phenomenon whose drivers and consequences are still poorly understood. In this thesis I provide a comprehensive framework for the analysis of the link between intensification, deforestation and development, focusing on four elements: (i) frontier migration, (ii) land speculation, (iii) the rebound effect hypothesis, and (iv) the boom and bust hypothesis.

I address two research questions. First, does rising land productivity of cattle ranching increase deforestation? If so, how? The debate between proponents of a rebound effect, where increased land yields backfire and cause deforestation to rise in the long run, and proponents of a land sparing effect, where intensification saves forests, has been ongoing for more than a decade with inconclusive results. Especially for the case of cattle, there is lack of evidence both at the theoretical and empirical levels, a gap that I address by advancing new elements to the theory of land use change in frontier settlements, generating primary data on one representative State in the Brazilian Amazon, and providing two sets of empirical tests of the rebound effect hypothesis.

The second question I cover is whether booms in deforestation lead to busts in welfare. I use different sources of secondary data to scrutinize the theory that predicts welfare to bust as deforestation advances, and find consistent evidence against any association between deforestation and welfare.

I start this conclusion by synthesizing my answers. More than simply restating what I already said in the individual chapters, I organize the text with a view to providing a more encompassing perspective on the broader topic that motivates this research: the fate of settlements in frontier areas. The answer to the first question above is divided into three steps. First, I look at the drivers of the intensification process; second, I look at the intensification-migration-deforestation link; third, I summarize the evidence on a land-sparing effect, discuss the limitations of my approach, and provide clues for future avenues of research. In the last section of this conclusion I appraise the results on the boom-bust hypothesis. This includes a subsection where I explore broader implications of the results to policy and theory.

Question 1. Does rising land productivity of cattle ranching increase deforestation? If so, how? My departing point is the interim assumption that intensification rebounds onto frontier deforestation. I build the case for an intensification-migration-deforestation link (Part One of the thesis), and illustrate the theoretical model with cross-sectional data from Rondônia (Part Two). I then use secondary evidence to test for a macro-level rebound effect in the Brazilian Amazon (Chapter 5), and conclude that the hypothesis can be rejected. This bears the question of what has gone wrong in my model of intensification-migration-deforestation, which is a crucial discussion that should provide interesting avenues for future research. Before reaching that point, however, I do a reappraisal of the empirical findings in Chapter 4.

1.1. <u>Three drivers of intensification</u>. I start by asking whether productivity of cattle ranching has been growing and why. After documenting the intensification process using different sources of evidence, I develop the argument that it has been driven by three factors: (i) higher costs to deforestation due to enforcement of the environmental legislation, which increases land scarcity; (ii) a biophysical process of soil degradation that has the same effect as a reduction in the land area, again increasing land scarcity; and (iii) higher costs to buying or leasing land due to rising land prices, a manifestation of land scarcity. The conclusions on each one of these are the following.

(i) The evidence on the effect of the environmental legislation comes from a measure of enforcement of the forest code based on farmers' perception of the likelihood of being punished for illegal deforestation. The result shows a generalized perception that enforcement of the law is very likely, especially in areas of older settlement. This is explainable by higher transport connectivity (paved roads) and presence of courts and policing infrastructure. In frontier areas the perceived enforcement is statistically the lowest between all regions, suggesting that a farmer is more likely to engage in deforestation in frontier locations. Moreover, land titling in new settlements is very scarce, so farmers are less fearful of losing valuable property rights in frontier locations.

The reasoning above is supported by qualitative evidence on farmers' narratives, which also point to higher costs to deforestation today, especially in consolidated areas. It must be noted, however, that probability of enforcement of the forest code is already high in frontier locations (68%[50]), suggesting that even in new settlements it may not be as easy to clear new plots as it used to be a few decades ago. I will argue below that this is one possible explanation for the land sparing effect of intensification that I have found.

(ii) The second factor, pasture degradation, is captured by a subjective measure of pasture quality reported by farmers. While the measure may be criticized for not reflecting objective biophysical characteristics of pastures, it does depict the detailed indigenous knowledge that farmers possess of their local environments. By asking respondents to compare the present quality of pastures to that of the previous three years, I produce an estimate of the change with respect to a benchmark level that the respondents assess based on their knowledge. This measure in unequivocal in showing a much stronger incidence of pasture degradation in transition locations.

I use the property grip obtained in the survey to link the household information to detailed external data on soil aptitude. The resulting analysis indicates a process of nutrient mining from frontier to transition areas. While farms in the first group tend to have a relatively homogeneous level of productivity given their soil aptitude and distance to markets, farms in transition areas see a high level of dispersion in the productivity measure, attesting that some farmers are unable to manage pastures in a way that keeps fertility and productivity constant.

[50] This figure corresponds to the qualitative statement that there is between "some" and "high" chance that a farmer engaging in illegal deforestation will be fined by the environmental agency.

(iii) The last factor, rising land prices, is captured by two variables reported by farmers: estimates of the value of the surveyed properties and the expected land price rise for the next three years. Current land prices are eight times higher in consolidated than in pre-frontier locations, and farmers anywhere in Rondônia expect a 10% average yearly price rise, above the average inflation and the gross returns of the savings account. Rising land prices are in part a reflection of increasing land scarcity, which is in turn related with the enforcement of the forest code but also with pasture degradation. The obvious consequence is that horizontal expansion becomes more expensive over time. Since transportation costs tend to fall as settlements evolve, this implies that the relative costs of traditional versus intensive farming systems tends to rise in a given location.

Having provided an explanation for the intensification process, I now turn to study the micro-level foundations of a possible indirect effect of land use intensification on frontier deforestation. The essential argument is as follows. Farmers who are not able or willing to start an intensification process are expected to sell out while prices are rising (due to the overall intensification process) and the process of land degradation is still incipient. They may migrate to a new frontier and clear a new plot or go to urban areas. If they migrate to a new frontier they are expected to engage in deforestation in order to start a plot with high levels of natural fertility. This is how a rebound effect would operate.

1.2. Necessary conditions for the intensification process to backfire on deforestation. First (i), there must be a frontier where land prices are near zero. Second (ii), a group of technological laggards needs to coexist with a group of technologically advanced farmers in established settlements. Third (iii), there needs to be a land market functioning well enough for farmers who are lagging behind in transition and consolidated areas to be able to transfer their assets to frontier locations. I now succinctly summarize the empirical evidence on each one of these before confronting these findings with the empirical results of a land-sparing effect of intensification.

(i) The evidence on the continuing reproduction of frontiers comes from my second wave of fieldwork in 2012, when I visited a number of frontier settlements and collected qualitative evidence on their history. My findings are in line with the literature that studies recent settlements in the Amazon: that whereas government-induced settlements are no longer created in the Amazon, a new form of spontaneous occupation activity has emerged whereby pioneers invade distant abandoned lands with a view to having the land possession recognized and titled by the government. The frontier locations I visited had a considerable deforestation activity, low land prices and high rates of immigration especially by poor farmers coming from other municipalities in the same State.

While it is probable that the rate of creation of new settlements is lower than it used to be in the 1980s and 1990s, it is nevertheless the case that there exist new settlements where farmers can get land for a near-zero price. One illustrative example is that of the settler I describe in the Preface. The question then is to what extent the 'supply' of frontier lands is sufficiently high to motivate farmers who cannot cope with the ongoing intensification process in consolidated areas to migrate to the frontier. This is an interesting question that would require a general assessment of frontier settlements across the Amazon, which I don't believe exists at the moment.

(ii) The arguments above on drivers of intensification and on the special characteristic of transition areas are further confirmed by an analysis of adoption of technologies. I create a technological index based on technologies such as liming, fertilizing and genetic improvement, and find that in transition areas there is a much higher dispersion in technological adoption than in other locations. This again suggests an association between biophysical processes and land use intensification. Moreover, capitalized farmers are the first to adopt technologies that deal with the cause of the problem, pasture degradation. Most farmers will instead concentrate on cheaper offtake-enhancing technologies—notably genetic improvement—which can be effective to counter the consequences of degradation in the short term but do not provide long term sustainability.

(iii) Land markets are the essential mechanism linking intensification to deforestation to frontier migration. The survey data shows that they become more established as settlements evolve, as measured by the participation of leased in and out land as a share of total pasture area, notably in transition locations. Land prices are positively associated with productivity levels, both in the same farm and in neighbouring farms, so that a process of intensification has a positive impact on local land prices. Under these conditions, a marginalized farmer who is unable to adopt costly density-enhancing technologies (liming, fertilization) sees the option of selling out his land in consolidated areas and migrating to a new frontier as one possible response to a falling output caused by pasture degradation.

Do farmers pursue 'speculative' or 'productive' motivations? The model I just described relies on the presumption that farmers take land use decisions based on productive motivations. But is that a reasonable assumption? This question is important for the intensification-migration-deforestation link because if ranchers are more interested in conspicuous gains than in beef and dairy production, they might prefer to keep their land idle in transition or consolidated areas and gain from the rising land prices caused by their neighbours who are intensifying.

To distinguish productive from speculative motivations I look for evidence of whether farmers respond to price signals only or to genuinely productive variables such as pasture degradation and use of labour per hectare. Purely speculative farmers are predicted not to demonstrate the intention to migrate to a frontier when they expect land prices to rise; productive farmers are expected to demonstrate the intention to migrate when pastures are degrading and labour requirements are high.

The evidence points to a mixture of both effects, but with a preponderance of productive behaviour. This confirms that a Boserupian framework, in which farmers are expected to migrate to new settlements to avoid intensification and a decreasing productivity of labour, is a valid basis to study frontier migration.

1.3. <u>Has rising productivity increased deforestation</u>? Now that the theoretical model on the intensification-migration-deforestation link has been spelled out and illustrated with household data, I have the necessary elements to look at the rebound effect from a more general perspective. I use the Amazon-wide municipality-level dataset to provide the first empirical test of the rebound effect hypothesis — that the intensification process induces more deforestation — for cattle ranching in the period 1996-2012.

I adapt the spatial econometric model by Arima et al. (2011), which links municipalities in frontier and consolidated locations using a spatial weights matrix, to look for evidence of a space and time-lagged rebound effect in cattle ranching. I follow Rodrigues et al. (2009)

in distinguishing frontier from consolidated municipalities based on the stock of deforestation (2004) and the flow of deforestation (2000-2004), and I implement two alternative classification methods, with similar results. In testing for an intrinsically dynamic process whose drivers can be both fixed characteristics (such as natural endowments) and dynamic factors (such as environmental policy), I follow Weinhold and Reis (2008) and incorporate initial levels as control variables in the growth rates model, generating a 'fixed effects in growth rates' specification.

The results from a model without the said fixed effects are in line with a rebound effects hypothesis. But with a more complete specification the results switch signs, indicating a substantial land-sparing effect of intensification. A set of robustness checks that makes use of the long deforestation time-series confirms the validity of the results.

How can the evidence on land sparing be explained in light of the theoretical mechanisms I had proposed earlier? In Parts One and Two of the thesis I advance and test theoretical propositions regarding the process of land use intensification in the Amazon and the possibility of a rebound effect. However, the empirical test I provide in Chapter 5 using panel data at the municipality level points towards a land sparing effect of intensification. This last result suggests that some or all of the necessary conditions for a rebound effect were not present.

In trying to solve the conundrum, I get back to the proposed theory and evaluate it in light of the evidence of a land-sparing process. Which of the conditions advanced were not met? How, at the micro-level, might the intensification process have caused less deforestation? While I do not analyse any new evidence here, I add to the previous discussion by providing further structure to the question and paving the way for future research focused on the land-sparing effect.

The regressions of the change in deforestation on productivity growth indicate that productivity initially has an effect on frontier locations, reducing deforestation in consolidated areas only at a later stage. Looking back at the migration story I depict above, this would suggest that farmers are initially prevented from migrating to frontier locations, but keep an unchanged pattern of land use in consolidated areas. At a later stage, their land use pattern in consolidated areas also reverts to being relatively more reliant on vertical expansion as opposed to horizontal expansion, which eventually causes deforestation to fall also in consolidated areas. Since the deforestation variable I use does not capture reforestation, the possibility of farmers staying in consolidated areas but keeping their plots idle to the point that forest regrows is ruled out.

The idea would therefore be that intensification in consolidated areas raises demand for labour and keeps marginalized farmers as off-farm workers. This type of mechanism was explored by Cattaneo (2002) and by Angensen and Kaimowitz (2001), and it should merit further attention in future research.

A central research avenue is therefore the further analysis of the migration pattern that stems from an intensification process. Migration is a rapidly changing phenomenon, and its impact on land use has been shown by demographers to depend on household dynamics. These have in turn also been largely affected by recent changes in fertility rates, access to health and education in urban areas, improvements in roads infrastructure, and access to cheap transportation (notably motorcycles) and communications (mobile phones). All of these need to be integrated into a model should the roles of migration and land sparing be properly understood.

In Chapter 1 I have explored a literature that provides some interesting hypotheses. One important point is that the decision to migrate is often segmented at the within-household level, so not all members of a household will engage in migration. Moreover, even those who end up migrating to a frontier may get segmented between the urban and the rural parts of the frontier. The relation between those who stay in consolidated areas, those who go to urban areas, and those who go rural frontiers is complex and needs to be better understood in light of the land sparing effect of intensification. For example, the role of remittances sent by out-migrants to those who stay in consolidated areas may further stimulate the intensification process (VanWey et al., 2012).

It is reasonable to assume that, if no rebound effect has been observed, then one or more of the three necessary conditions I advanced above must have failed. One possibility that needs to be further explored is that the relative supply of frontier locations may have shrunk, despite the continuing process of spontaneous colonization led by social movements. A detailed assessment of new settlements across the Amazon is currently unavailable. More research is thus necessary: where are the new frontiers in the Amazon? What are the differences with the old-type induced settlement frontiers? What are the new migration patterns?

A related possibility is that farmers are aware that even in new frontiers deforestation is nowadays more costly—from the perspective of the enforcement of the environmental legislation—than it used to be one generation ago. Farmers may respond either by migrating to frontiers but using land more intensively to start with, or by migrating to urban areas instead. The fact that productivity of cattle has grown even in frontier locations could be a starting point for this interpretation.

With regards to economic behaviour, I find evidence of speculative motivations informing land use decisions, so intensification in consolidated areas may incentivize some farmers to keep their lands idle in order to realize capital gains in the future. If demand for labour rises due to intensification, then laggard farmers may be able to substitute farming income for off-farm wages. Of course if they keep farming their pastures the degradation process will worsen and they will eventually see land values fall. But they may adopt a severe reduction of cattle densities that effectively curbs the degradation process.

Finally, the fact that land markets deepen as settlements evolve means not only that farmers can sell out and migrate to a frontier, but also that they can lease out their lands to more capitalized farmers. If the leasing contract is relatively long-term (a few years), the tenant can then invest in recovering the degraded soil to produce intensive livestock, mechanized agriculture or a combination of both. Provided that the landlord restrains from renting out other land, this should create no displacement effect, thus allowing for land sparing.

Limitations. The empirical analysis in this study is based on cross-sectional household data and panel data at the municipality-level. While the combined use of these two sources of information can be helpful in elucidating dynamic land use patterns that operate across scales—such as the one I am tackling—the conclusions are nonetheless limited by the lack of time-series variation at the micro level. Ideally, the study of intensification, migration and deforestation would use a panel dataset at the household level. The type of data that would be necessary is rare because it requires households to be tracked over time and across space so that migration patterns can be related to land use practices. Generating this kind of data is particularly difficult and expensive, and in the survey I conducted it cannot be done since I do not have personal information on the respondents, which prevents me from being able to track them once they move out of their plots.

Another possible argument is that the Rondônia State may be unrepresentative of the Amazon, which would lead the theoretical considerations to not be valid for the region as a whole. This could be tested by studying land use and migration dynamics within each State. For example, census data at the sub-municipality level could be used to study the State of Rondônia only for the period 1996-2006.

While further studies that tackle the limitations discussed here and those presented in the individual chapters should be stimulated, what I believe is most in need is an aggregative outlook of the Amazon that updates the understanding of land use dynamics in light of new patterns of frontier settlement, a much changed demographic structure, a new role of urban areas, better connected rural areas, stronger market integration both within the Amazon and with the rest of the world, and the process of land use intensification that started with cropping (soya and others) and is now expanding to cattle.

In short, a central conclusion from this thesis is that more productive cattle ranching can save forests. More research needs to be done to establish the key causal mechanisms and to confirm the land-sparing effect, and the discussion above provides some clues to the key questions that need to be approached. I now turn to present the results of the second problem addressed in this thesis.

Question 2. Do booms in deforestation lead to busts in development? In Chapter 6 I provide a comprehensive assessment of the boom-bust hypothesis based on the triangulation of results from different methods of analysis and sources of data. I initially develop a simple theoretical model that singles out the main channels linking deforestation to welfare. I then reproduce the cross-sectional findings from the existing literature, showing that the results are to a large extent driven by omitted spatial factors from two clusters of low development in the States of Amazonas and Maranhão. I next use a new United Nations Development Programme dataset on Municipal Human Development Index (HDI) to run a fixed effects in growth rates model of the change in HDI (2000-2010) on the change in deforestation (1997-2009).

In line with the cross-sectional results, I find no evidence of a direct effect of deforestation on welfare, and very limited evidence of an indirect effect through technology. I further substantiate the empirical results by summarizing the results of four longitudinal case-studies from across the Amazon whose published data show not only lack of evidence of a bust, but also that the areas studied have seen a sustained rise in welfare.

The results on the boom-bust hypothesis are contrary to what was found by Rodrigues et al. (2009) and Celentano et al. (2012). The single explanation for the contrasting results is that in this thesis I capture a spatial pattern in the HDI and deforestation data that I show to be a central confounding factor to the boom-bust theory. The simplest way to notice that clusters of low-low development and deforestation in Amazonas and low-high development and deforestation in Maranhão are driving the results is to plot the data on a map as I did in figures 6.3 and 6.4. It then remains clear that without those two clusters there would be no inverted-U shape in the curve.

An unconditional pattern of causation between deforestation and welfare is thus not warranted by the evidence. Similarly, a cross-sectional multivariate framework does not resist the inclusion of State dummy variables either, confirming that a partial causation is not supported by the evidence. The time-series analysis further confirms that the boom and bust theory does not provide a good description of development outcomes in the Amazon. This in turn speaks to similar theoretical frameworks, such as the one based on the idea of a resource curse, which equally predict that settlements in highly forested areas are likely to fail as forests are converted into agricultural uses.

An important future avenue of research would be to study the welfare outcomes of the intensification process. While I do not try to establish a nexus between intensification and welfare, it would be reasonable to expect that more productive farmers would also have higher welfare. This is due to two reasons. The first is that the technologies used in the intensification process require a set of skills that is very different from what is required from traditional cattle ranching, so demand for skilled labour is increased and the immediate consequence is that salaries go up; the negative consequence is that those unable to adapt tend to remain marginalized. The second reason is that many of the technologies employed to intensify cattle ranching are common to agricultural and livestock raising production functions, so farmers who start an intensification process are likely to end up diversifying their production functions, and farmers who diversify production are more resilient to economic shocks.

Implications for policy and theory. The idea that deforestation can be a policy variable for welfare outcomes, at least at the local level, is challenged by the results in this thesis. While the common wisdom tends to attribute a central role for deforestation in shaping local wellbeing, I show that little evidence can in fact be singled out to support that claim. This does not preclude welfare from being affected by deforestation when larger spatial and temporal scales are considered. For example, it is feasible that when looked at from a longer term perspective, the falling of forests subtracts from the material base of development and leads to lower welfare. It is equally possible, though, that the benefits from deforestation are channelled to other economic sectors that in the long run boost the development process.

In terms of scholarly debates, the results in this thesis relate to three main branches of the land use literature. First, the analysis on the intensification-migration-deforestation link speaks to the Boserupian theories of induced intensification (e.g.: Turner and Ali, 1996). I show how an analytical framework that puts marginal productivity of labour and technical change at centrestage can contribute to the analysis of land use change in the Amazon. Additionally, I summarize evidence from two studies (Bell, 2011; Vosti et al., 2002) that confirm that land use intensification is associated with lower productivity of labour, the key assumption that leads farmers to resist intensification in a Boserupian model.

Secondly, I show that a theoretical framework based on the 3-phased rural settlement model By John Hudson provides a better depiction of the evolution of settlements in Rondônia (as captured by my survey data and two waves of fieldwork) than theories of hollow frontier. The fact that a rising settler density increases competition for land, and the consequences of this for land markets and migration flows, are crucial to the understanding of the evolution of settlements. The insight by Hudson that a phase of land consolidation should be expected when less successful farmers are crowded out by more successful ones is key to explaining the emergence of land use intensification.

Finally, I provide an update to the nutrient mining model by Schneider (1995) by considering the effect of land use intensification in cattle ranching. His was already a very good account of the relation between soil degradation, economic rationality and migration, and I show that the recent trend of intensification and the increased enforcement of the forest code can be easily integrated to his model to make sense of recent land use developments in the Amazon.

Success or failure? This thesis offers three main conclusions relevant to the analysis of the fate of settlements in frontier locations. First, the hypothesis that settlements bust as a result of deforestation implies that welfare is limited to a maximum level that can be achieved when some optimum amount of deforestation is reached. The rejection of this hypothesis thus suggests that at least from the point of view of deforestation there is no ceiling to welfare, so settlements can in principle expect that if the necessary conditions are fulfilled their development is unconstrained.

Another important result is to show that a substantial process of land use intensification is taking place in the Amazon, especially in older settlements. Documented in detail as it is in this thesis, this finding is a novel contribution to discussions of land use change in the Amazon. This in turn suggests that cattle ranching can, under the right circumstances, become a less environmentally damaging activity, which is positive news for a region that is increasingly dominated by livestock. Finally, the intensification process is predicted to save forests both in frontier and consolidated locations, yielding a desirable environmental outcome.

Now that parts of the Amazon have gone over the initial phases of occupation, the region can be taken as an experimentation field where the outcomes of policies can be compared and contrasted between localities in different stages of the settlement process. Valuable lessons can thus be taken that may be relevant for the study of land use change and development in other highly forested areas, especially in the neighbouring South-American countries. Taken together, the conclusions in this thesis provide a fresh view on the outcomes of colonization in frontier areas.

I close this thesis by referring back to Sergio, the settler I described in the Preface. His story shows that the expansion of frontiers is in many ways similar to what it was in the heyday of the induced-colonization movement. The choice set of poor peasants was and still is so restricted that they see benefit in migrating to a pioneer front in the middle of the forest with nearly no welfare infrastructure whatsoever. This was and still is to a large extent based on a relation with the environment that is far from ideal from a sustainable development point of view. Yet what this thesis suggests is that processes of social change *can* emerge in a way that is conducive to development and to a more rational use of the environment. Sergio's fate is being changed, and unless we are willing to miss the cow in the room, the evidence that his children may face an enlarged choice set is compelling.

References

Abreu, Urbano, and Paulo Lopes. 2005. Análise de sistemas de produção animal-bases conceituais. In *Documentos*. Corumbá, Brazil: Embrapa Pantanal.

Acemoglu, Daron, and James Robinson. 2002. "The political economy of the Kuznets curve." *Review of development economics* no. 6 (2): 183-203.

Aldrich, Stephen, Robert Walker, Eugenio Arima, Marcellus Caldas, John Browder, and Stephen Perz. 2006. "Land-Cover and Land-Use Change in the Brazilian Amazon: Smallholders, Ranchers, and Frontier Stratification." *Economic Geography* no. 82 (3): 265-288.

Almeida, Anna Luisa Ozório. 1992. *The Colonization of the Amazon*. Austin: University of Texas Press.

Almeida, Ana Luisa Ozório, and João Campari. 1995. *Sustainable settlement in the Brazilian Amazon*. New York: Oxford University Press.

Anagol, Santosh, Alvin Etang, and Dean Karlan. 2013. Continued Existence of Cows Disproves Central Tenets of Capitalism? : National Bureau of Economic Research.

Andersen, Lykke, Clive Granger, Eustáquio Reis, Diana Weinhold, and Sven Wunder. 2002. *The dynamics of deforestation and economic growth in the Brazilian Amazon*. Cambridge: Cambridge University Press.

Angelsen, Arild. 2010. "Policies for reduced deforestation and their impact on agricultural production." *Proceedings of the National Academy of Sciences* no. 107 (46): 19639-19644.

Angelsen, Arild, and David Kaimowitz, eds. 2001. *Agricultural technologies and tropical deforestation*. Wallingford: CABi.

Anselin, Luc. 2002. "Under the hood issues in the specification and interpretation of spatial regression models." *Agricultural economics* no. 27 (3): 247-267.

Arima, Eugenio, Paulo Barreto, Elis Araújo, and Britaldo Soares-Filho. 2014. "Public policies can reduce tropical deforestation: Lessons and challenges from Brazil." *Land Use Policy* 41:465-473.

Arima, Eugenio, Peter Richards, Robert Walker, and Marcellus Caldas. 2011. "Statistical confirmation of indirect land use change in the Brazilian Amazon." *Environmental Research Letters* no. 6 (2): 7p.

Assunção, Juliano. 2008. "Rural organization and land reform in Brazil: The role of nonagricultural benefits of landholding." *Economic Development and Cultural Change* no. 56 (4): 851-870.

Assunção, Juliano, Clarissa Gandour, and Romero Rocha. 2014. DETERring deforestation in the Brazilian Amazon: environmental monitoring and law enforcement. LACERLACEA working paper.

Barbier, Edward. 1997. "The economic determinants of land degradation in developing countries." *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* no. 352 (1356): 891-899.

Barbier, Edward. 2004. "Agricultural expansion, resource booms and growth in Latin America: implications for long-run economic development." *World Development* no. 32 (1): 137-157.

Barbier, Edward. 2011. *Scarcity and Frontiers: how economies have developed through natural resource exploitation*. Cambridge: Cambridge University Press.

Barbieri, Alisson, David Carr, and Richard Bilsborrow. 2009. "Migration within the frontier: the second generation colonization in the Ecuadorian Amazon." *Population Research and Policy Review* no. 28 (3): 291-320.

Barreto, Paulo, and Daniel Silva da Silva. 2013. Como desenvolver a economia rural sem desmatar a Amazônia? Belém, Brazil: IMAZON.

Barretto, Alberto, Göran Berndes, Gerd Sparovek, and Stefan Wirsenius. 2013. "Agricultural intensification in Brazil and its effects on land-use patterns: an analysis of the 1975—2006 period." *Global change biology* no. 19 (6): 1804-1815.

Baruch, Yehuda, and Brooks Holtom. 2008. "Survey response rate levels and trends in organizational research." *Human Relations* no. 61 (8): 1139-1160.

Batistella, Mateus, and Emilio Moran. 2005. "Dimensões humanas do uso e cobertura das terras na Amazônia: uma contribuição do LBA." *Acta Amazonica* no. 35 (2): 239-247.

Bell, Andrew. 2011. "Highly Optimized Tolerant (HOT) Farms in Rondônia: Productivity and Farm Size, and Implications for Environmental Licensing." *Ecology and Society* no. 16 (2): 7p.

Berger, Thomas. 2001. "Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis." *Agricultural economics* no. 25 (2-3): 245-260.

Börjeson, Lowe. 2007. "Boserup backwards? Agricultural intensification as 'its own driving force'in the Mbulu Highlands, Tanzania." *Geografiska Annaler: Series B, Human Geography* no. 89 (3): 249-267.

Boserup, Ester. 1965. *The conditions of agricultural growth*, *The Economics of Agrarian Change under Population Pressure*. London: George Allen and Unwin.

Bourne, Richard. 1978. *Assault on the Amazon*. London: Gollancz.

Bowman, Maria, Britaldo Soares-Filho, Frank Merry, Daniel Nepstad, Hermann Rodrigues, and Oriana Almeida. 2012. "Persistence of cattle ranching in the Brazilian Amazon: a spatial analysis of the rationale for beef production." *Land Use Policy* no. 29 (3): 558-568.

Browder, John, and Brian Godfrey. 1990. Frontier urbanization in the Brazilian Amazon: A theoretical framework for urban transition. Paper read at Yearbook. Conference of Latin Americanist Geographers.

Browder, John, Marcos Pedlowski, Robert Walker, Randolph Wynne, Percy Summers, Ana Abad, Nancy Becerra-Cordoba, and João Mil-Homens. 2008. "Revisiting theories of frontier expansion in the Brazilian Amazon: a survey of the colonist farming population in Rondonia's post-frontier, 1992—2002." *World Development* no. 36 (8): 1469-1492.

Brown, Christopher, Matthew Koeppe, Benjamin Coles, and Kevin Price. 2005. "Soybean production and conversion of tropical forest in the Brazilian Amazon: The case of Vilhena, Rondonia." *AMBIO: A Journal of the Human Environment* no. 34 (6): 462-469.

Buchmann, Gabriel. 2006. *Determinantes do mau funcionamento do mercado de terras no Brasil*, Economics, PUC, Rio de Janeiro.

Buse, Rueben, ed. 1989. *The Economics of Meat Demand: proceedings of the Conference on the Economics of Meat Demand, October 20-21, 1986, Charleston, South Carolina*: University of Wisconsin, Department of Agricultural Economics.

Caldas, Marcellus, Cynthia Simmons, Robert Walker, Stephen Perz, Stephen Aldrich, Ritaumaria Pereira, Flavia Leite, and Eugenio Arima. 2010. "Settlement Formation and Land Cover and Land Use Change: A Case Study in the Brazilian Amazon." *Journal of Latin American Geography* no. 9 (1): 125-144.

Campari, João. 2002. *Challenging the Turnover Hypothesis of Amazon Deforestation: Evidence from Colonization Projects in Brazil*, Economics, University of Texas, Austin.

Carr, David. 2008. "Farm households and land use in a core conservation zone of the Maya Biosphere Reserve, Guatemala." *Human Ecology* no. 36 (2): 231-248.

Carr, David. 2009. "Population and deforestation: why rural migration matters." *Progress in Human Geography* no. 33 (3): 355-378.

Casetti, Emilio, and Howard Gauthier. 1977. "A formalization and test of the "hollow frontier" hypothesis." *Economic Geography* no. 53 (1): 70-78.

Castro, Marcia, and Burton Singer. 2012. "Agricultural settlement and soil quality in the Brazilian Amazon." *Population and environment* no. 34 (1): 22-43.

Cattaneo, Andrea. 2002. Balancing agricultural development and deforestation in the Brazilian Amazon. In *Research Report*. Washington D.C: IFPRI.

Caviglia-Harris, Jill, and Daniel Harris. 2008. "Integrating survey and remote sensing data to analyze land use at a fine scale: insights from agricultural households in the Brazilian Amazon." *International regional science review* no. 31 (2): 115-137.

Caviglia-Harris, Jill, and Erin Sills. 2005. "Land use and income diversification: comparing traditional and colonist populations in the Brazilian Amazon." *Agricultural Economics* no. 32 (3): 221-237.

Caviglia-Harris, Jill, Erin Sills, and Katrina Mullan. 2013. "Migration and mobility on the Amazon frontier." *Population and Environment* no. 34 (3): 338-369.

Ceddia, Michele, S Sedlacek, NO Bardsley, and S Gomez-y-Paloma. 2013. "Sustainable agricultural intensification or Jevons paradox? The role of public governance in tropical South America." *Global Environmental Change* no. 23 (5): 1052-1063.

Celentano, Danielle, Erin Sills, Marcio Sales, and Adalberto Veríssimo. 2012. "Welfare outcomes and the advance of the deforestation frontier in the Brazilian Amazon." *World Development* no. 40 (4): 850-864.

Celentano, Danielle, and Adalberto Veríssimo. 2007. O avanço da fronteira na Amazônia: do boom ao colapso. In *O estado da Amazônia*. Belém, Brazil: IMAZON, Instituto do Homem e Meio Ambiente da Amazônia.

Cerri, Carlos, Jerry Melillo, Brigitte Feigl, Marisa Piccolo, Christopher Neill, Paul Steudler, Maria da Conceição Carvalho, Vicente Godinho, Carlos Eduardo Cerri, and Martial Bernoux. 2005. "Recent history of the agriculture of the Brazilian Amazon Basin: prospects for sustainable development and a first look at the biogeochemical consequences of pasture reformation." *Outlook on agriculture* no. 34 (4): 215-223.

Chen, Yang, Douglas Morton, Yufang Jin, G. James Collatz, Prasad Kasibhatla, Guido van der Werf, Ruth DeFries, and James Randerson. 2013. "Long-term trends and interannual variability of forest, savanna and agricultural fires in South America." *Carbon Management* no. 4 (6): 617-638.

Chomitz, Kenneth, and Timothy Thomas. 2001. Geographic patterns of land use and land intensity in the Brazilian Amazon. The World Bank.

Cleary, David. 1993. "After the frontier: Problems with political economy in the modern Brazilian Amazon." *Journal of Latin American Studies* no. 25 (02): 331-349.

Cohn, Avery, Maria Bowman, David Zilberman, and Kate O'Neill. 2011. The viability of cattle ranching intensification in Brazil as a strategy to spare land and mitigate greenhouse gas emissions. *Working Paper*. Copenhagen: CGIAR Research Programme on Climate Change, Agriculture and Food Security.

Oxford Martin Commission. 2013. Now for the Long Term: The Report of the Oxford Martin Commission for Future Generations. University of Oxford.

Costa, Francisco de Assis. 2000. *Formação agropecuária da Amazônia: os desafios do desenvolvimento sustentável*. Belém, Brazil: NAEA Proj. Editorial.

Costa, Francisco de Assis. 2012. "Base de Exportação e Desenvolvimento de Economias Locais na Amazônia: Estrutura e Dinâmica do Sudeste Paraense (1995-2005)." *Revista EconomiA* no. 13 (1): 199-244.

Coy, Martin. 1983. Desenvolvimento regional na periferia amazônica. Organização do espaço, conflitos de interesses e programas de planejamento dentro de uma região de" fronteira": o caso de Rondônia. Geographisches Institut der Universität Tübingen.

Crotty, Raymond. 1980. *Cattle, economics and development*: Commonwealth Agricultural Bureaux.

Cunha, Eliaquim. 2011. Os projetos de colonização em Rondônia. *Revista Zona de Impacto* 16, http://www.albertolinscaldas.unir.br/eliaquimdacunha_vol_16.html.

Davern, Michael, Todd Rockwood, Randy Sherrod, and Stephen Campbell. 2003. "Prepaid monetary incentives and data quality in face-to-face interviews: Data from the 1996 survey of income and program participation incentive experiment." *Public Opinion Quarterly* no. 67: 139-147.

Deroïan, Frédéric. 2002. "Formation of social networks and diffusion of innovations." *Research policy* no. 31 (5): 835-846.

Desjardins, Thierry, P Lavelle, E Barros, Michel Brossard, L Chapuis-Lardy, Armand Chauvel, Michel Grimaldi, F Guimarães, P Martins, and D Mitja. 2000. "Dégradation des pâturages amazoniens." *Étude et gestion des sols* no. 7 (4): 353-378.

Dias-Filho, Moacyr. 2011. "Os desafios da produção animal em pastagens na fronteira agrícola brasileira." *Revista Brasileira de Zootecnia* no. 40: 243-252.

Diniz, Alexandre. 2002. Migração e evolução da fronteira agrícola. Paper read at XIII Encontro da Associação Brasileira de Estudos Populacionais, at Ouro Preto, Brazil.

D'Silva, Joyce, and John Webster, eds. 2010. *The meat crisis: Developing more sustainable production and consumption*. New York: Earthscan.

Duflo, Esther, Michael Kremer, and Jonathan Robinson. 2011. "Nudging Farmers to Use Fertilizer: Theory and Experimental Evidence from Kenya." *The American Economic Review* no. 101 (6): 2350-90.

Faminow, Merle. 1998. *Cattle, deforestation and development in the Amazon: an economic, agronomic and environmental perspective*: Cab International.

Fearnside, Philip. 1986. *Human carrying capacity of the Brazilian rainforest*. New York: Columbia University Press.

Fearnside, Philip. 2004. A intensificação da pastagem pode frear o desmatamento no Brasil? In *Instituto Nacional de Pesquisas da Amazônia*. Manaus, Brazil.

Fearnside, Philip. 2005. "Deforestation in Brazilian Amazonia: history, rates, and consequences." *Conservation Biology* no. 19 (3): 680-688.

Fox, Jefferson, Ronald Rindfuss, Stephen Walsh, and Vinod Mishra, eds. 2004. *People and the environment: Approaches for linking household and community surveys to remote sensing and GIS*. New York: Kluwer Academic Publisher.

Futemma, Célia, and Eduardo Brondizio. 2003. "Land reform and land-use changes in the lower Amazon: Implications for agricultural intensification." *Human Ecology* no. 31 (3): 369-402.

Gama, Michelliny, Márcio Silva, Luciano Vilcahuamán, and Marilia Locatelli. 2005. "Análise econômica de sistemas agroflorestais na Amazônia Ocidental, Machadinho D'Oeste-RO." *Revista Árvore* no. 29 (3): 401-411.

Geertz, Clifford. 1963. *Agricultural involution. The process of ecological change in Indonesia*. Berkeley: University of California Press.

Gibbons, Stephen, and Henry Overman. 2012. "Mostly pointless spatial econometrics?" *Journal of Regional Science* no. 52 (2): 172-191.

Gillingham, Kenneth, Matthew Kotchen, David Rapson, and Gernot Wagner. 2013. "Energy policy: The rebound effect is overplayed." *Nature* no. 493 (7433):475-476.

Gourou, Pierre. 1953. *Tropical world: its social and economic conditions and its future status*. United Kingdom: Longman Group.

Griliches, Zvi, and Jerry Hausman. 1986. "Errors in variables in panel data." *Journal of econometrics* no. 31 (1): 93-118.

Grossman, Gene, and Alan Krueger. 1991. Environmental impacts of a North American free trade agreement. National Bureau of Economic Research.

Grupo de Trabalho da Pecuária Sustentável, GTPS. 2012. Mechanisms for control and mitigation of deforestation in the Brazilian Amazon Biome.

Guedes, Gilvan, Eduardo Brondízio, Alisson Barbieri, Resende Anne, Rodrigo Penna-Firme, and Álvaro D'Antona. 2012. "Poverty and Inequality in the Rural Brazilian Amazon: A Multidimensional Approach." *Human Ecology* no. 40 (1): 41-57.

Hall, Simon, and Jill Caviglia-Harris. 2013. "Agricultural development and the industry life cycle on the Brazilian frontier." *Environment and Development Economics* no. 18 (03): 326-353.

Hansen, Matthew, Stephen Stehman, and Peter Potapov. 2010. "Quantification of global gross forest cover loss." *Proceedings of the National Academy of Sciences* no. 107 (19): 8650-8655.

Hansen, Robert. 1980. "A self-perception interpretation of the effect of monetary and nonmonetary incentives on mail survey respondent behavior." *Journal of Marketing Research* no. 17 (1): 77-83.

Hargrave, Jorge, and Krisztina Kis-Katos. 2013. "Economic causes of deforestation in the Brazilian Amazon: A panel data analysis for the 2000s." *Environmental and Resource Economics* no. 54 (4): 471-494.

Heath, John, and Hans Binswanger. 1998. "Policy-induced effects of natural resource degradation: The case of Colombia." *Agriculture and the Environment: Perspectives on Sustainable Rural Development* no. 1 (1): 22-34.

Herrero, M, PK Thornton, AM Notenbaert, Stanley Wood, Siwa Msangi, HA Freeman, D Bossio, J Dixon, M Peters, and Jvd Steeg. 2010. "Smart investments in sustainable food production: revisiting mixed crop-livestock systems." *Science* no. 327: 822-825.

Hudson, John. 1969. "A location theory for rural settlement." *Annals of the Association of American Geographers* no. 59 (2): 365-381.

Hunt, Robert. 2000. "Labor productivity and agricultural development: Boserup revisited." *Human Ecology* no. 28 (2): 251-277.

James, Preston. 1938. "The changing patterns of population in São Paulo State, Brazil." *Geographical Review* no. 28 (3): 353-362.

Jolliffe, Ian. 2005. *Principal component analysis*. Aberdeen: Springer.

Kamtsiuris, Panagiotis, Michael Lange, Robert Hoffmann, Angelika Rosario, Stefan Dahm, Ronny Kuhnert, and Bärbel-Maria Kurth. 2013. "The first wave of the German Health Interview and Examination Survey for Adults (DEGS1)." *Bundesgesundheitsbl* no. 56: 620-630.

Kjaerby, Finn. 1980. Agricultural productivity and surplus production in Tanzania. Paper read at BRALUP Seminar Paper, March 1979.

Knight, Peter. 1971. *Brazilian agricultural technology and trade. A study of five commodities*. London: Praeger Publishers.

Kuznets, Simon. 1955. "Economic growth and income inequality." *The American economic review* no. 45 (1): 1-28.

Lambin, Eric, and Patrick Meyfroidt. 2011. "Global land use change, economic globalization, and the looming land scarcity." *Proceedings of the National Academy of Sciences* no. 108 (9): 3465-3472.

Lambin, Eric, Billie Lee Turner, Helmut Geist, Samuel Agbola, Arild Angelsen, John Bruce, Oliver Coomes, Rodolfo Dirzo, Günther Fischer, and Carl Folke. 2001. "The causes of land-use and land-cover change: moving beyond the myths." *Global environmental change* no. 11 (4): 261-269.

Laney, Rheyna. 2002. "Disaggregating Induced Intensification for Land-Change Analysis: A Case Study from Madagascar." *Annals of the Association of American Geographers* no. 92 (4): 702-726.

Lapola, David, Luiz Martinelli, Carlos Peres, Jean Ometto, Manuel Ferreira, Carlos Nobre, Ana Paula Aguiar, Mercedes Bustamante, Manoel Cardoso, and Marcos Costa. 2014. "Pervasive transition of the Brazilian land-use system." *Nature Climate Change* no. 4 (1): 27-35.

Levins, Richard, and Willard Cochrane. 1996. "The treadmill revisited." *Land Economics* no. 72 (4): 550-553.

Lévi-Strauss, Claude. 1961. *Tristes Tropiques: An anthropological study of primitive societies in Brazil*. London: Hutchinson & Co.

Lorena, Rodrigo, and Eric Lambin. 2009. "The spatial dynamics of deforestation and agent use in the Amazon." *Applied Geography* no. 29 (2): 171-181.

Macdonald, Trilby, and Antoinette Winklerprins. 2014. "Searching for a Better Life: Peri-Urban Migration in Western Para State, Brazil." *Geographical Review* no. 104 (3): 294-309.

Macedo, Marcia, Ruth DeFries, Douglas Morton, Claudia Stickler, Gillian Galford, and Yosio Shimabukuro. 2012. "Decoupling of deforestation and soy production in the southern Amazon during the late 2000s." *Proceedings of the National Academy of Sciences* no. 109 (4): 1341-1346.

Maertens, Miet, Manfred Zeller, and Regina Birner. 2006. "Sustainable agricultural intensification in forest frontier areas." *Agricultural Economics* no. 34 (2): 197-206.

Mahar, Dennis. 1979. *Frontier development policy in Brazil: a study of Amazonia*. New York: Praeger.

Mangabeira, João Alfredo. 2010. *Serviços ecossistemicos e trajetoria de capitalização agricola: o caso de Machadinho do Oeste*, Economics, Unicamp, Campinas.

Mann, Michael, Robert Kaufmann, Dana Bauer, Sucharita Gopal, Mallory Nomack, Jesse Womack, Kerry Sullivan, and Britaldo Soares-Filho. 2014. "Pasture conversion and competitive cattle rents in the Amazon." *Ecological Economics* no. 97: 182-190.

Marchand, Sébastien. 2012. "The relationship between technical efficiency in agriculture and deforestation in the Brazilian Amazon." *Ecological Economics* no. 77: 166-175.

Margulis, Sergio. 2004. Causes of Deforestation of the Brazilian Rainforest. Washington D.C.: The World Bank.

Martha, Geraldo. 2010. Oportunidades para aumentar a produção agropecuária, sem desmatamento, pela intensificação da produção animal em sistemas pastoris e recuperação de APPs. In *Proposed Cuiabá Plan*.

Martha, Geraldo, Eliseu Alves, and Elisio Contini. 2012. "Land-saving approaches and beef production growth in Brazil." *Agricultural Systems* no. 110: 173-177.

Martinelli, Luiz, Rosamond Naylor, Peter Vitousek, and Paulo Moutinho. 2010. "Agriculture in Brazil: impacts, costs, and opportunities for a sustainable future." *Current Opinion in Environmental Sustainability* no. 2 (5): 431-438.

Martınez, L, and J Zinck. 2004. "Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia." *Soil and Tillage Research* no. 75 (1): 3-18.

Martins, José de Souza. 1996. "O tempo da fronteira." *Tempo Social. Revista de Sociologia* no. 8 (1): 25-70.

Matson, Pamela, and Peter Vitousek. 2006. "Agricultural intensification: will land spared from farming be land spared for nature?" *Conservation Biology* no. 20 (3): 709-710.

McCracken, Stephen, Eduardo Brondizio, Donald Nelson, Emilio Moran, Andrea Siqueira, and Carlos Rodriguez-Pedraza. 1999. "Remote sensing and GIS at farm property level: Demography and deforestation in the Brazilian Amazon." *Photogrammetric Engineering and Remote Sensing* no. 65: 1311-1320.

Merry, Frank, Gregory Amacher, Daniel Nepstad, Eirivelthon Lima, Paul Lefebvre, and Simone Bauch. 2006. "Industrial development on logging frontiers in the Brazilian Amazon." *International journal of sustainable development* no. 9 (3): 277-296.

Mizes, Scott, Louis Fleece, and Cindy Roos. 1984. "Incentives for Increasing Return Rates: Magnitude Levels, Response Bias, amd Format." *Public Opinion Quarterly* no. 48 (4): 794-800.

Moran, Emilio. 1989. "Adaptation and maladaptation in newly settled areas." In *The human ecology of tropical land settlement in Latin America*, edited by D. Schumann and W. Partridge, 20-41. Boulder, Colorado: Westview Press.

Moran, Emilio, Andréa Siqueira, and Eduardo Brondizio. 2004. "Household demographic structure and its relationship to deforestation in the Amazon Basin." In *People and the environment: approaches for linking household and community surveys to remote sensing and GIS*, edited by Jefferson Fox, Ronald Rindfuss, Stephen Walsh and Vinod Mishra, 61-89. New York: Kluwer Academic Publishers.

Morton, Douglas, Ruth DeFries, Yosio Shimabukuro, Liana Anderson, Egidio Arai, Fernando del Bon Espirito-Santo, Ramon Freitas, and Jeff Morisette. 2006. "Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon." *Proceedings of the National Academy of Sciences* no. 103 (39): 14637-14641.

Muchagata, Marcia, and Katrina Brown. 2003. "Cows, colonists and trees: rethinking cattle and environmental degradation in Brazilian Amazonia." *Agricultural systems* no. 76 (3): 797-816.

Mueller, Bernardo. 1997. "Property rights and the evolution of a frontier." *Land Economics* no. 73 (1): 42-57.

Mueller, Charles, and Geraldo Martha. 2008. "A agropecuária eo desenvolvimento sócioeconômico recente do Cerrado." In *Savanas: desafios e estratégias para o equilíbrio entre sociedade, agronegócio e recursos naturais*, edited by Fábio Faleiro and Austeclinio Neto, 35-99. Planaltina, Brazil: Embrapa Cerrados.

Neto, José Bernardo de Medeiros. 1970. *Desafio à pecuária brasileira*. Porto Alegre, Brazil: Editora Sulina.

Numata, Izaya, Oliver Chadwick, Dar Roberts, Joshua Schimel, Fernando Sampaio, Francisco Leonidas, and João Soares. 2007. "Temporal nutrient variation in soil and vegetation of post-forest pastures as a function of soil order, pasture age, and management, Rondônia, Brazil." *Agriculture, ecosystems & environment* no. 118 (1): 159-172.

Numata, Izaya, Dar Roberts, Yoshito Sawada, Oliver Chadwick, Joshua Schimel, and João Soares. 2007a. "Regional Characterization of Pasture Changes through Time and Space in Rondônia, Brazil." *Earth Interactions* no. 11 (1): 1-25.

Oliveira, José Lopes. 2010. *Rondônia: Geopolítica e Estrutura Fundiária*. Porto Velho: Grafiel.

Pacheco, Pablo. 2012. "Actor and frontier types in the Brazilian Amazon: Assessing interactions and outcomes associated with frontier expansion." *Geoforum* no. 43 (4): 864-874.

Pacheco, Pablo, and Rene Poccard-Chapuis. 2012. "The complex evolution of cattle ranching development amid market integration and policy shifts in the Brazilian Amazon." *Annals of the Association of American Geographers* no. 102 (6): 1366-1390.

Parry, Luke, Carlos Peres, Brett Day, and Silvana Amaral. 2010. "Rural—urban migration brings conservation threats and opportunities to Amazonian watersheds." *Conservation Letters* no. 3 (4): 251-259.

Pascual, Unai, and Edward Barbier. 2006. "Deprived land-use intensification in shifting cultivation: the population pressure hypothesis revisited." *Agricultural Economics* no. 34 (2): 155-165.

Pelletier, Nathan, and Peter Tyedmers. 2010. "Forecasting potential global environmental costs of livestock production 2000—2050." *Proceedings of the National Academy of Sciences* no. 107 (43): 18371-18374.

Perz, Stephen, Flavia Leite, Cynthia Simmons, Robert Walker, Stephen Aldrich, and Marcellus Caldas. 2010. "Intraregional migration, direct action land reform, and new land settlements in the Brazilian Amazon." *Bulletin of Latin American Research* no. 29 (4): 459-476.

Perz, Stephen, Liliana Cabrera, Lucas Carvalho, Jorge Castillo, Rosmery Chacacanta, Rosa Cossio, Yeni Solano, Jeffrey Hoelle, Leonor Perales, and Israel Puerta. 2012. "Regional integration and local change: road paving, community connectivity, and social—ecological resilience in a tri-national frontier, southwestern Amazonia." *Regional Environmental Change* no. 12 (1): 35-53.

Phelps, Jacob, Luis Carrasco, Edward Webb, Lian Koh, and Unai Pascual. 2013. "Agricultural intensification escalates future conservation costs." *Proceedings of the National Academy of Sciences* no. 110 (19): 7601-7606.

Piñedo-Vasquez, Miguel, Daniel Zarin, Kevin Coffey, Christine Padoch, and Fernando Rabelo. 2001. "Post-boom logging in Amazonia." *Human Ecology* no. 29 (2): 219-239.

Poccard-Chapuis, René, Marcelo Thalês, Adriano Venturieri, Marie-Gabrielle Piketty, Benoît Mertens, Jonas Bastos da Veiga, and Jean-François Tourrand. 2005. "A cadeia produtiva da carne: uma ferramenta para monitorar dinâmicas nas frentes pioneiras brasileiras?" *Cadernos de Ciência & Tecnologia* no. 22 (1): 125-138.

Pocewicz, Amy, Max Nielsen-Pincus, Caren Goldberg, Melanie Johnson, Penelope Morgan, Jo Force, Lisette Waits, and Lee Vierling. 2008. "Predicting land use change: comparison of models based on landowner surveys and historical land cover trends." *Landscape Ecology* no. 23 (2): 195-210.

Porter, Stephen, and Michael Whitcomb. 2003. "The impact of lottery incentives on student survey response rates." *Research in Higher Education* no. 44 (4): 389-407.

Possas, Mário, Sérgio Salles-Filho, and José Maria Silveira. 1996. "An evolutionary approach to technological innovation in agriculture: some preliminary remarks." *Research Policy* no. 25 (6): 933-945.

Rodrigues, Ana, Robert Ewers, Luke Parry, Carlos Souza, Adalberto Veríssimo, and Andrew Balmford. 2009. "Boom-and-bust development patterns across the Amazon deforestation frontier." *Science* no. 324 (5933): 1435-1437.

Rudel, Thomas, Diane Bates, and Rafael Machinguiashi. 2002. "A tropical forest transition? Agricultural change, out-migration, and secondary forests in the Ecuadorian Amazon." *Annals of the Association of American Geographers* no. 92 (1): 87-102.

Rudel, Thomas, Laura Schneider, Maria Uriarte, Billie Lee Turner, Ruth DeFries, Deborah Lawrence, Jacqueline Geoghegan, Susanna Hecht, Amy Ickowitz, and Eric Lambin. 2009. "Agricultural intensification and changes in cultivated areas, 1970—2005." *Proceedings of the National Academy of Sciences* no. 106 (49): 20675-20680.

Sá, Saraly, Charles Palmer, and Salvatore Di Falco. 2013. "Dynamics of indirect land-use change: empirical evidence from Brazil." *Journal of Environmental Economics and Management* no. 65 (3): 377-393.

Särndal, Carl-Erik, and Sixten Lundström. 2005. *Estimation in surveys with nonresponse*. Chichester: John Wiley & Sons.

Sartre, Xavier. 2003. "Family farming in an Amazonian frontier: the sedentarisation in question." *Natures Sciences Societes* no. 11 (2): 158-168.

Sartre, Xavier, Christophe Albaladejo, Paulo Martins, Iran Veiga, and Michel Grimaldi. 2005. "Identificação e avaliação da diversidade dos tipos de exploração do ambiente na Amazônia oriental." *Cadernos de Ciência & Tecnologia* no. 22 (1): 207-220.

Schneider, Robert. 1995. Government and the Economy on the Amazon Frontier. The World Bank.

Schneider, Robert, Eugenio Arima, Adalberto Veríssimo, Carlos Souza Junior, and Paulo Barreto. 2002. Sustainable Amazon: Limitations and opportunities for rural development. Washington D.C.: The World Bank.

Sears, Robin, Christine Padoch, and Miguel Piñedo-Vasquez. 2007. "Amazon forestry tranformed: integrating knowledge for smallholder timber managemet in Eastern Brazil." *Human Ecology* no. 35 (6): 697-707.

Siegmund-Schultze, M, B Rischkowsky, JB Da Veiga, and JM King. 2007. "Cattle are cash generating assets for mixed smallholder farms in the Eastern Amazon." *Agricultural Systems* no. 94 (3): 738-749.

Sills, Erin, and Jill Caviglia-Harris. 2009. "Evolution of the Amazonian frontier: Land values in Rondônia, Brazil." *Land Use Policy* no. 26 (1): 55-67.

Singer, Eleanor. 2002. The use of incentives to reduce nonresponse in household surveys. In *Survey Methodology Program*, edited by The University of Michigan.

Soares, Álvaro Teixeira. 1967. *Amazônia: a exploração econômica do espaço geográfico e a integração do homem*. Rio de Janeiro, Brazil: Companhia Brasileira de Artes Gráficas.

Soler, Luciana, and Peter Verburg. 2010. "Combining remote sensing and household level data for regional scale analysis of land cover change in the Brazilian Amazon." *Regional Environmental Change* no. 10 (4): 371-386.

Stella, Schons, Andrea Azevedo, and Anna Alencar. 2013. "PRONAF" na Amazônia: quais os desafios? In *Boletim Amazônia em Pauta*. Brasília, Brazil: IPAM.

Stern, David. 2004. "The rise and fall of the environmental Kuznets curve." *World development* no. 32 (8): 1419-1439.

Stickler, Claudia, Daniel Nepstad, Andrea Azevedo, and David McGrath. 2013. "Defending public interests in private lands: compliance, costs and potential environmental consequences of the Brazilian Forest Code in Mato Grosso." *Philosophical Transactions of the Royal Society B: Biological Sciences* no. 368 (1619).

Strassburg, Bernardo, Annabel Kelly, Andrew Balmford, Richard Davies, Holly Gibbs, Andrew Lovett, Lera Miles, David Orme, Jeff Price, and Kerry Turner. 2010. "Global congruence of carbon storage and biodiversity in terrestrial ecosystems." *Conservation Letters* no. 3 (2): 98-105.

Strassburg, Bernardo, L Micol, F Ramos, R Seroa da Motta, A Latawiec, and F Lisauskas. 2012. Increasing agricultural output while avoiding deforestation—A case study for Mato Grosso, Brazil. Rio de Janeiro, Brazil: International Institute for Sustainability, Instituto Centro de Vida.

Szott, Larry, Muhammed Ibrahim, and John Beer. 2000. The hamburger connection hangover: cattle, pasture land degradation and alternative land use in Central America. In *Informe Tecnico*. Turrialba, Costa Rica: CATIE.

Sydenstricker, John. 2012. "Population and deforestation in the Brazilian Amazon: a mediating perspective and a mixed-method analysis." *Population and Environment* no. 34 (1): 86-112.

Tachibana, Towa, Trung Nguyen, and Keijiro Otsuka. 2001. "Agricultural intensification versus extensification: a case study of deforestation in the northern-hill region of Vietnam." *Journal of Environmental Economics and Management* no. 41 (1): 44-69.

Taylor, Harry. 1973. "São Paulo's hollow frontier." *Revista Geográfica (Mexico)* no. 79: 149-155.

Tocantins, Leandro. 1982. *Amazônia : natureza homem e tempo : uma planificaçâo ecológica*. Rio de Janeiro, Brazil: Civilizaçao brasileira.

Townsend, Claudio, Newton Costa, and Ricardo Pereira. 2012. Recuperação e práticas sustentáveis de manejo de pastagens na Amazônia. Documentos Embrapa 148.

Townsend, Claudio, Newton Costa, and Ricardo Pereira. 2010. "Aspectos econômicos da recuperação de pastagens na Amazônia brasileira." *Amazônia: Ciência & Desenvolvimento* no. 5 (10): 27-49.

Trivedi, Mandar, Duarte Costa, Luis Meneses-Filho, Nick Oakes, Andrew Mitchell, Bernardo Strassburg, Ramon Ortiz, Ronaldo Seroa da Motta, Luis Pinto, Anthony Hall, and Jean Ometto. 2012. Think PINC: Securing Brazil's food, water and energy with Proactive Investment in Natural Capital. Oxford: Global Canopy Programme.

Turner, Billie Lee, and Shajaat Ali. 1996. "Induced intensification: Agricultural change in Bangladesh with implications for Malthus and Boserup." *Proceedings of the National Academy of Sciences* no. 93 (25): 14984-14991.

Turner, Billie Lee, and Marina Fischer-Kowalski. 2010. "Ester Boserup: An interdisciplinary visionary relevant for sustainability." *Proceedings of the National Academy of Sciences* no. 107 (51): 21963-21965.

Turner, Billie Lee, and Jacqueline Geoghegan. 2003. "Land-cover and land-use change (LCLUC) in the southern Yucatán peninsular region (SYPR): an integrated approach." In *People and the environment: approaches for linking household and community surveys to remote sensing and GIS*, edited by Jefferson Fox, Ronald Rindfuss, Stephen Walsh and Vinod Mishra, 31-60. Boston: Kluwer Acad Press.

Turner, Frederick. 1921. *The Significance of the Frontier in American History*. New York: Henry Holt and Company. Original edition, 1893.

Vale, Petterson Molina, and Daniel Caixeta Andrade. 2011. Produtividade e preservação ambiental: um estudo exploratório para a pecuária do estado de Rondônia.

Vale, Petterson Molina, and Daniel Caixeta Andrade. 2013. "Comer carne e salvar a Amazônia? A produtividade da pecuária em Rondônia e sua relação com o desmatamento." *Estudos Sociedade e Agricultura* no. 20 (2): 381-408.

Van Evera, Stephen. 1997. *Guide to methods for students of political science*. New York: Cornell University Press.

VanWey, Leah, Elinor Ostrom, Vicky Meretsky, Emilio Moran, and Elinor Ostrom. 2005. "Theories underlying the study of human-environment interactions." In *Seeing the forest and the trees: Human-environment interactions in forest ecosystems*, edited by Emilio Moran and Elinor Ostrom, 23-56. Cambridge, USA: MIT Press.

VanWey, Leah, Gilvan Guedes, and Álvaro D'Antona. 2012. "Out-migration and land-use change in agricultural frontiers: insights from Altamira settlement project." *Population and environment* no. 34 (1): 44-68.

VanWey, Leah, Stephanie Spera, Rebecca de Sa, Dan Mahr, and John Mustard. 2013. "Socioeconomic development and agricultural intensification in Mato Grosso." *Philosophical Transactions of the Royal Society B: Biological Sciences* no. 368 (1619).

Villoria, Nelson, Derek Byerlee, and James Stevenson. 2014 "The Effects of Agricultural Technological Progress on Deforestation: What Do We Really Know?." *Applied Economic Perspectives and Policy* no. 2 (36): 211-237.

Vosti, Stephen, Chantal Carpentier, Julie Witcover, Judson Valentim, Arild Angelsen, and David Kaimowitz. 2001. "Intensified small-scale livestock systems in the Western Brazilian Amazon." In *Agricultural technologies and tropical deforestation*, edited by Arild Angelsen and David Kaimowitz, 113-133. San José, Costa Rica: CABI Publishing.

Vosti, Stephen, Julie Witcover, and Chantal Carpentier. 2002. Agricultural intensification by smallholders in the western Brazilian Amazon: from deforestation to sustainable land use. In *Research Report*. Washington D.C.: IFPRI.

Wade, Robert. 2011. Boulevard of broken dreams: the inside story of the World Bank's Polonoroeste Road Project in Brazil's Amazon. Grantham Research Institute on Climate Change and the Environment.

Walker, Robert, John Browder, Eugenio Arima, Cynthia Simmons, Ritaumaria Pereira, Marcellus Caldas, Ricardo Shirota, and Sergio de Zen. 2009. "Ranching and the new global range: Amazônia in the 21st century." *Geoforum* no. 40 (5): 732-745.

Walsh, Stephen, Richard Bilsborrow, Stephen McGregor, B Frizzelle, Joseph Messina, W Pan, Kelley Crews-Meyer, Gregory Taff, and Francis Baquero. 2004. "Integration of longitudinal surveys, remote sensing time series, and spatial analyses." In *People and the environment: approaches for linking household and community surveys to remote sensing and GIS*, edited by Jefferson Fox, Ronald Rindfuss, Stephen Walsh and Vinod Mishra, 91-130. New York: Kluwer Academic Publishers.

Walsh, Stephen, and William Welsh. 2003. "Approaches for linking people, place, and environment for human dimensions research." *GeoCarto International* no. 18 (3): 51-61.

Weinhold, Diana, and Eustaquio Reis. 2008. "Transportation costs and the spatial distribution of land use in the Brazilian Amazon." *Global Environmental Change* no. 18 (1): 54-68.

Weinhold, Diana, Eustáquio Reis, and Petterson Molina Vale. 2012. Sustainability in the tropics: does a boom in deforestation lead to a bust in development? : Grantham Research Institute on Climate Change and the Environment.

Weinhold, Diana, Eustáquio Reis, and Petterson Molina Vale. 2014. Sustainability in the Amazon: do booms in deforestation lead to busts in development? (Submitted).

Willimack, Diane, Howard Schuman, Beth-Ellen Pennell, and James Lepkowski. 1995. "Effects of a prepaid nonmonetary incentive on response rates and response quality in a face-to-face survey." *Public Opinion Quarterly* no. 59 (1): 78-92.

Winfrey, William, and William Darity Jr. 1997. "Increasing returns and intensification: A reprise on ester Boserup's model of agricultural growth." *Metroeconomica* no. 48 (1):60-80.

Witcover, Julie, Stephen Vosti, Chantal Carpentier, and Tâmara Gomes. 2006. "Impacts of soil quality differences on deforestation, use of cleared land, and farm income." *Environment and Development Economics* no. 11 (03): 343-370.

Wunder, Sven. 2005. *Oil wealth and the fate of the forest: a comparative study of eight tropical countries*. London: Routledge.

Zanine, Anderson, Edson Santos, Daniele de Jesus, and Gleidson Ferreira. 2006. Potencialidade da integração lavoura-pecuária: relação planta. *Revista Electrónica de Veterinaria REDVET* VII (1).

Appendices

Appendix A. Pre-frontier to consolidated: definitions

For a better flow of the text I have placed the definitions immediately before the relevant sections, but this has meant that the definitions are somewhat scattered over the thesis. This appendix is a reference point to which the reader can refer to get a quick overview of what the classification represents.

The categories of pre-frontier, frontier, transition and consolidated municipalities are central to this thesis. These are not purely temporal nor purely spatial abstractions: rather, they are spatiotemporal units. In a stylized world, a given municipality is expected to be a pre-frontier until the moment when a settlement process starts, turning the area into an agricultural frontier. The open access situation attracts flows of migrants in search of cheap and fertile lands, but at some point the process is checked by both economic and biophysical factors. A crisis then arises that forces farmers to choose between land use intensification and out-migration: this is the transition phase. Eventually, the area evolves to a consolidated situation where the private property regime takes over and land use intensification is much more prevalent.

The assumption that three of these categories (frontier, transition and consolidated) are realizations of the same process that are only separated by time and a set of observed covariates is the backbone of chapter 4. The process in question is a massive flow of immigrants that rapidly changes the economic, social and ecological structures of these localities.

<u>Pre-frontier</u>: deeply forested municipalities with economic and land use dynamics that are approximately exogenous to the settlement process taking place elsewhere.

Pre-frontier areas are where induced colonization projects have been inexistent or insignificant. Without the initial migration flow, social and economic dynamics remain similar to those that prevailed across the Amazon before the major colonization movement of the 1960s. These can be called 'forest economies' or 'extractive economies', for their reliance on the forest as a source of economic value.

Frontier: where a process of 'rush to the gold' causes high rates of immigration and leads to high deforestation activity. In simple words, frontiers are places that are only worth it for the poorest, most marginalized individuals.

For operational purposes I adopt the approach of Rodrigues et al. (2009), whose demarcation criteria are based on the most salient feature of frontiers: deforestation. They define frontiers as areas with high deforestation activity and low deforestation extent, and consolidated areas as the inverse—low deforestation activity and high deforestation extent. These criteria only require data on deforestation and the choice of 'high' and 'low' deforestation thresholds.

Transition: where soils are degrading and the competition phase is setting in. These areas have the atmosphere of a busting place, very much in the spirit of a hollow frontier, as defined by James Preston and subsequent authors. These are places where the difference between successful and failed farmers is the clearest, for many have remained as technological laggards and have not been able to tackle the various ecological problems that emerge as soils are used without proper management. Farmers are facing the key decision of intensifying or selling out.

Consolidated: where immigration rates and deforestation have converged to the State averages. The initial phases of settlement have faded and conditions are in the process of catching up with the rest of the country.

As the intensification process evolves, property rights become increasingly enforced, the economic infrastructure converges to the levels of the rest of the country, and land prices rise sharply along with opportunity costs. Eventually the crisis is over and a more dynamic, consolidated rural settlement is born. In this third phase of development, deforestation is very low and agriculture is on track with the process of modernization that is seen in many parts of the country.

Appendix B1. Research ethics review checklist

This checklist should be completed for every research project that involves human participants, personal, medical or otherwise sensitive data or methodologically controversial approaches. It is used to identify whether a full application for ethics approval needs to be submitted. The research ethics review process is not designed to assess the merits of the research in question, but is merely a device to ensure that external risks have been fully considered and that an acceptable research methodology has been applied. This checklist applies to research undertaken by *both* staff and students, but it should be noted that the way the checklist is processed differs between these two groups.

For staff: if a full application is required please ensure that you complete the Ethics Review Questionnaire for Researchers and send the completed form to Michael Nelson in the Research Division (RD).

Please accompany the questionnaire with a copy of this checklist and a copy of the research proposal.

For MSc/PhD students: if a full application is required please ensure that you complete the Ethics Review Questionnaire for Researchers and discuss the issues raised with your student supervisor in the first instance. You should ensure that the completed forms are accompanied with a copy of the research proposal to ensure that your supervisor can make a fully informed decision on the ethical implications of the research. Where the supervisor is satisfied that all ethical concerns have been addressed s/he must sign the checklist and ensure that a copy is retained within the department as a record of the decision reached. It is appreciated that in certain cases the student supervisor may not be able to reach a decision on the ethical concerns raised. In such instances the matter should be referred to the Research Ethics Committee (please send all relevant forms and a copy of the proposal to Michael Nelson in RD). *Only where an informed decision cannot be reached by the supervisor should paperwork be submitted to the Research Ethics Committee.*

Before completing this form, please refer to the LSE Research Ethics Policy. The principal investigator or, where the principal investigator is a student, the supervisor, is responsible for exercising appropriate professional judgement in this review. For students, your supervisor should be able to provide you with guidance on the ethical implications of the research project. If members of staff have any queries regarding the completion of the checklist they should address these to Michael Nelson (RD) in the first instance.

This checklist must be completed before potential participants are approached to take part in any research.

Section I: Applicant Details

Name of researcher:	Petterson Molina Vale
Status:	PhD Student
Email address:	p.m.vale@lse.ac.uk
Contact address:	LSE (Destin), Houghton street, London WC2A 2AE, UK

Section II: Project Details

Title of the proposal and brief abstract: Eating beef and saving the Amazon: does livestock intensification reduce deforestation? In this proposal I explore the role of intensification of cattle ranching in avoiding tropical deforestation. Livestock raising is the most important driver of Amazon forest clearance, and at the same time an essential economic activity for the region. The question that I address is whether and how increasing land productivity of cattle ranching can reduce deforestation. There is an open question in the land use literature as to whether intensification causes forests to be saved at all, and it has not been satisfactorily answered neither at the theoretical nor at the empirical level.

Section III: Student Details:

Details of study:	The research aims to uncover spatial relations between the expansion of cattle-led deforestation in areas of agricultural frontier in the Brazilian Amazon and intensification of cattle raising activities in more established (non-frontier) areas. The data collected will be used to explore this question in different ways. The main use will be to assess the validity of some theoretical statements that I am proposing, but another potential use is a statistical model of the advancement of cattle towards the frontier. Respondents will be cattle farmers in a selected group of municipalities in one State in the Brazilian Amazon, and they will be asked mostly close-ended questions that have to do with technical aspects of their farm and the land uses they have as well as how these evolved in time.
Supervisor's name:	Diana Weinhold
Email address:	d.weinhold@lse.ac.uk

Section IV: Research Checklist
Consent

	Yes	No	Not certain
Does the study involve participants who are in any way			X

vulnerable or may have any difficulty giving consent? *If you have answered yes or are not certain about this please complete Section 1 of the Research Questionnaire. As general guidance, the Research Ethics Committee feels that research participants under the age of 18 may be vulnerable.*			
Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g. covert observation of people in public places) *If you have answered yes or are not certain about this please complete Section 1 of the Research Questionnaire.*		**X**	

Research Design/Methodology

Does the research methodology use deception? *If you have answered yes or are not certain about this please complete Section 2 of the Research Questionnaire.*		X	
Are there any significant concerns regarding the design of the research project? a) If the proposed research relates to the provision of social or human services is it feasible and/or appropriate that service users or service user representatives should be in some way involved in or consulted upon the development of the project? b) Does the project involve the handling of any sensitive information? *If you have answered yes or not certain to these questions please complete Section 3 of the Research Questionnaire.*			X

Financial Incentives/Sponsorship

Will the independence of the research be affected by the source of the funding? *If you have answered yes or not certain about this please complete Section 4 of the Research Questionnaire.*		X	
Are there payments to researchers/participants that may have an impact on the objectivity of the research? *If you have answered yes or not certain about this please complete Section 4 of the Research Questionnaire.*	X		
Will financial inducements (other than reasonable expenses and			X

compensation for time) be offered to participants? *If you have answered yes or not certain about this please complete Section 4 of the Research Questionnaire.*			

Research Subjects

Is pain or more than mild discomfort likely to result from the study? *If you have answered yes or not certain about this please complete Section 5 of the Research Questionnaire.*		X	
Could the study induce unacceptable psychological stress or anxiety or cause harm or negative consequences beyond the risks encountered in normal life? Will the study involve prolonged or repetitive testing? *If you have answered yes or not certain about this please complete Section 5 of the Research Questionnaire.*		X	
Are drugs, placebos or other substances to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind? *If you have answered yes or not certain about this please complete Section 5 of the Research Questionnaire.*		X	

Risk to Researchers

Do you have any doubts or concerns regarding your (or your colleagues) physical or psychological wellbeing during the research period? *If you have answered yes or not certain about this please complete Section 6 of the Research Questionnaire.*		X	

Confidentiality

Do you or your supervisor have any concerns regarding confidentiality, privacy or data protection? *If you have answered yes or not certain about this please complete Section 7 of the Research Questionnaire.*		X	

Dissemination

Are there any particular groups who are likely to be harmed by dissemination of the results of this project? *If you have answered yes or not certain about this please complete Section 8 of the Research Questionnaire.*		X	

If you have answered **no** to all the questions, staff members should file the completed form for their records. Students should retain a copy of the form and submit it with their research report or dissertation.

If you have answered **yes** or **not certain** to any of the questions you will need to describe more fully how you plan to deal with the ethical issues raised by your research. You will need to answer the **relevant** questions in the Ethics Review Questionnaire for Researchers form addressing the ethical issues raised by your proposal. Staff should ensure that the completed questionnaire is sent to Michael Nelson in RD. Students should submit their completed questionnaire to their supervisor in the first instance. It will be at the discretion of the supervisor whether they feel that the research should be considered by the Research Ethics Committee.

Please note that it is your responsibility to follow the School's Research Ethics Policy and any relevant academic or professional guidelines in the conduct of your study. This includes providing details of your proposal and completed questionnaire, and ensuring confidentiality in the storage and use of data.

Any significant change in the question, design or conduct over the course of the research should be notified to Michael Nelson in RD.

I have read and understood the LSE Research Ethics Policy and the questions contained in the Research Checklist above.

Academic Research Staff

Principal Investigator Signature:
Date:

Undergraduate/MSc Student/PhD Student

Student Signature: [signature]
Student Name (Please print): Petterson Molina Vale
Department: International Development
Date: 12/03/2013
Date of Research Ethics Seminar attended: _

Summary of any ethical issues identified: There will be interviews that include some collection of sensitive information. Petterson will provide a good description of his research so participants understand, and sensitive information (location of ranch) will be strictly confidential. Given the procedures in place I don't foresee ethical problems.
Supervisor Signature*: [signature]

Supervisor Name (Please print): DIANA WEINHOLD
Department: ID
Date: 12/3/13

* By signing this document the student supervisor attests to the fact that any ethical issues raised have been dealt with adequately.

Appendix B2. Questionnaire (translated from Portuguese)

Full survey questionnaire

The data collection took place between April 11th and May 22nd 2013 in eight municipalities of Rondônia. During five weeks, surveyors interviewed 384 farmers.

A) Basic information

1. Surveyor; 2. IDARON agency.

B) Properties in this municipality

(Attention: properties are not the same as plots. A property may contain more than one plot. Spatially disconnected plots constitute different properties. If none, finish the interview. If more than one, the surveyed property is the one that the interviewee has possessed / rented for the longest time. If more than one, pick the first one that was mentioned.)

3. How many properties do you own (or rent) in this municipality (consider only those where you have cattle)?

4. What is the total area in alqueires[51] of these properties?

Comments

5. Do you wish to take part in the drawing of one vaccination gun?

6. Would you agree to giving us your name and phone number strictly for the purpose of the drawing?

(Explain: personal information will be discarded immediately after the end of the vaccination reporting period. We will not keep your personal information in our database.)

C) Economic activities and discount rate

7. Primary, secondary and tertiary activities in the surveyed property (order activities in terms revenue. The activity with the highest revenue receives number 1, then 2, 3, etc, where applicable).

Activities: beef cattle, dairy cattle, agriculture, silviculture, aquaculture, logging, other.

Comments

8. If you were to receive one of the following prizes, which one would you prefer? (The aim of this question is to understand how farmers make investment decisions)

Choose between a prize today and a prize in the future:

8.1. R$ 540 today or R$ 657 within 5 months?

8.2. R$ 930 today R$ 1,023 within one year?

8.3. R$ 87 today R$ 248 within 11 months?

[51] Locally used measure of area, equal to 2.42 hectares.

9. Suppose you have been drawn for a R$ 550 prize to be paid within 6 months. You may choose to forgo part of the prize in order to receive it immediately today. How much would you be willing to forgo in order to receive the prize today (R$)?

Comments

10. If you won the lottery, what would invest the money in? (Attention: please only consider "investment" as opposed to "consumption")

Comments

D) General views about pasture degradation and information about the property

11. In your opinion, over time the productivity of pastures (generally considered, not your own pastures only) tends to:

(Productivity: how much output a pasture with fixed size yields)

Remain stable / fall / rise / I don't know

12. Please explain why

Comments

E) Current size of the surveyed property (alqueires)

13. Total area; 14. Total pasture area; 15. Total area of degraded / "dirty" pasture; 16. Area of pasture affected by leafhoppers; 17. Area of native forest; 18. Area in fallow; 19. Area in crops; 20. Area with reforestation / silviculture.

F) Technical assistance in the last 12 months

21. Municipality; 22. How many visits did you do / receive?; 23. Select public assistance agency: Emater, Embrapa, IDARON (only technical visits); 24. Have you been assisted by hired professionals or those provided by suppliers (only technical visits)?

Comments

G) Income from land

25. In the last 3 years, the income from the land in the surveyed property has been: (including all land covers—pastures, crops, forest, etc)

Diminishing / stable / rising

25.1. If rising:

A lot / a little

25.2. If stable, with a tendency to:

Fall slightly / remain stable / rise slightly

25.3. If falling:

A lot / a little

Comments

H) Pastures

26. In the last 3 years, the pastureland in the surveyed property has been:

Getting better / the same / getting worse

26.1. If getting better:

Much better / a little better

26.2. If the same, with a tendency to:

Improve slightly / stay the same / get slightly worse

26.3. If getting worse:

Much worse / a little worse

Comments

27. If chose "income from land stable", "diminishing", pasturelands "the same" or "getting worse": does this worry you? (y / n)

28. If yes: what do you intend to do?

Wait / invest to solve the problem / sell out here and buy land somewhere else (please specify where) / other (please specify)

Comments

I) Migration of cattle, history of property and titling

Have you had / do you have cattle in other municipalities from the year 2000 to this day?

29. Municipality; 30. Since the year; 31. Until year; 32. Reason for having moved out; 33. How many heads of cattle have you had?; 34. How many alqueires in total?; 35. How many alqueires in pastureland?

36. Since what year do you own (rent) the surveyed property?

J) History of surveyed property (years 2000, 2005 and 2010)

37. Total area; 38. Total pasture area; 39. Total area of degraded / "dirty" pasture;

Comments

K) Land titling

40. How many plots in the surveyed property?

How many plots in the surveyed property have:

41. Full land title; 42. Contract of purchase only; 43. Temporary title only; 44. Other INCRA document; 45. No document at all; 46. Other (specify).

Comments

L) Zootechnical information

Cattle herd in surveyed property (heads)

47. Total; 48. Reproductive cows (white cows, specific for reproduction); 49. Milk cows; 50. Calves; 51. Steers / heifers; 52. Fattening steers; 53. Bulls; 54. Goats / sheep; 55. Horses, mules, donkeys, etc.

If you have milk cows, average production in last 6 months:

56. Litres / cow (average for all cows); 57. R$ per litre (gross price paid by dairy plant); 58. Distance to dairy plant (Km).

If you have at least one cow specifically for breeding:

59. Average weaning age (months); 60. Average weaning weight (Kg); 61. In the last mating season (or in the last 12 months), how many calves weaned?

In the last 2 years, did you purchase calves / steers / heifers? If yes:

62. Average weight (for calves / steers / heifers).

M) Animals sold in the last 12 months

63. Did you sell: calves, steers / heifers, animals for slaughter, disposal animals?

64. How many of each?; 65. Average weight of each; 66. Average age of each (years); 67. R$ / Kg (price received); 68. Distance from farm to slaughterhouse (Km).

Comments

N) Land prices

In the same region as the surveyed property, what is the current market price (R$) for:

69. One alqueire of land where quality of pasture is same as in surveyed property and the land has 10% forested area

70. One alqueire of land where quality of pasture is same as in surveyed property and the land has 40% forested area

What do you expect the market price (R$) will be within 3 years, in the same region as the surveyed property, for:

71. One alqueire of land where quality of pasture is same as in surveyed property and the land has 10% forested area

72. One alqueire of land where quality of pasture is same as in surveyed property and the land has 40% forested area

Comments

O) Pasture rentals

Pasturelands let:

73. How many alqueires?; 74. Since when (year)?

Pastureland rented from others:

75. How many alqueires?; 76. Since when (year)?

Expected rentals in the next 3 years:

78. Do you intend to rent pastures from others in the next 3 years?

Yes / no / maybe

79. Do you intend to buy pastures from others in the next 3 years?

Yes / no / maybe

Comments

80. Do you intend to possess cattle in another locality in the next 3 years (please specify municipality)

Yes / no / maybe

Comments

P) Technology

Soil management technologies:

81. Liming: since when (year)? Alqueires?

82. Fertilizing: since when (year)? Alqueires?

Comments

Paddocks:

83. How many paddocks / subdivisions?

Comments

84. Genetic improvement over last 12 months (indicate number of heads and year when first adopted the technology):

High breed bulls; Artificially inseminated cows; Fixed-time inseminated cows.

Comments

Have you ever been supported by a government programme for genetic improvement? If yes:

85. Since what year?; 86. Programme: Proleite (Emater) / municipality / Promeg (Machadinho) / don’t remember where from / other.

Pasture recovery over the last 12 months:

87. How much did you invest in pasture recovery (R$)?

88. How many tractor-hours did you use in the surveyed property?

Comments

Q) Frontier migration

89. How many acquaintances do you have in a frontier location (Campo Novo, Buritis, Rio Banco, Jacinópolis, Nova Mamoré, Cujubim, Rio Pardo, União Bandeirantes, Nova Samuel)?

Zero / between 1 and 5 / between 5 and 20 / over 20

90. In the coming 3 years, would you like to sell out (or rent out) your land here and buy (or rent) somewhere else?

Yes / no / maybe

91. If yes or maybe, why do you think about moving there?

Health or personal issues / income from land is too low here / land price is high here / other

Comments

92. What needs to happen for you to go?

Comments

R) Investment and cattle herd

93. Do you intend to increase your herd in the next 3 years?

Yes / no / maybe

Comments

94. If no, why?

I have no money / my pastures wouldn't support more cattle / other

95. If you had enough money to double the size of your herd in the next 3 years, in what pastures would you put the extra cattle? Why?

I would: clear new areas / buy / rent pastures / use the existing pastureland / other

Comments

S) Investment and credit

Investment:

96. The best pastureland you know supports how many heads of cattle per alqueire?

97. For your pastures to reach that level, how much would you need to invest per alqueire?

98. Without taking credit, how many alqueires would you be able to improve to that level in the next 12 months?

99. Do you intend to implement such a project in the coming 3 years?

Yes / no / maybe

Comments

100. With respect to the farmers you know, your availability of capital for investment is:

Higher / equal / lower

101. In the 3 past years, how much of the investment was made with borrowed money (from credit, in %):

Do you take credit from banks? If yes:

102. Credit line; 103. Annual interest rate; 104. Term (years).

In case for some reason you cannot take credit, would you like to?

105. Credit line you would like to use; 106. Annual interest rate; 107. Term (years).

Comments

T) Property map

(Tell the interviewee: we are mapping the properties that we survey. We would like to locate your property on the map and draw its borders.)

106. Could you tell us where you property is? If yes, do you know the plot number?

[Draw map using QuantumGIS]

Comments

U) Environment

107. Do you think cattle ranchers gain or lose by complying with the environmental legislation?

Gain / doesn't change anything / lose / don't know

Comments

108. Are you aware of the Environmental Rural Register being implemented by the Federal Government? (y/n)

109. Do you know what it is? (y/n); 110. Have you implemented it? (y/n); 111. Do you intend to? (y/n)

Comments

112. Suppose one your neighbours clears a forested area of medium size. You expect that:

112.1. He will surely get a fine from the environmental agency the very next day

112.2. There is a high chance that he will get a fine from the environmental agency

112.3. There is some chance that he will get a fine from the environmental agency

112.4. There is little chance that he will get a fine from the environmental agency

112.5. He will surely not get a fine from the environmental agency

Comments

113. When was the last time there was an action by the environmental agency (only actions on the ground) in the region (year)?

114. According to the law, what is the minimum size of the legal reserve in the surveyed property (%)?

115. According to the law, what is the size of the preservation area on the banks of the widest river in the surveyed property (metres)?

Comments

V) Enforcement

116. Do you think the environmental agents are honest?

Yes / no / more or less / don't know

117. Did the last modification in the forest code change anything for the surveyed property?

118. When you purchased the first plot, what guidelines were there with respect to forest preservation?

Preserve 80% / preserve 50% / clear as much as possible / clear 100% / no guidelines / other

W) Information about the farmer

(Farmer: the person who takes most decisions in the surveyed property)

119. Gender; 120. Year of birth; 121. State of birth; 122. Current residence (municipality); 123. Year of arrival in Rondônia; 124. How many people live in your residence?; 125. How many work at least half-time in the property?; 126. Current residence (Urban / rural); 127. Years of schooling.

128. Respondent's occupation (in terms of income: 1 for primary, 2 for secondary, etc)

Cattle rancher / farmer (agriculture) / rural worker / public servant / retired / urban business / urban worker / other

Comments

--

End

Thank you very much for having taken part in this survey. Your participation is very important.

Appendix B3. Interview protocol (translated from Portuguese)

This document was handed in and explained to all surveyors.

--

1. **The choice of the person to be interviewed** is of utmost importance to the quality of work. We will not choose a person at random, but strictly follow a simple rule: when the surveyor is free to start a new interview, she will address the first person who has completed the vaccination report and is leaving the agency at that exact time. Once the person to address has been determined, in no circumstances should the surveyor fail to address him / her for whatever reason: appearance, sex, humour, etc.

2. The first step is the **presentation of the surveyor**.

"*Good afternoon, my name is Petterson and I am a student at UNOPAR Machadinho. I am working on a study on cattle ranching in Rondônia which is funded by the Ministry of Science and Technology and conducted by a doctoral student at the University of London in association with various institutions, including Embrapa Porto Velho, the Amazon Institute for Environmental Research (IPAM), and the Federal University of Uberlândia, with the support of IDARON.*

The research will assess how livestock is conducted in several municipalities and how farmers make decisions on land use - agriculture, livestock, fisheries, forestry, etc. The results of the study will be published by the mentioned institutions in order to improve the understanding of the different ways in which livestock can affect the development of the region.

Could you contribute to this research by answering a few questions about the property that you come from reporting? The interview lasts 25-35 minutes and you get free biscuits and drinks. The survey is completely anonymous—I will not ask you for you name or other personal information. In this leaflet you will find a detailed explanation of the project and the names of the persons responsible. Participation in the survey is optional and you can drop out at any time after you start.

The information we collect will be used solely for the research cited above, and in no event shall it be provided to third parties, be they private entities or government bodies.

To reward you for the time spent in the interview, we will be drawing two vaccination guns among respondents. If you wish to take part, you only need to provide us with a name and phone number so we can deliver the gun to the raffled persons. You may choose not to take part in the drawing, or you may choose to leave someone else's name and phone number.

Once the survey is completed, we will make the results—aggregated and anonymous—available to the IDARON agencies, in case you shall be interested.

Would you like to participate?"

3. If the subject accepts to participate, **move on to the interview**.

4. If subject does not accept:

"*There is no problem. Although you are unable to take part in the interview, could you contribute to this research by giving us only three pieces of information? Would you accept?"*

5. If yes, ask the "baseline questionnaire" questions, write down the answers on paper, and transfer the results to the "baseline offline questionnaire" at the end of the day.

Baseline questionnaire:

5.1. Do you take decisions for the property that you came to declare?

5.1.1. If not, could we obtain the name, address and phone number of the appropriate person so we can try to interview her?

5.2. How many alqueires of pasture are there on the property that you declared?

5.3. How many heads of cattle?

5.4. For how long have you possessed / rented that property?

6. If no: "*thank you and have a nice day.*"

7. When you get to the map drawing section:

"*We are collecting information on the location and boundaries of farms. We do this by locating the property on the map. This information is used to get a better idea of the physical characteristics of* *the property (access to water, distance from the city centre), and also to identify the parts of the municipality that have more dairy farming, beef cattle, etc. The information on the property's location is used solely for the purpose of scientific research, and cannot be accessed by anyone outside of our team. If you accept, we will do the mapping of your property.*"

8. "*Thank you and have a nice day!*"

-- ------

DOS AND DON'TS

- Do follow strictly the procedure bellow:

1. Explain what you intend to do (questionnaire, map of the property);

2. Explain what for;

3. Ask for agreement;

4. If agreement cleared, proceed.

- Do NOT: start the survey without having explicitly requested and obtained the agreement. Do not say: "*Now we'll draw the map of your property (...)*" without having asked and obtained the agreement.

- **Do not provide answers to questions**. For example: "*in 2000, what was the area of the surveyed property?*" as opposed to "*in 2000, the area of the surveyed property was the same as today?*". In the latter case an answer was given along with the question. Human psychology induces subjects to prefer "yes" responses to "no" responses, or to anything that implies the use of cognitive capacity, i.e., to reflect, search for memories, perform calculations. If we formulate the question with a built-in shortcut to the "yes"-type of response, the interviewee will have the tendency to prefer those easy answers. If we instead leave the question open, the subject will have no other option but reflect.

- **Language**: beware of using "you" with older people, or with people who normally expect to be treated as "Sir" [in Portuguese there is an important distinction between the uses of personal pronouns]. Our goal is to respect the social norms that people consider important, given that what we want is that the subject feels comfortable in answering questions, not that she gets her mind busy by telling herself: "this guy is kinda loose… etc, etc, etc ".

- **How to read out questions**. It is essential that questions be read out literally. The questions should not be reinterpreted by the surveyor and formulated in any other way than exactly as they are written. Of course, once read out, if the respondent has not understood the question, it will be important to rephrase it. The answer options should also be read out to the letter. For example: "*If a neighbour of yours makes a clearing, you think that:*", and then read out the option: "*surely surveillance will hit up the next day.*" Do not rephrase this as: "*It is sure that the inspection will come*", or "*there is a 100% chance of IBAMA issuing a fine*", or anything else.

- Do not forget to hand in the leaflet and annotate the basic questionnaire responses.

Appendix B4. Informed consent form (translated from Portuguese).

INFORMED CONSENT FORM FOR PARTICIPATION IN SCIENTIFIC SURVEY

Project title: Sustainable cattle ranching? Land use intensification, migration and deforestation in the Amazon frontier

Lead author: Petterson Molina Vale (Economist). Tel. (12) 8703-0902 / (69) 3581-2212. E-mail: p.m.vale@lse.ac.uk

Other authors: Daniel Caixeta Andrade (Economist); Marcelo Stabile (Researcher at the Amazon Environmental Research Institute, IPAM); Leonardo Ventura De Araújo (Economist).

1. Purpose: you are invited to take part in a study that aims to understand how the intensification of livestock production is related to land use decisions—pasture, cropland, fisheries, forests, etc.—and migration to regions of recent colonization in Rondônia. The research is part of the doctoral thesis of Petterson Molina Vale, to be completed in 2014 under the guidance of Dr. Diana Weinhold and Dr. Anthony Hall. The respondents are selected ranchers that came to report the vaccination of their herds at the IDARON agencies.

2. Procedures: if you agree to answer this survey, we will ask you to give us information about how you manage livestock on your property, the characteristics of your property, among other issues. There are no right or wrong answers, we want to know what is the current situation of livestock production in your property, without judging if it's good of bad.

3. Duration: the interview will take about 30 minutes.

4. Risks: participation in this study involves no foreseeable risks.

5. Benefits: the interview will stimulate you to reflect upon the way you manage cattle ranching. The results of the study will be presented to the authorities of the State to motivate reflection on the situation of livestock production. However, there are no direct benefits of participation.

6. Voluntary participation: you are free to choose not to answer any question that you do not wish to answer, and you can also drop out of the interview at any time at no cost.

7. Anonymity: This is an anonymous survey and we will not disclose your name. The data we are gathering will be published in scientific studies, but the anonymity of informants will always be guaranteed. The data on the location of the properties will be used solely by the institutions implementing this study, and will not be given to other researchers or institutions under any circumstances nor will the spatial data be made available for public access or government institutions.

8. Questions about this study? In case of queries, complaints or comments, please contact the lead author (see contact information above).

9. Signature and awareness: by signing below, you indicate that you are voluntarily agreeing to take part in this survey and that the procedures are satisfactory to you. The researcher will give you a copy of this term.

Appendix C1. OLS regressions of stocking rate, offtake rate and productivity on technology indexes.

Dependent variable: ln (stocking rate)[1]

	(1)	(2)	(3)	(4)
Density technologies	0.0768**	0.0663**	0.0898***	0.0772**
Offtake technologies	—	-0.168**	—	-0.154**
Soil type dummies	no	no	yes	yes
Productive system dummies	no	no	yes	yes
Constant	0.278***	0.482***	1.508***	1.775***
Observations	207	207	207	207
R-squared	0.027	0.067	0.188	0.206
Adj. R-squared	0.0221	0.039	0.129	0.125

1. Animal Units (450 Kg live weight) per hectare.

*** p<0.01, ** p<0.05, * p<0.1

Standard-errors adjusted for 49 clusters in surveyor / municipality.

Dependent variable: ln (offtake rate)[1]

	(1)	(2)	(3)	(4)
Offtake technologies	0.107***	0.126**	0.102*	0.167***
Density technologies	—	0.0359	—	0.0463
Soil type dummies	no	no	no	yes
Productive system dummies	no	no	yes	yes
Constant	-1.364***	-1.319***	-3.080***	-4.799***
Observations	158	158	158	158
R-squared	0.006	0.008	0.104	0.353
Adj. R-squared	-0.00081	-0.00431	0.0159	0.264

1. Animal Units (450 Kg live weight) sold in one year divided by total Animal Units in the ranch.

*** p<0.01, ** p<0.05, * p<0.1

Standard-errors adjusted for 42 clusters in surveyor / municipality.

Dependent variable: ln (physical productivity)[1]

	(1)	(2)	(3)	(4)
Density technologies	0.0808**	0.101*	0.107***	0.116**
Offtake technologies	-0.0326	-0.0168	0.0171	0.0264
Soil type dummies	no	no	yes	yes
Productive system dummies	no	yes	no	yes
Constant	-0.875***	-1.258***	-1.378***	-2.766***
Observations	158	158	158	158
R-squared	0.02	0.196	0.35	0.433
Adj. R-squared	0.00718	0.111	0.324	0.355

1. Kg/ha/year

*** p<0.01, ** p<0.05, * p<0.1

Standard-errors adjusted for 42 clusters in surveyor / municipality.

Dependent variable: ln (productivity in value)[1]

	(1)	(2)	(3)	(4)	(5)
Density technologies	-0.215**	-0.207*	-0.196	-0.133	-0.158
Offtake technologies	-0.0211	-0.0231	0.00866	-0.0448	-0.0788
Distance to markets (Km)	—	0.00221	0.00353**	0.000606	0.00149
Soil type dummies	no	no	yes	no	yes
Productive system dummies	no	no	no	yes	yes
Constant	5.294***	5.138***	1.979	4.795***	1.677
Observations	162	162	162	162	162
R-squared	0.035	0.048	0.230	0.336	0.446
Adj. R-squared	0.0224	0.0178	0.139	0.301	0.367

1. R$/ha/year

*** p<0.01, ** p<0.05, * p<0.1

Errors adjusted for 45 clusters in surveyor / municipality

Appendix C2. Poisson regression of leased land on region (pre-frontier, transition and consolidated). Dependent variable: leased land (% of pasture area)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Region							
Pre-frontier	-11.7***	-11.9***	-12.8***	-12.7***	-12.0***	-13.6***	-13.9***
Frontier				*-- baseline --*			
Transition	2.022***	1.915**	1.968***	1.979***	1.982***	2.034***	2.136***
Consolidated	1.936	1.678	3.031	3.063	3.055	3.177	3.013
Settlement age	-0.0743	-0.0543	-0.170	-0.171	-0.172	-0.174	-0.172
ln (land value)	—	-0.0780	-0.250	-0.236	-0.236	-0.176	-0.0407
Land titling	—	—	1.208***	1.179***	1.180***	1.283***	1.261***
Pasture quality	—	—	—	-0.0222	-0.0215	-0.0181	-0.00263
Cattle herd	—	—	—	—	6e-05	3.2e-05	0.000105
Mean distance to markets (Km)	—	—	—	—	—	0.00274	0.00461
Soil aptitude dummies	no	no	no	no	no	no	yes
Constant	-0.667	-1.034	1.597	1.631	1.633	1.318	0.971
Observations	179	179	179	179	179	179	179

*** p<0.01, ** p<0.05, * p<0.1

Standard-errors adjusted for 46 clusters in surveyor / municipality.

Appendix C3. OLS regression of value of pastureland (R$/ha) on average neighbour's productivity (R$/ha/year).
Dependent variable: ln (value of pastureland)

	Frontier	Transition and consolidated			
Average neighbours' productivity[1]	0.000344	0.000209**	0.000181*	0.000184**	0.000184*
ln (productivity in value)	0.0668**	—	0.0839**	0.102***	0.106***
Mean distance to markets (Km)	-0.000527	—	—	-0.00649***	-0.00615***
Cleared area	0.738**	1.808***	1.775***	1.245***	1.321***
Soil aptitude	yes	no	no	no	yes
Constant	0.624**	0.234	-0.184	0.499	0.422
Observations	40	137	137	137	137
R-squared	0.356	0.166	0.207	0.432	0.443
Adj. R-squared	0.215	0.147	0.183	0.410	0.408

[1]Calculated by multiplying a spatial weights matrix W by the variable productivity. The spatial matrix defines neighbouring municipalities as those located within a distance band that is calculated to give all farms at least one neighbour.

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Appendix C4. OLS regression of expected land price appreciation within 3 years (R$) on pasture degradation. Dependent variable: ln (expected land appreciation)

Highly degraded pastures	-0.301**
ln (cleared area)	-0.313
Land titling	0.0260
Mean distance to markets (Km)	0.00199***
Soil type dummies	yes
Constant	-2.922*
Observations	150
R-squared	0.376
Adj. R-squared	0.279

*** p<0.01, ** p<0.05, * p<0.1

Standard-errors adjusted for 44 clusters in surveyor / municipality.

Appendix C5. OLS regression of productivity and returns to labour on number of previous migrations.
Dependent variable: ln (productivity in value)

	(1)	(2)	(3)	(4)
Previous migrations (since 2000)	0.386*	0.316	0.432**	0.360**
Time in the plot	0.0218*	0.0257**	0.0165*	0.0193*
Education	0.00506	0.00971	-0.00394	-0.00664
Age	-0.0213**	-0.0207**	-0.0205**	-0.0218**
Mean distance to markets (Km)	—	0.00395**	0.00219	0.00216
Productive system dummies	no	no	yes	yes
Soil aptitude dummies	no	no	no	yes
Constant	5.862***	5.533***	5.504***	5.364***
Observations	192	192	192	192
R-squared	0.049	0.069	0.279	0.304
Adj. R-squared	0.0177	0.0332	0.231	0.245

*** p<0.01, ** p<0.05, * p<0.1

Standard-errors adjusted for 46 clusters in surveyor / municipality.

Appendix D1. Variable calculations

Gate beef prices

This variable is traditionally measured by CEPEA (Centro Paulista de Estudos Agropecuários) for a few trading centres in Brazil, including São Paulo, Campo Grande and Cuiabá. The time series is available starting in 2003, but prices for São Paulo are available since 1995 (Seagri, Secretaria da Agricultura), so I predict the prices for Cuiabá in 1996 using the time-series:

(1) $price_{Cuiaba,t} = \alpha + \beta price_{SP,t} + \varepsilon_t$

One agricultural consultancy in the State of Matro Grosso (IMEA, Mato Grosso Institute of Agricultural Economics) has published daily estimates of the price of finished cattle (R$ / 30 Kg) for a number of cities in Mato Grosso since 2011.

I use the IMEA time series to estimate the following regression:

(2) $price_{m,t} = \alpha + \beta price_{Cuiaba,t} + \varepsilon_t$, where m are 4 municipalities in Mato Grosso.

Based on (2) and the Cuiabá data for 2006 and 1996 obtained in (1), I predict the prices for 4 municipalities in Mato Grosso. Next I use the variable distance to State capita (*dist*) provided by IBGE to estimate a model of *price* on distance:

(3) $price_{m,t} = \alpha + \beta dist_{m,t} + \varepsilon_i$

I use the estimated coefficients to predict the prices for all municipalities in Mato Grosso for the years 1996 and 2006.

Finally, I use the variable transportation costs (*tcost*) to São Paulo (IPEA) to estimate the following cross-sectional model:

(4) $price_i = \alpha + \beta tcost_i + \varepsilon_i$, where i are all municipalities in Mato Grosso.

The estimated coefficients give me the association between transportation costs to São Paulo and prices, for 1996 and for 2006. I use these to predict the prices in all other municipalities in the Amazon.

Mandatory legal reserve

I use the percentages specified in the law for the years 1965, 1996, 1997, 1998, 2000 and 2005, and the spatial variation according to vegetation type—forests, savannahs, amazonic grasslands—political boundaries—North Region, Legal Amazon—and agricultural zoning (for the State of Rondônia). I overlay shapefiles of vegetation type (Embrapa) and protected areas (Ministry of Environment, 1996 and 2006) to calculate the share of the private lands in each municipality that is available for agricultural exploitation according to the law.

Appendix D2. Euclidean distance band weighting scheme

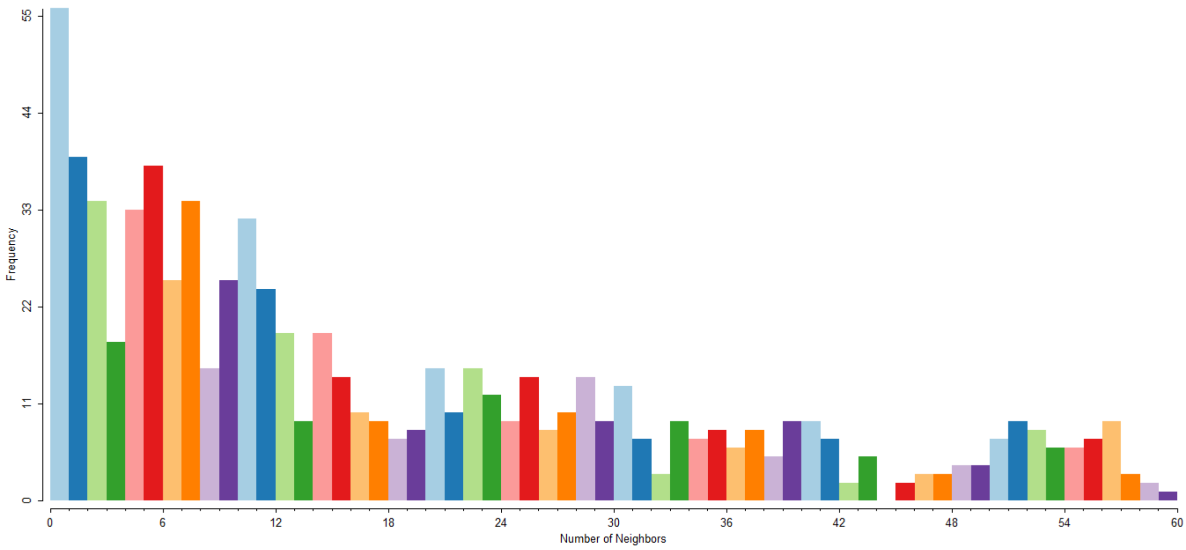

Figure 1. Connectivity histogram from distance weighting. This figure shows the result of the weighting scheme I adopt in matrix W_1 in terms of frequency of neighbours. W1 reads from the group of consolidated municipalities to determine which ones are neighbours to frontier municipalities. The histogram shows that at least 50 frontier municipalities have been allocated only 1 neighbour in consolidated areas.

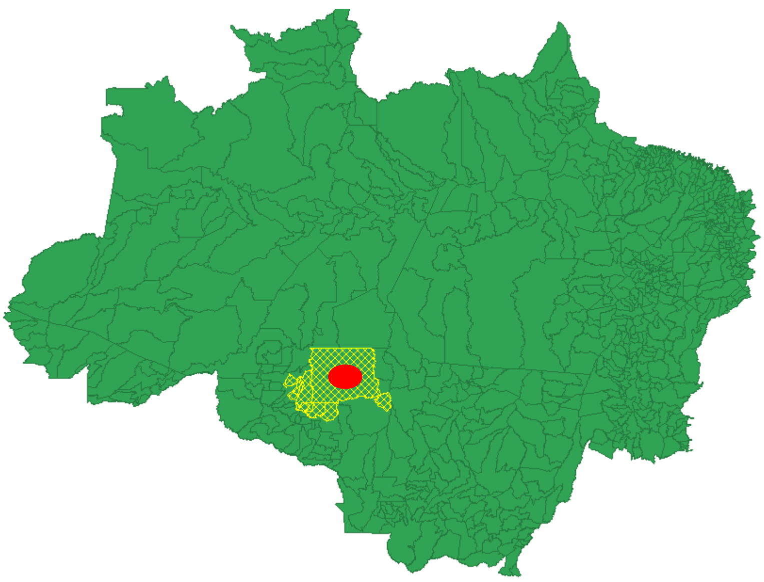

Figure 2. Example of one frontier municipality (red circle) and its neighbouring consolidated municipalities (yellow)

Appendix D3. Creation of pre-frontier, frontier and consolidated clusters of municipalities

I use the variables def04 and def00, equal to the extension of deforestation (km^2) divided by the total forested area in each municipality in the years 2004 and 2000.

I define the variable MTE1 (municipality's total extension 1) equal to 1 where the total extension of deforestation was lower than the minimum value between all municipalities plus 2/3 of the difference between the minimum and the mean:

MTE1=1 if def04<=(r(min)+((r(mean)-r(min))/1.5)) ; MTE=0 otherwise

I define the variable MTA1 (municipality's total activity) equal to 1 where deforestation activity between 2000 and 2004 was lower than the median between all municipalities:

MTA1=1 if def00_04<=r(p50)

From this I create the clusters as follows:

prefrontier=1 if MTE1==1 & MTA1==1 ; prefrontier=0 otherwise

frontier=1 if MTE1==1 & MTA1==0 ; frontier=0 otherwise

consolidated=1 if MTE1==0 & MTA1==1 ; consolidated=0 otherwise

I do this procedure in two alternative ways: I either use the mean, median, minimum and maximum values of the full population of municipalities, or I do it separately by State. The latter is the one I use in the main model.

Appendix D4. Robustness check. First difference regression of deforestation on productivity of cattle, (OLS, including fixed-effects in growth rates).

Dependent variable: natural logarithm of change in deforestation (2007-2012), frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ΔW_1*prod*	-3.724***	-4.192***	-3.361**	-3.181**	-4.416***	-4.058***	-1.656***	-2.591***
W_1*prod*$_{96}$	-2.774***	-2.988***	-2.515***	-2.512***	-2.826***	-2.691***	-1.381***	-2.709***
ΔW_1*price*	15,390	8,097	1,915	1,562	4,467	-4.201**	—	—
W_1*price*$_{96}$	-983.3	-517.5	-122.5	-99.92	-285.7	—	—	—
ΔW_2*cattle*	9.68e-06	—	—	—	—	—	—	—
W_2*cattle*$_{96}$	-1.10e-05	—	—	—	—	—	—	—
Δ*LR*	15.11***	12.12***	—	—	—	—	—	—
RL$_{96}$	—	—	7.868***	8.081***	—	—	—	—
Δ*title*	0.000668	-0.000244	-0.000835	—	—	—	—	—
title$_{96}$	0.0239	0.0200	0.00532	—	—	—	—	—
Δ*pr.areas*	-1.954	-2.908	0.640	—	—	—	—	—
pr.areas$_{96}$	5.480	5.964	2.061	—	—	—	—	—
Δ*fines*	-0.0932	0.0926	0.157**	—	—	—	—	—
fines$_{96}$	2.516	3.042	-3.311	—	—	—	—	—
State dummies	yes	yes	no	no	no	no	no	no
Init. deforest. (2007)	0.0996	0.124	0.500***	0.515***	0.622***	0.633***	0.603***	—
Year	11.41	9.174	-1.710	-1.135	9.618	6.343**	-0.114	4.374***
Observations	65	65	65	65	65	65	65	65
R-squared	0.778	0.771	0.593	0.574	0.500	0.498	0.469	0.278
Adj. R-squared	0.662	0.667	0.499	0.530	0.458	0.464	0.443	0.255

Note: the reduced number of observations (64) is due to these regressions being estimated over frontier municipalities only. The information on consolidated municipalities is captured by the spatial weights matrix W_1.

*** p<0.01, ** p<0.05, * p<0.1 Robust t-statistics.

Appendix D5. Specification check. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates), different time frames.

Dependent variable: natural logarithm of change in deforestation, frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Time frame:	00-12	00-12	01-12	01-12	00-12	00-12	01-12	01-12
ΔW_1*prod*	-0.00416	0.390	1.808***	1.459**	-0.218	-1.793	-2.400	-6.018***
ΔW_2*cattle*	1.61e-05***	1.23e-05***	1.59e-05***	1.20e-05**	2.12e-05***	1.61e-05**	8.56e-06	-5.02e-06
Year	3.287*	2.216	1.040	0.631	9.137*	16.82**	12.23*	24.79***
Init. levels	no	no	no	no	yes	yes	yes	yes
State dummies	no	yes	no	yes	no	yes	no	yes
F-test on state dummies (p-value)	—	0.0001	—	0.0001	—	0.0014	—	0.0013
F-test on state dummies and initial levels (p-value)	—	—	—	—	—	0.0001	—	0.0001
Observations	76	76	76	76	76	76	76	76
R-squared	0.537	0.619	0.625	0.669	0.589	0.647	0.697	0.752
Adj. R-squared	0.485	0.521	0.580	0.579	0.487	0.500	0.621	0.643

Note: the reduced number of observations (76) is due to these regressions being estimated over frontier municipalities only. The information on consolidated municipalities is captured by the spatial weights matrix W_1.

*** p<0.01, ** p<0.05, * p<0.1 Robust t-statistics.