Keeping waters clean: Environmental Licensing in Rondônia

by

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**A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Natural Resources and Environment)
in the University of Michigan
2010**

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For Thida, Tegan, and Kira,

the brightest spots in my day.

Acknowledgements

The work in this study was funded by grants from the Graham Environmental Sustainability Institute, the Rackham Graduate School, the School of Natural Resources and the Environment, and the International Institute, all at the University of Michigan, and the Canadian Natural Science and Engineering Research Council (NSERC).

The questionnaire developed for this study drew from material previously developed by the ACT Institute at Indiana University.

Logistic support in the administration of questionnaires was provided by the agency for technical assistance and rural extension for Rondônia, EMATER-RO.

I wish to thank Rosa Formiga-Johnsson for her guidance as I began this work in Rio de Janeiro, as well as Tatiane Checchia and Paulo Schröder for giving up their time, and space in their home, to help me get started in Rondônia. Thank you also to Célio Dionizio Tavares and mother Alzira, son Caius, and daughter Aivllis, for putting up with three months of a Canadian guest always locked in his room writing.

I am very grateful for the assistance in project coordination I received from Dr. Margarida Marchetto, formerly of the Federal University of Rondônia (UNIR), and for the hard work of the research team – Thiago Emanuel Figueiredo Possmoser Nascimento, Ingrid Alexandrina Martins Veronez, Emerson Andrade de Souza, Mônica Chagas Cerquiera, João Paulo Papaleo Costa Moreira, Carina Stre Holanda, and Leonardo Rosa Andrade – from the Department of Environmental Engineering at UNIR Ji-Paraná.

I also wish to acknowledge my co-chairs Don and Maria, and committee members Rick, Scott, and Margarida, for their invaluable counsel throughout the planning, execution, and writing phases of this work. Don and Maria are contributing authors to Chapter 2.

Finally, I have eternal gratitude to my family – my parents John and Janet, my siblings Chris and Alison, my partner Thida, and my girls Tegan and Kira – for their support and tolerance of 5 years focused on one little book.

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List of Abbreviations

APP	Areas of Permanent Preservation
BMP	Best Management Practices
BOD	Biological Oxygen Demand
BWC	Bulk Water Charge
COD	Chemical Oxygen Demand
CONAMA	National Environment Council, Brazil
EMATER-RO	Agency for Technical Assistance and Rural Extension Services, Rondônia
HOT	Highly Optimized, Tolerant
IBAMA	Environmental Protection Agency, Brazil
IBGE	Institute of Geography and Statistics, Brazil
INCRA	Institute for Colonization and Agrarian Reform, Brazil
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
LAPRO	Environmental Licensing for Rural Properties, Rondônia
LR	Legal Reserve
LUF	Land Use Fine
RBC	River Basin Council
SAF	Agroforestry System
SDM	Systems Dynamics Model
SEDAM-RO	Secretary of Environmental Protection, Rondônia
SES	Social Ecological System
UNIR	Federal University of Rondônia
VOP	Value Of Production

ABSTRACT

In the Amazonian agricultural frontier, pasture for cattle ranching is an important and potentially damaging form of land use due to erosion as pastures degrade. This dissertation presents three approaches to understanding policy options to govern this land-use problem: 1) a systems dynamics model (SDM), 2) empirical social research, and 3) an agent-based model (ABM). In the SDM, I examine the role that river basin councils (RBCs) – one of the water governance options in Brazil's National Water Act – might play in managing this non-point-source pollution issue in the Amazônian State of Rondônia. I compare the central tool of the RBC, a bulk water charge (BWC), to a stylized land-use fine (LUF) for failing to maintain riparian cover, across several scenarios of climate change. The results show no significant advantage to the BWC over LUF in reducing erosion while keeping ranching profitable; moreover, the comparative success of programs similar to LUF suggests these programs may have potential to manage agricultural pollution in the region. One program in Rondônia is the environmental licensing program for rural properties (LAPRO), which will require farms to remove significant amounts of land from production, and may shift production intensity as farms comply. I present empirical data from Rondônia's Ji-Paraná River Basin that show decreased production intensity and income diversification on larger properties. These results suggest that for smaller properties, complying with LAPRO may bring an increase in land sale to cover debts and an increase in land consolidation in the region. Examining this further, I develop an ABM of ranching and land exchange, inform it with results from my survey research, and investigate the outcomes that could be expected from LAPRO in the context of climate change. Model results show that while LAPRO may increase forest cover in ranching landscapes, it may occur at the expense of the small producer. To the extent that effective monitoring and enforcement exist, a focus on larger holdings will help to mediate this negative social impact. These results suggest that a middle ground may exist in cases where current environmental goals conflict with legacies of past colonization and resource-use regimes.

Chapter 1

Introduction

Within the Amazonian agricultural frontier, forest clearing for cropland and the creation of pasture for cattle ranching are both important land uses economically, as well as problematic ones environmentally as drivers of soil erosion and sedimentation in surface waters. While Amazônia is typically associated with a wealth of water resources, the drought of 2005 demonstrated that it too was vulnerable to water scarcity (Boyd 2008); as the climate changes over the coming decades and brings an increase in the frequency and severity of extreme events (Magrin et al. 2007), the security of clean water resources in Amazônia will become even more critical. To date, little has been done in Amazônia to protect water resources. The water reform that has taken hold in other regions of Brazil, and which implements a form of integrated water resources management (IWRM) and governance of water at the level of the hydrographic basin (Brazil 1997), has had little impact in the Amazonian states. Various pilot projects targeting rural land use and the maintenance of riparian buffers have been developed across Amazônia with mixed results that have yet to be expanded to any comprehensive scale.

This dissertation investigates the potential for either of these approaches – through IWRM or through environmental programs tied to land use – to preserve the quality of water resources and the livelihoods of Amazonian farmers. Finding greater potential in land-use initiatives than in water reform yet to happen, it then explores in greater detail the possible outcomes from one such initiative, the environmental licensing scheme for rural properties (LAPRO) in the State of Rondônia. Specifically, it asks whether LAPRO, which will require farmers to restore significant fractions of their productive land to forest, can preserve rural livelihoods while attempting to achieve environmental goals for forest cover (and by extension, surface water quality). It investigates the way in which the burden of licensing is shared across the scale of rural production from small to large family farms, and how robust the outcomes of LAPRO are to changes in the climate. By answering these questions, this dissertation aims to inform the important policy decision of how best to allocate scarce resources into the preservation of Amazônia's water future, as well as contribute to the growing literature of socio-ecological systems (SES)-based approaches to understanding natural resource management issues.

Frontier Colonization and Water Resources

The historical process of colonization of the Amazon and expansion of the agricultural frontier has been well documented. Driven by a desire to cement Brazil's claim to the Amazon, massive colonization projects in the 1970s and 1980s brought thousands of migrant families to the region. Demand for land soon outstripped the capacity of the colonization projects to place families, and settlers from outside the region were able to lay claim to land simply by clearing and thus "improving" it (Schmink and Wood 1992, Caldas et al. 2007). However, policy shifted in the mid 1970s away from small farmers and towards more formal granting of land titles to larger ranching, mining, and other operations (Schmink and Wood 1992). Conflicts thus began to arise over claims to land by farmers who had occupied an area only to have the title granted to someone else, with the government in general issuing compensation to the small farmer for their "improvement" of the land and upholding the larger firm's land title settled these claims (Schmink and Wood 1992). This created a perverse incentive for small farmers to deforest land, receive compensation for their work in clearing the land, and drop further back into the forest to repeat the cycle. The result, across more than 40 years of settlement, is a broad landscape with varying degrees of agricultural development and abandonment, and vast areas stripped of forest cover.

This region is commonly associated with an abundance of water resources; however, these resources are not uniformly distributed across space or time. Throughout the region, at different points in the year, drought is a reality to which its natural systems are well adapted. Yet, the joint stresses of agricultural/ranching development and the advent of global climate change threaten water resources in Amazônia. In addition to slow changes in temperature and the overall precipitation volume in the region, two other expected impacts of climate change are increases in the frequency of extreme climate events (storms and droughts), and increases in inter-annual and seasonal variability (Magrin et al. 2007). Coupled with uncertainty regarding climate expectations on the part of ranchers, these changes could enhance erosion and sedimentation processes, degrading water quality in agricultural landscapes. In the Amazonian state of Rondônia, where the landscape is dominated by ranchland for cattle (5,000,000 ha of pasture compared to 500,000 ha of croplands in Rondônia in 2006 (IBGE 2006)), sedimentation and associated declines in water quality are a potential regional-scale water issue for the future (Coe et al. 2008, Stickler et al. 2009). Sediment load is a key vector in the transport of other water pollutants such as nutrients, organic carbon, and other contaminants. It plays a role in the availability of spawning habitat for fish, as well as in the lifetime of hydroelectric dams, a major source of electricity from Amazônia. Also importantly, the effects of sediment loading extend beyond the local area to have regional scale impacts (Coe et al. 2008, Stickler et al. 2009).

Water stress and scarcity has been an issue in other regions of the country for some time, and the past two decades in Brazil have seen a process of gradual water reform, punctuated by a new constitution in 1988 and a National Water Act in 1997, which together sought to reframe the idea of water as a resource with economic value (Benjamin et al. 2005). The new system creates new structures for integrated governance of all water uses at the level of the hydrographic basin—river basin councils (RBCs)—that work in tandem with other more traditional forms of management such as municipal and state water and environmental agencies and organizations. These tripartite councils (committees and consortia) are composed by federal and state actors, water users and user groups, and representatives of organized civil society (Brasil 1997). Waters flowing entirely within the borders of a single state fall under state jurisdiction; those crossing state borders fall under federal jurisdiction, requiring greater federal representation on the basin councils (Brasil 1997). As designed, the basin councils have two central tools at their disposal to rationalize water use – *outorga* (water use permits), and *cobrança* (bulk water charges), the revenue from which is in principle to be reinvested in water projects within the basin (Lemos and De Oliveira 2004, Formiga-Johnsson et al. 2007). To date, the water reform has created over 100 stakeholder-driven river basin councils across Brazil to support water management with mixed levels of success (Abers and Dino Jorge 2005); reform has advanced the furthest in the semi-arid Northeast (Lemos and De Oliveira 2004) and the highly industrialized South and Southeast (Benjamin et al. 2005). Comparatively, little has occurred in Amazônia where a single council has formed in the Tarumã-Açú River Basin in the state of Amazonas.

Despite this slow pace of progress, the exacerbation of water quality problems in Rondônia under climate changes suggests that decision-makers will soon be faced with either implementing available institutions or designing new ones to address this problem. In Chapter 2, I aim to inform this process by exploring, through modeling and institutional analysis, two potential policy choices in a comparative approach. The first option is a bulk water charge tool that seeks incentivize efforts to curb pollution by creating a price scale that punishes polluters and rewards cleaner forms of water use (Formiga-Johnsson et al. 2007). The second option is based on other environmental approaches in Amazônia that have attempted to penalize farmers for failing to maintain adequate riparian buffer around watercourses. The goals of this chapter are threefold. First, to examine which policy choice is the best option to improve water quality. Second, to inform the institutional design of RBCs in the region by exploring whether pollution control instruments implemented in other parts of Brazil would work in the Rondonia context. Finally, by including future climate changes in the analysis, to inform policy makers of which options are likely to fare better under the threat of yet uncertain but predicted climate stressors.

If not basin councils, then what? Rondônia's LAPRO program

My findings in Chapter 2 suggest that the potential for the tools of basin councils to address water quality issues in the region is no greater than that of policies and incentives tied to land-use. These latter programs already have a greater presence in the Amazon region, and are tied to an issue (what to do with agricultural land) that is more central to farmer thinking. Turning thus away from the focus on water management, Chapters 3 and 4 focus on the potential outcomes from one program in Rondônia that is being developed to help rationalize the use of land on rural properties. The environmental licensing program for rural properties (LAPRO) in Rondônia will require farmers to place significant amounts of their productive land in legal reserve (LR) forest in order to gain access to rural credit or markets for their products (SEDAM-RO 2004).

LAPRO is meant to bring properties in line with Brazilian laws for land use. While the need to stake claim to land by clearing it and by demonstrating intention to use it productively provided a clear incentive to deforest (Hecht and Cockburn 1989, Fearnside 2001, Caldas et al. 2007), the Brazilian Forest Code has since 1965, required colonists to maintain half of their lands in LR forest. This includes maintaining forest cover along all water courses and steep hillslopes in what are called 'areas of permanent preservation' (APP) (Brazil 1965). The push from LAPRO to bring properties in line with the Forest Code is very much a reversal from what colonists had been encouraged and incentivized to do over much of the last 40 years.

To obtain a license, properties must demonstrate a management plan to bring their properties in line with the requirements of the forest code within a period of 30 years. LAPRO will require maintenance of APP and an area equivalent to 50% of the property in LR for properties that were deforested as of 2005; properties forested as of 2005 will be allowed to clear only 20% of that new land under LAPRO. For many smaller properties, this will mean a huge cut in income essential to meeting basic household needs. To lessen the burden that LAPRO might place on smaller farms, proposals have been put forward by several organizations in the state to change the requirements of the program (Amazônia 2009). One such proposal suggests modifying the Forest Code such that:

i. All farms up to 1 fiscal module (60 hectares) would be required to restore APP

ii. All farms between 1 and 2 fiscal modules (120 hectares) would be required to restore APP and maintain 20% of the property in legal reserve forest.

iii. All farms greater than 2 fiscal modules would be required to restore APP and maintain 50% of the property in legal reserve forest. (de Jesus 2009)

LAPRO is an interesting problem to consider, from the perspective of harmonizing social and environmental goals for rural landscapes, because the unique history of Amazonian colonization means that there is no one 'typical' farmer to regulate. Colonization in Rondônia occurred over decades, partly organized through the Brazilian Institute for Colonization and Agrarian Reform (INCRA) and other private agencies, and partly ad hoc, with landless migrants following access roads and staking claim by clearing land (Schmink and Wood 1992). This diversity in endowments, coupled with decades of land parcels bought, sold, and inherited (Browder et al. 2008) has led to a broad distribution of rural property sizes in the region, with different modes of production (Ellis 1993) and differing capacities to respond to shifts in public policy.

In Chapter 3 I illustrate that farmers on smaller properties operate in a regime close to highly-optimized tolerance (HOT) (Carlson and Doyle 1999, Janssen et al. 2007), where adaptations to improve robustness to expected disturbances (like poor yields or market prices) introduce new sensitivities to other disturbances (like shifts in input prices). As farmers pull land out of production to meet licensing requirement, their properties will be pulled closer to the HOT boundary, making the landscape as a whole more vulnerable and some properties socially and economically non-viable.

I hypothesize that this shift toward HOT and the increase in vulnerability would be significant at the scale of family agricultural production in the region, and look to current patterns of land use across property size for signals of the shifts in production that might occur under LAPRO. While it may be intuitive that smaller properties will lie closer to the HOT threshold, this study looks in more detail at what qualifies as ‘small’, with respect to HOT, in this particular socio-ecological system. To explore this hypothesis I use empirical data collected in the region across the scale of family farm production (from 1 up to about 240ha in size) on land use, production, costs, and goals, and examined how these variables shifted across scale. Differences among size classes in these results signal the closer proximity of smaller farms within the sample to the HOT boundary, and indicate the movement toward HOT that could be expected as land is pulled out of production under LAPRO. LAPRO requirements have caused concern among many family farmers in the region, and farmers groups have put forward proposals for a tiered licensing structure that would reduce the requirements under the licensing for properties less than 120ha in size. The empirical results in this paper highlight the need for more careful consideration of proposals like the tiered approach.

Digging in deeper – An agent-based model of LAPRO in action

Chapter 4 develops an agent-based model of the Rondônian ranching landscape to investigate the potential social, economic, and environmental outcomes of LAPRO under the additional stressor of a change in climate. Agent-based analysis of changes in farm structure is a relatively new field of research (Zimmermann et al. 2009), and the model in this chapter incorporates features of particular relevance to the Amazonian context – land sale by struggling farmers, and climate variability – that have not appeared in other agent-based approaches to farm change. The coupled model of ranching and climate asks whether the joint pressures of licensing and a changed cost structure due to climate change will act to force producers on small properties off of their land, and whether this social impact can be mediated while still achieving landscape-scale land-use goals.

The goal of Chapter 4 is to investigate the ways in which climate change and LAPRO will affect environmental quality, measured through the fraction of land that is forested; the profitability of ranching in the region, measured by the average profit earned per hectare of property per year; and social equity, measured by distribution of land among farmers. Additionally, the chapter investigates the ways in which modification of the Forest Code or LAPRO may shift how small farmers are affected by licensing requirements. While programs like LAPRO may help to restore critical environmental services in rural areas, it is important to consider in detail the burdens that they place on rural production. The model results suggest that environmental goals *can* be harmonized with social and economic goals in the ranching landscape, but that this will require particular care in implementation, with monitoring programs that emphasize larger properties. This chapter contributes both to the nascent literature on agent-based approaches to analyzing rural policy, and to the broader discussion within natural resource management of how, in a socially just manner, to match today's goals for environmental and ecological services with the legacies of colonization and resource-exploitation regimes of the past.

SUMMARY

This dissertation examines the agriculture and ranching socio-ecological system (SES) of the Brazilian Amazon. Initially, the motivation of this work was to understand the potential of the new Brazilian system of decentralized water management to address agricultural water quality issues in the region. This initial work soon gave way to a focus on nascent environmental legislation in the State of Rondônia that has similar goals for keeping waters clean. Chapter 2 presents a systems dynamics model and institutional analysis of stylized policy approaches to addressing water quality – one based on the bulk water charge, a central tool of the decentralized water management regime; and one tied to land use, the approach taken by several environmental initiatives in the Amazon Region. Chapters 3 and 4 turn to one such initiative, the environmental licensing program of Rondônia, and analyze through social survey research and an agent-based model the potential environmental, social, and economic outcomes the program may bring to the region.

Together, these three chapters paint a cautiously optimistic picture for the future of clean water resources in the Amazon Region. A lack of mobilization around water issues may hinder the advance of water reform that has been successful elsewhere in Brazil, but there is potential within other programs pushed forward by worldwide concern regarding Amazonian deforestation. The LAPRO program in Rondônia, implemented effectively and with consideration to the broad range of capacities to comply across rural households, has potential to harmonize environmental goals for forest cover with economic and social goals for the ranching landscape.

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Chapter 2

Cattle, Clean Water, and Climate Change: Policy Choices for the Brazilian Agricultural Frontier

ABSTRACT

In the Amazonian agricultural frontier, pasture for cattle ranching is an important and potentially hazardous form of land use because of sediment erosion as pastures degrade. This relationship between ranching, sediment load and water quality is likely to further exacerbate environmental impacts in the region, particularly in the context of climate change. We examine the role that river basin councils (RBCs) – one of the water governance options written into Brazil's 1997 National Water Act – might play in managing this non-point-source pollution issue in the Amazônian state of Rondônia. We implement a simple systems dynamics model of the coupled rancher-water system to compare between two potential governance options: first, a bulk water clean-up charge (BWC) implemented by RBCs and, second, a land-use fine (LUF) for failing to maintain riparian buffers based on other approaches being developed across the Amazon. We find no significant advantage to BWC over LUF in reducing sediment loading while keeping ranching profitable, across scenarios of climate change. We also fail to find in the Rondônian ranching landscape the stake in water issues that has driven water reform elsewhere in Brazil. Moreover, the comparative success of environmental programs driven by concerns over forest cover suggests that these programs may have potential to manage the issue of non-point-source agricultural pollution in the region.

INTRODUCTION

The Amazon region, or Amazônia, is commonly associated with an abundance of water resources; however, these resources are not uniformly distributed across space or time. Throughout the region, at different points in the year, drought is a reality to which its natural systems are well adapted. Yet, the joint stresses of agricultural/ranching development and the advent of global climate change threaten water resources in Amazônia. In addition to slow changes in temperature and the overall precipitation volume in the region (Table 2.1), two other expected impacts of climate change are increases in the frequency of extreme climate events (storms and droughts), and increases in inter-annual and seasonal variability (Magrin et al. 2007). Coupled with uncertainty regarding climate expectations on the part of ranchers, these changes could enhance erosion and sedimentation processes, degrading water quality in agricultural landscapes.

Table 2.1: Climate Projections for Amazônia (adapted from IPCC 2007 Report)

		2020	**2050**	**2080**
Δ Temperature (C)	Dry Season	+0.7 to +1.8	+1.0 to +4.0	+1.8 to +7.5
	Wet Season	+0.5 to +1.5	+1.0 to +4.0	+1.6 to +6.0
Δ Precipitation (%)	Dry Season	-10 to +4	-20 to +10	-40 to +10
	Wet Season	-3 to +6	-5 to +10	-10 to +10

Water stress and scarcity has been an issue in other regions of the country for some time, and the past two decades in Brazil have seen a process of gradual water reform, punctuated by a new constitution in 1988 and a National Water Act in 1997, which together sought to reframe the idea of water as a resource with economic value (Benjamin et al. 2005). The new system creates new structures for integrated governance of all water uses at the level of the hydrographic basin—river basin councils (RBCs)—that work in tandem with other more traditional forms of management such as municipal and state water and environmental agencies and organizations. These tripartite councils (committees and consortia) are composed by federal and state actors, water users and user groups, and representatives of organized civil society (Brasil 1997). Waters flowing entirely within the borders of a single state fall under state jurisdiction; those crossing state borders fall under federal jurisdiction, requiring greater federal representation on the basin councils (Brasil 1997). As designed, the basin councils have two central tools at their disposal to rationalize water use – *outorga* (water use permits), and *cobrança* (bulk water charges), the revenue from which is in principle to be reinvested in water projects within the basin (Lemos and De Oliveira 2004, Formiga-Johnsson et al. 2007). To date, the water reform has created over 100 stakeholder-driven river basin councils across Brazil to support water management with mixed levels of success (Abers and Dino Jorge 2005); reform has advanced the furthest in the semi-arid Northeast (Lemos and De Oliveira 2004) and the highly industrialized South and Southeast (Benjamin et al. 2005). However, little has occurred in Amazônia where a single council has formed in the Tarumã-Açú River Basin in the state of Amazonas.

Yet, despite this slow pace of progress, the exacerbation of water quality problems in Rondonia, especially under climate changes, suggests that decision-makers will soon be faced with either implementing available institutions or designing new ones to address this problem. In this study, we aim at informing this process by exploring, through modeling and institutional analysis, two potential policy choices in a comparative approach. Our goals are threefold. First, we examine which policy choice is the best option to improve water quality. Second, we seek to inform the institutional design of RBCs in the region by exploring whether pollution control instruments implemented in other parts of Brazil would work in the Rondonia context. Finally, by including future climate changes in our analysis, we aim at informing policy makers of which options are likely to fare better under the threat of yet uncertain but predicted climate stressors.

We use a simple systems dynamics model (SDM) of a ranching property to compare the two policy options to improve the quality of water leaving the property. The first option is a bulk water charge tool that seeks incentivize efforts to curb pollution by creating a price scale that punishes polluters and rewards cleaner forms of water use (Formiga-Johnsson et al. 2007). The second option is based on other environmental approaches in Amazônia that have attempted to penalize farmers for failing to maintain adequate riparian buffer around watercourses.

The model is informed by conditions prevalent in the Amazonian state of Rondônia, where the landscape is dominated by ranchland for cattle (5,000,000 ha of pasture compared to 500,000 ha of croplands in Rondônia in 2006 (IBGE 2006)), making sedimentation and associated declines in water quality the potential major regional-scale water issue for the future (Coe et al. 2008, Stickler et al. 2009). We use sediment load as a proxy for pollution because it is a key vector in the transport of other water pollutants such as nutrients, organic carbon, and other contaminants. It plays a role in the availability of spawning habitat for fish, as well as in the lifetime of hydroelectric dams, a major source of electricity from Amazônia. Also importantly, the effects of sediment loading extend beyond the local area to have regional scale impacts (Coe et al. 2008, Stickler et al. 2009).

Despite the importance of sedimentation as an issue, most ranchers – the agents of land-use change – get water for domestic use from wells, and have no stake in the condition of surface waters (Bell et al. 2009). In this sense, the landscape mirrors cases in other areas of the world where non-point source pollution has been of lower concern in deliberative water management processes (Hermans 2008). The most advanced work toward the formation of a basin council in the state has been a set of studies in the municipality of Ouro Preto d'Oeste (PROBACIAS 2008), whose urban water demand is fed by the agriculturally developed Boa Vista River Basin. However, this catchment covers an area of only about 18,000 ha – stake in water resource management is thus far very localized and isolated in the region.

The sheer number of ranchers spread across large basins and the associated transaction costs for interactions among them present a further barrier to collective action in the region (Tompkins and Adger 2005, Ostrom 2009), in sharp contrast to conditions elsewhere in Brazil, where industrial actors responsible for water contamination are both organized and visible. Compared to other regions of Brazil where the citizenry has been mobilized to initiate water reform, agriculture in Rondônia is less intensive, less dense, and less mechanized (IBGE 1996). This highlights the need for an understanding of the effect of public policy on livelihoods alongside impacts on water quality, as much of the environmental degradation in Amazônia is related to the inability of poorer farmers to maintain their land's productivity (Hecht and Cockburn 1989, Asner et al. 2004, Fearnside 2005). In this context, policies that overly burden farmers with penalties in the narrow interest of improving environmental quality may end up exacerbating environmental impacts. Moreover, in the wake of projected climate change—and its potential negative impacts on livelihoods in the region, it is critical to better understand the role of alternative policy choices to achieve both environmental and socio-economic goals. In the next section, we develop our SDM model and explore two existing governance options to improve water quality.

MODELING WATER POLICY IN RURAL LANDSCAPES

SDM Model Summary

In the SDM in this study, a lone rancher makes decisions about how to change his land-use from year to year, given limited ability to change land each period. Specifically, the rancher stocks the land with cattle, and decides how to allocate limited effort among:

i. Restoration of degraded pasture to pasture
ii. Restoration of pasture to forest
iii. Clearance of new forest for pasture

The rancher makes decisions from a purely economic, rational viewpoint. Land use in the SDM affects the degree to which surface waters leading out of the property become polluted. Daily precipitation is drawn from an exponential distribution, with some water entering the ground, some being lost to evapotranspiration, and the remainder traveling over the surface as overland flow, according to a basic hydrological model (Appendix A). Overland flow accumulates sediment eroding from pastureland, with erosion rates greater for degraded pastureland. Riparian buffers bordering surface water on the property are able to trap this sediment with an efficiency that is a function of buffer width as well as the overland flow rate. From the perspective of sediment loading, the central question of this paper is whether policies tied to land-use and the environment provide for water quality and livelihoods outcomes better than those tied directly to water quality itself within this bounded situation. This question is investigated across scenarios of high and low climate variability, reflecting the increases in extreme weather events and uncertainty over climate that are expected in the coming decades (Magrin et al. 2007), as well as scenarios of increased or decreased precipitation.

The complete description of the model is found in Appendix A.

Policy Scenarios

1 – Bulk Water Charges: One of the instruments of Brazilian IRBM laid out in the National Water Act is the *cobrança pelo uso de água* – bulk water charges (BWC) levied against consumptive uses of water, including extraction and pollution (Brazil 1997). In this scheme, large users pay a charge per unit volume of contaminated water for its cleanup. In this paper, we examine a BWC levied against rural non-point source polluters for contamination of river water by sediment. While, from a monitoring and implementation perspective, charges for non-point source polluters might be challenging and costly (O'Shea 2002), they are not impossible (Azzellino et al. 2006). In addition, the clear trend of land aggregation into larger properties along the frontier (Pedlowski et al. 1997) will reduce the difficulty in attribution. As well, the *cobrança*, in conjunction with water quality criteria such as laid out by the National Environment Council CONAMA (CONAMA 2005), are a salient example in Brazilian water policy of enforcement institutions tied directly to water quality itself, in contrast to the second policy scenario, land-use fines, which tie in with water quality only indirectly. Implementation of BWC in Brazil has been challenging, with significant resistance both from users (who have generally had water for free) and some state agencies (who are unwilling to cede control over water resources) (Formiga-Johnsson and Kemper 2005a, b, Abers and Keck 2009). A small number of basins have successfully negotiated formulas for BWC, such as in the Jaguaribe Basin in Ceará (Formiga-Johnsson and Kemper 2005b) and the federal basin of the Paraiba do Sul River, whose BWC formula allows collection for consumptive, withdrawal, and effluent dilutive uses of water resources (Formiga-Johnsson et al. 2007).

2 – Land Use Fines: The 1965 Brazilian Forest Code mandates the maintenance of riparian buffer zones (a component of what are known as Areas of Permanent Preservation, or APP) along watercourses on rural properties, the required widths of which depend on the width of the river. For example, watercourses up to 10m across must be bounded by 30m of riparian vegetation (Brazil 1965). Current attempts to enforce this rule in Rondônia include a new environmental licensing scheme, under which all producers need to provide a management plan showing their progress toward compliance with the Forest Code to access rural credit programs (SEDAM-RO 2004). In consequence of non-compliance with the Forest Code, farmers can be fined, as some large producers in Amazônia have been, for not maintaining adequate riparian vegetation (Magalhães 2007). Results from licensing schemes elsewhere in Amazônia have been mixed (Lima et al. 2005), much of which may be attributable to poor enforcement by environmental agencies lacking in resources and capacity (Hall 2008). As a proxy for the enforcement of the Code's environmental variables (e.g. maintenance of forest cover), in this paper we introduce a land-use fine (LUF) levied against each unit area of deficient riparian forest below the regulation width, charged once yearly.

Model Experiments

Each of the policy options explored in this paper – fines for deficient riparian vegetation and charges for volumes of contaminated water – is defined along two dimensions. For the LUF, these dimensions are the required width of the buffer, and the nominal fine per unit area deficient. For the BWC, the dimensions are the threshold sediment load that is considered contaminated, and the charge per unit volume to clean the water. A factorial experiment (Table 2.2) was carried out for each policy option along each of its two dimensions as well as for the scenarios of climate variability. Response surfaces were generated for the total revenues obtained, total costs incurred, and total sediment eroded over the period of the policy. Where possible, values for model parameters have been drawn from the literature (Appendix B) and other values assumed in order to simulate a ranch supporting 1-3 head of cattle per hectare.

Table 2.2: Policy Parameters in Experimental Design

	Parameter Values
S_{BW} (\$/m^3)	0, 0.04, 0.08, 0.12, 0.16, 0.2, 0.24
L_R (t/m$_3$)	0.0001, 0.00005, 0.000001, 0.000005, 0.000001, 0.0000005, 0.0000001
S_{LU} (\$/ha)	0, 100, 200, 1000, 1500, 2000, 3000, 4500, 6000, 7500, 9000
W_R (m)	0, 30, 60, 90, 120, 150, 180

There are several physical relationships in this model that have strong influences on the role that policy will play – the relationships between precipitation and overland flow, between overland flow and erosion as well as sediment trapping by buffers, and between buffer width and sediment trapping. A detailed calibration effort along these physical dimensions is not in the spirit of this low-fidelity modeling approach nor representative of what may be very heterogeneous relationships across a landscape. In each simulation in this study, a set of physical parameters governing the relationships mentioned above were set randomly in a Monte Carlo approach to factor out any specific bias that a particular parameter set may have (Table 2.3). The results of this study can thus be thought of as the results across a rugged landscape of physical relationships between water, soil, vegetation, and erosion.

Table 2.3: Ranges for Monte Carlo Analysis

Variable	**Range (Uniform distribution)**
Soil Depth, SD (m)	0.5-1
Nominal Overland Flow, $H_{OVF,0}$ (mm)	10-20
Nominal Buffer Width, $A_{Buffer,0}$ (m)	20-40
Exponent for Trap Efficiency – Overland Flow	0.75-1.25
Exponent for Trap Efficiency – Buffer Width	0.75-1
Exponent for Erosion – Overland Flow	0.75-1.25

Model Results

A set of typical runs for each of the BWC and LUF cases are shown in Appendix C, along with complete response surfaces showing the modeling outcomes across smooth increases in both unit sanction and sanction threshold. A sample of these surfaces is shown in Figure 2.1, illustrating the decreases in both profits and sediment loading that accrue in response to increasingly strict sanctions and thresholds under the BWC. The current discussion will focus on a set of two representative ‘slices’ across these surfaces – A) a constant stiff unit sanction for noncompliance and a continuously stricter requirement, and B) a constant stiff requirement and a continuously increasing unit sanction for noncompliance – for each of the BWC and LUF scenarios, viewed across different scenarios of climate. To compare results, we present the data in ‘sanction response curves’ (described completely in Appendix D) where the two outcomes of sediment loading and the profitability of the ranch are plotted against each other. The increasing strictness of the sanction is implicit as the curve moves from right to left in the chart, and the slope of the curve at any point is analogous to a measure of cost effectiveness – the steeper the curve, the greater improvement in water quality per unit economic burden on the rancher.

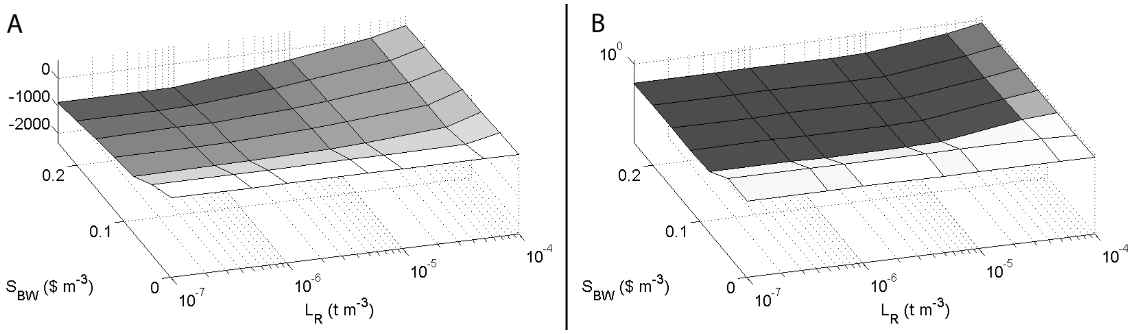

Figure 2.1: Response surfaces for BWC across sanction threshold L_R and unit sanction S_{BW}. L_R increasingly strict from right to left; S_{BW} is increasingly strict going into the page. A) Profit (\$/ha/y) B) Erosion (t/ha/y). Each point on the surface represents the mean profit per hectare per year over the final 10 years of the simulation, averaged across 100 Monte Carlo runs.

These sanction response curves typically contain up to three distinct regions: an initial flat region ‘A’, in which increasing sanction costs have not yet encouraged the rancher to change behavior; a declining region ‘B’ where increments in sanction strength induce responses by the rancher and lead to better environmental outcomes; and finally a flat region ‘C’ where the rancher is unable to make further improvements to environmental outcomes.

For the case of BWC, we look first along a curve of decreasing pollutant threshold (L_R) at constant unit water charge (S_{BW}), then along a curve of increasing S_{BW} with constant L_R. For the LUF case, we look at a curve generated by increasing the required buffer width (W_R) at constant unit area fine (S_{LU}), then finally at a curve of increasing S_{LU} with constant W_R.

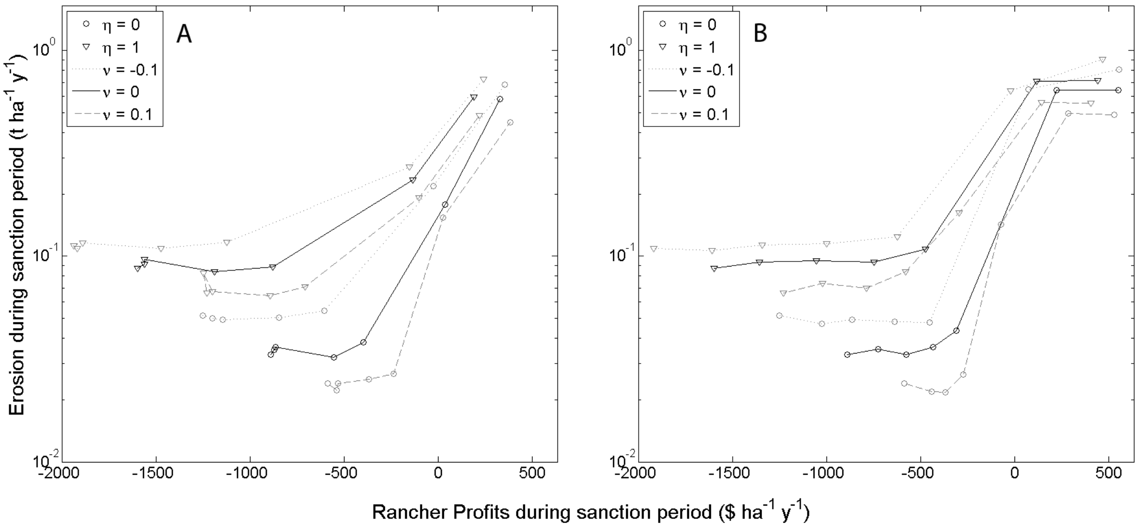

Figure 2.2: Sanction Response Curves over Climate Scenarios across A) Constant Unit Sanction S_{BW} = \$0.24/m^3 and B) Constant Threshold of L_R = 1e-6 t/m^3 for BWC. Curves associated with low climate variability are marked with circles, those with high climate variability are marked with triangles. Increased precipitation is marked by a dashed line; decreased precipitation by a dotted line.

The responses to BWC and LUF policies share a number of features. First, making requirements stricter (requiring cleaner water, or wider buffers moving from right to left in Figures 2.2A and 2.3A) under a stiff unit sanction brings immediate results for both policies. In contrast, when the rancher is given a strict requirement to meet, his behavior does not begin to shift until the unit sanction increases to a point that, from his rational decision making point and level of information, warrants it (Figures 2.2B and 2.3B). In all cases, the curves flatten out where the rancher is no longer able to make improvements in environmental performance, and increasingly stringent requirements or sanctions simply cost the rancher more money. Both policies exhibit a similar response to changes in climate – increases in climate variability and increases in overall precipitation lead to decreased environmental performance and greater costs to the rancher (shifts up and to the left in Figures 2.2 and 2.3).

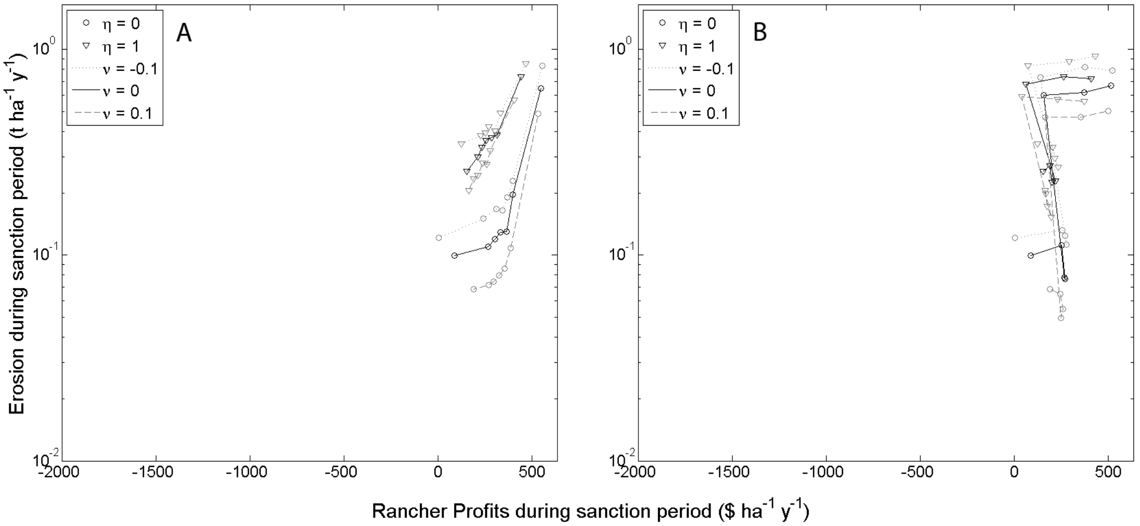

Figure 2.3: Sanction Response Curves over Climate Scenarios across A) Constant Unit Sanction of S_{LU} = $9000/ha and B) Constant Target Buffer Width of W_R = 180m for LUF. Curves associated with low climate variability are marked with circles, those with high climate variability are marked with triangles. Increased precipitation is marked by a dashed line; decreased precipitation by a dotted line.

However, there are several important differences to note between the two approaches. First, across all climate scenarios, BWC appears to achieve better environmental outcomes. This is due in part to the push by the BWC not only to maintain riparian cover, but also to reduce exposed soils by restoring degraded pasture. The LUF, in contrast, does not shift the economics of restoring degraded pasture at all. Second, these environmental gains under BWC come at much greater cost to the rancher. Much of the improvement in sediment loading occurs after profits for the rancher have dropped below 0. In our simple model, the rancher is able to continue to operate at a loss and make the best of a bad situation, leading to these eventual improvements in water quality, but this is a big break from reality. Onerous sanctions such as this would force the rancher off the landscape or, perhaps more likely given the low capacity for monitoring and enforcement in Amazônia (Hall 2008, Lemos and Roberts 2008), would simply be ignored. The reason for these incredible costs to the rancher in the model is that, where climate is uncertain and where the relationship between riparian cover and sediment loading is not perfectly known, it is difficult to make a good decision about how much riparian cover to maintain. In contrast, when the required width of the buffer is specified, as in the LUF, decision-making is much simpler for the rancher, reflected by the comparatively minor drops in profitability that the rancher incurs under LUF.

Looking only at improvements to water quality where profits remain positive (and where we could more reasonably expect some degree of compliance), BWC no longer appears to outperform LUF from the perspective of sediment loading. Further, from a 'cost-effectiveness' perspective (the slopes of the curves in this range), the LUF approach brings about greater improvement to water quality per unit drop in rancher profitability.

DISCUSSION

Model Limitations

Implementing the coupled human-natural ranching environment in a stock-and-flow model necessarily simplifies many aspects of the real system. For example, ranching decisions are likely to be more sophisticated and more continuously spread over time than they can reasonably be represented in such a model. Land and soil hydrological properties will vary within and across farm plots, leading to great variation in erosion potential across the landscape (da Silva 2004, Lu et al. 2004). The sediment trapping efficiency of riparian buffers may be modeled as a more detailed function of overland flow rate and buffer width (Verstraeten et al. 2006) and of vegetation, and agricultural performance is subject to a number of natural and environmental factors not addressed by this model. Finally, differences among ranchers in their decision-making, as well as their cost structures and land endowments, will lead to quantitatively different outcomes at the landscape scale than predicted by our model at the ranch scale.

However, the purpose of this model is not to simulate detailed ranching operations and make specific predictions of economic and environmental performance. Rather, it is to generate reasonable scenarios of ranching operations, and look for patterns and general characteristics in the scenarios that offer insight into the effects of climate and public policy. In this sense, the construction of coupled human/ecological models to better understand impact and response to climate change has been identified as a critical priority of climate change research in the U.S. and abroad (National Research Council (U.S.). Panel on Strategies and Methods for Climate-Related Decision Support. 2009).

Implementing BWC and LUF in practice

The implication of our model results is that, from the perspective of the tools available to basin councils as part of the water reform, the bulk water charge does not offer any particular advantage over other approaches tied directly to land use, assuming rational behavior and perfect compliance. Simply put, a standard for land use is much easier to understand and thus comply with than is a standard of water quality. But how might the two approaches compare where compliance is less than perfect? Put another way, what is the comparative ability of RBCs (who would implement the BWC) and environmental agencies (who have begun implementing incentive and regulations programs tied to land use, like the LUF) to be effective?

One part of the answer to this question lies in how aware land users are of regulation. Our own research in Rondônia has demonstrated relatively low awareness of policies relating to water or water quality, but relatively widespread understanding of the requirement to use buffers on rural properties (Bell et al. 2009), suggesting a stronger existing knowledge base for LUF to operate than for BWC. A second part of the answer lies in comparing the effort required for monitoring and enforcement. While either approach would likely have similar requirements for enforcement (in the form of site visits with the land owner), monitoring requirements would differ considerably. Brazil is relatively well-positioned to perform near-real-time satellite monitoring of land use and deforestation (Shimabukuro et al. 2006), but cost-effective means of monitoring and attributing non-point-source pollution remain elusive in agricultural landscapes worldwide (Ruffolo 1999, O'Shea 2002, Van Koppen 2003, Jiang 2009). Attempts to levy BWC against agricultural users elsewhere in Brazil have met with much resistance. Farmers in the Paraiba do Sul Basin agreed to pay only symbolic levels (Formiga-Johnsson et al. 2007), while in Ceará, farmers have outrightly refused to pay – only large, visible users such as electric utilities have agreed to participate (Formiga-Johnsson and Kemper 2005b).

Finally, the likelihood of either approach to be put into legislation and implemented must be compared. For RBCs, evidence from other regions in Brazil suggests two important drivers of successful water reform in Brazil. First, stake is critical in mobilizing participation in water governance. In the state of Ceará in Northeast Brazil for example, perennial drought has meant that the allocation of scarce water resources among a diverse set of user stakeholders – irrigated agriculture, industry, and the metropolitan area of the state capital in Fortaleza – has long been a priority (Lemos and De Oliveira 2004, Taddei et al. Forthcoming). In the Southeast of Brazil, drought is more the exception than the rule, but dense urban populations, intensive agriculture, and powerful industries make access to water of sufficient quality nevertheless an issue. Urban demand in the Alto Tietê basin (which supplies the metropolitan area of São Paulo) already outstrips supply, and with access to water resources at stake, a broad stakeholder base has been mobilized over recent decades to support and participate in integrated water management (Formiga-Johnsson and Kemper 2005a). Whether driven by aridity or by user density, conditions of water scarcity create incentive for all users to join the deliberative process and ensure that i) they have access to their share of water resources, or ii) that the resources are of sufficient quality for them to use.

Second, where water quality issues have made it onto the agenda of basin councils at all, they have focused largely on larger point sources, such as in the Alto Tietê Basin where bulk water charges cover effluents such as BOD and COD, inorganic effluents as well as sediment residues, but are limited to waters for which users have been issued permits (Formiga-Johnsson and Kemper 2005a). These permits are issued only to municipalities and industrial users, at least initially, with a plan to extend charges to irrigated agriculture in the future for withdrawals; non-point-source pollution from agricultural landscapes has not so far been a driver of the reform process in other areas in Brazil.

Large point-source water users and conditions of high stake are absent in the Rondônian context which, while not precluding water reform from being driven forward by some other actor or issue, allows us to speculate that the implementation of RBCs in Rondônia may be slow. One further observation on the successful cases in the Northeast and Southeast of Brazil is that they involved groups of technical experts working over an extended period (since as early as the 1970s) who capitalized on the process of democratization in Brazil in the 1980s to advance the process of water reform in their respective basins (Lemos and De Oliveira 2004). Discussing the Paraibá do Sul case in particular, Formiga-Johnsson et al. (2007) draw on Kingdon's policy streams model to explain the progress of water reform in Brazil (Formiga-Johnsson et al. 2007), suggesting that particular focusing events (drought and water conflict) combined with political moods or climates (the 1980s shift to democracy) to create 'policy windows' through which policy entrepreneurs (the technical experts in Ceará and Alto Tietê) were able to advance an agenda (Kingdon 1995, Zahariadis 2007). The lack of similar focusing events in Rondônia add further support to the idea of slow implementation and a lack of mobilization around water issues.

Looking now to policy tools that compare to the LUF, evidence is beginning to be collected on the capacity for different forms of incentive and regulation to rationalize land use in Amazônia (and the results are mixed) (Boyd 2008, Hall 2008). The Proambiente project has established a pilot program in the payment for ecosystem services involving about 4000 households localized around 12 different 'poles' throughout Amazônia (Hall 2008); as well, Rondônia along with several other Amazônian states have begun to implement environmental licensing schemes for rural properties in which farmers and ranchers must demonstrate plans to bring their land use in alignment with the Brazilian Forest Code to gain access to rural credit (SEDAM-RO 2004). While these programs are distinct both from each other and from the stylized fine for land use implemented in the model used in the current paper, they share common goals and mechanisms – farmers are rewarded, or fail to be punished, by restoring and maintaining riparian cover along watercourses, with the underlying goal of preserving ecosystems services.

Thus far, these projects too have only been partially implemented, and run up against the barriers that a lack of capacity for implementation and monitoring place on all regulatory or incentive programs in Amazônia (Hall 2008, Economist 2009). However, a focus on incentives tied to land-use practices to improve water quality has precedent elsewhere. In the United States, the difficulty in measuring or attributing non-point source pollutants to particular properties, the expense associated with some forms of non-point source pollutant control, and the resistance generated by non-point source polluters to attempts at regulation have led many states to adopt voluntary best management programs (BMPs) as a means to encourage land use that preserves water quality (Ruffolo 1999); the jury is still out as to what factors, in the US case, lead to BMP adoption (Prokopy et al. 2008). For Amazônia, the inherent measurability of land-use criteria (through near-real-time satellite monitoring, for example) coupled with a simpler set of objectives for farmers to follow (a width of riparian buffer versus a water quality outcome) and greater mobilization around the issue of deforestation and environmental services suggest that the future of water quality in Amazônia may be better served through these innovations in environmental legislation than through the reform in water management that has been successful in other areas of the country.

CONCLUSIONS

This study investigated the potential for decentralized river basin councils to govern the issue of non-point-source pollution in rural Amazônia.

We implemented a simple set of climate, hydrological, ecological, and rational actor models in a systems dynamics framework to evaluate the potential differences between two different approaches to sanctioning ranchers as a means to regulate agricultural erosion impacts on water quality. A bulk water charge brought strong reductions in erosion by pushing the rational actor to both plant buffer zones and to restore degraded pasture, but laid a strong financial burden on the rancher. In contrast, a fine based solely on the presence of buffer zones brought more modest erosion reductions, since it placed no additional emphasis on the maintenance of pasturelands, but also placed less of a burden on the rancher. Both policies showed similar robustness with respect to erosion reduction under changes in precipitation volume and variability, while the bulk water charge placed progressively higher burdens on the rancher with increased precipitation and climate variability. These results fail to show a particular advantage of bulk water charges in confronting the agricultural impact of erosion and sediment loading to surface waters over sanctions tied by proxy to these agricultural impacts via land use and the maintenance of vegetated buffer zones.

Stake has been a major driver for participation in basins where water reform is most advanced, manifested as the need to claim a share of scarce water resources or stand up to a major industrial polluter, and this helps to explain why efforts at water management in Amazônia have been sparse and localized (the basin feeding the industrial center in Manaus, or the small catchment supplying drinking water to the municipality of Ouro Preto). The general abundance of water, prevalence of extensive agriculture, and reliance on groundwater on most rural properties in Rondônia do not suggest much incentive in the region to mobilize around water issues. However, the attention paid in recent decades to deforestation and land-use change have created policy windows for an assortment of projects and regulations aimed at improving forest cover on rural properties – the same goals of legislation aimed at reducing non-point-source pollution and improving water quality in rural areas. While, like most government programs in Amazônia, they are poorly funded and have limited capacity, these initiatives may be in a better position to protect the future of Amazônia's water resources. Voluntary BMP programs in the US that include the maintenance of riparian buffers have had some success in rationalizing land use (Prokopy et al. 2008), and success observed in Amazônia could point toward more generalizability of the BMP approach across different institutional and cultural contexts.

Basin councils and the decentralized approach to water management may indeed have a role in managing water distribution and industrial water pollution, as it is coming to have in other areas in Brazil, though this study suggests it is not likely that it will be the means to govern the agricultural impacts to water quality which dominate human water impacts at the regional scale in Amazônia.

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Chapter 3

Productivity and farm size in Rondônia: Implications for Environmental Licensing

ABSTRACT

An environmental licensing scheme is being implemented in Rondônia, Brazil, and its environmental goals for maintaining forest cover have come into conflict with social and economic goals of previous colonization projects. Licensing will require farms to remove significant amounts of land from production, and may lead to shifts in production intensity as farms move to comply. This is a concern for smaller properties, whose production is already more intensive and who may have difficulty meeting basic household needs on less land. This paper seeks to understand how property size and other farm characteristics influence farm sensitivity to external disturbance, including climate change and environmental regulation. It argues that as production intensifies, properties move closer to a state of highly-optimized tolerance, where resources are committed to maintaining robustness against expected disturbances (like shifts in yields or crop prices), making the property more vulnerable to other unexpected disturbances, like shifts in input prices or availability. We measured the shifts in production and costs that occur across scale in the Ji-Paraná River Basin in Rondônia. We found decreasing production intensity with increasing property size in the sample, coupled with decreasing contracted and family labor-use intensity, and decreased income diversification. Farms smaller than 60ha in size in the sample differed markedly in production and cost structure from those larger. For these smaller properties, meeting the licensing requirements may lead to an increase in the sale of land parcels to cover debts and a speeding up of land consolidation in the region. Should the scheme be implemented in such a way that farmers are motivated to follow its requirements, and if the social goals of providing livelihoods for the colonists that have come to the

region remain, a tiered licensing proposal that relaxes requirements for smaller properties is worthy of consideration and further study.

INTRODUCTION

Environmental and social goals for rural areas are increasingly coming into conflict as growing interest in forest and biodiversity conservation draws attention to land-use practices across rural settlements in the developing world, many of which are legacies of past policies for planned colonization (Fearnside 1997, Ekoko 2000, Rachman et al. 2009). The threat of climate change has potential to heighten this conflict – forest cover becomes increasingly important as a means of carbon sequestration, evaporative cooling and other environmental services under climate change (Bonan 2008), while at the same time, maintaining productive land becomes increasingly important for rural smallholders whose vulnerability to climate shocks is rising (see for example (Eakin and Appendini 2008)).

In the Amazon Region, international attention to deforestation has spurred a number of initiatives to improve forest cover (Hall 2008), such as the environmental licensing program for rural properties (LAPRO) in the Brazilian state of Rondônia that is a focus of this study. LAPRO will require farmers in Rondônia to place significant amounts of their productive land in legal reserve (LR) forest to gain access to rural credit or markets for their products (SEDAM-RO 2004). However, the unique history of Amazonian colonization means that there is no one 'typical' farmer to regulate. Colonization in Rondônia occurred over decades, partly organized through the Brazilian Institute for Colonization and Agrarian Reform (INCRA) and other private agencies, and partly ad hoc, with landless migrants following access roads and staking claim by clearing land (Schmink and Wood 1992). This diversity in endowments, coupled with decades of land parcels bought, sold, and inherited (Browder et al. 2008) has led to a broad distribution of rural property sizes in the region, with different modes of production (Ellis 1993a) and differing capacities to respond to shifts in public policy.

I illustrate in this paper that farmers on smaller properties operate in a regime close to highly-optimized tolerance (HOT) (Carlson and Doyle 1999, Janssen et al. 2007), where adaptations to improve robustness to expected disturbances (like poor yields or market prices) introduce new sensitivities to other disturbances (like shifts in input prices). As farmers pull land out of production to meet licensing requirement, their properties will be pulled closer to the HOT boundary, making the landscape as a whole more vulnerable and some properties socially and economically non-viable.

I hypothesize that this shift toward HOT and the increase in vulnerability would be significant at the scale of family agricultural production in the region, and look to current patterns of land use across property size for signals of the shifts in production that might occur under LAPRO. While it may be intuitive that smaller properties will lie closer to the HOT threshold, this study looks in more detail at what qualifies as ‘small’, with respect to HOT, in this particular socio-ecological system. To explore this hypothesis I use empirical data collected in the region across the scale of family farm production (from 1 up to about 240ha in size) on land use, production, costs, and goals, and examined how these variables shifted across scale. Differences among size classes in these results signal the closer proximity of smaller farms within the sample to the HOT boundary, and indicate the movement toward HOT that could be expected as land is pulled out of production under LAPRO. LAPRO requirements have caused concern among many family farmers in the region, and farmers groups have put forward proposals for a tiered licensing structure that would reduce the requirements under the licensing for properties less than 120ha in size. The empirical results in this paper highlight the need for more careful consideration of proposals like the tiered approach.

This paper extends the work of Janssen et al. (2007) to make more explicit the link between rural smallholder production and highly optimized tolerance, and uses it to examine the change in resilience of smallholder production to multiple stressors and a regime change in environmental governance. It contributes to the growing literature on trade-offs in goals for sustainability within socio-ecological systems by analyzing the conflict that has arisen between the environmental goals of the licensing scheme on the one hand, and the economic and social goals of the original Amazonian colonization projects on the other.

BACKGROUND

Frontier Colonization

The historical process of colonization of the Amazon and expansion of the agricultural frontier has been well documented. Driven by a desire to cement Brazil's claim to the Amazon, massive colonization projects in the 1970s and 1980s brought thousands of migrant families to the region. Demand for land soon outstripped the capacity of the colonization projects to place families, and settlers from outside the region were able to lay claim to land simply by clearing and thus "improving" it (Schmink and Wood 1992, Caldas et al. 2007). However, policy shifted in the mid 1970s away from small farmers and towards more formal granting of land titles to larger ranching, mining, and other operations (Schmink and Wood 1992). Conflicts thus began to arise over claims to land by farmers who had occupied an area only to have the title granted to someone else, with the government in general issuing compensation to the small farmer for their "improvement" of the land and upholding the larger firm's land title settled these claims (Schmink and Wood 1992). This created a perverse incentive for small farmers to deforest land, receive compensation for their work in clearing the land, and drop further back into the forest to repeat the cycle. The result, across more than 40 years of settlement, is a broad landscape with varying degrees of agricultural development and abandonment, and vast areas stripped of forest cover.

Environmental Licensing

While the need to stake claim to land by clearing it and by demonstrating intention to use it productively provided a clear incentive to deforest (Hecht and Cockburn 1989, Fearnside 2001, Caldas et al. 2007), the Brazilian Forest Code has since 1965, required colonists to maintain half of their lands in what is called 'legal reserve' (LR) forest. This includes maintaining forest cover along all water courses and steep hillslopes in what is called ‘areas of permanent preservation’ (APP) (Brazil 1965). In recent years, a number of Amazonian states have begun implementing environmental licensing schemes for rural properties to bring them in line with the Forest Code, in what is a reversal from what colonists had been encouraged and incentivized to do over much of the last 40 years.

In Rondônia, the state environmental secretary SEDAM-RO has recently begun implementing their own licensing scheme for rural properties, LAPRO (SEDAM-RO 2008). To obtain a license, properties must demonstrate a management plan to bring their properties in line with the requirements of the forest code within a period of 30 years. At present, this license is in theory required for properties to access any form of rural credit. In the future, SEDAM-RO hopes to make licenses a requirement for farmers to access markets for their production.

LAPRO will require maintenance of APP and an area equivalent to 50% of the property in LR for properties that were deforested as of 2005; properties were not cleared prior to 2005 will be allowed to clear only 20% of that new land under LAPRO. For many smaller properties, this will mean a huge cut in income essential to meeting basic household needs. To lessen the burden that LAPRO might place on smaller farms, proposals have been put forward by several organizations in the state to change the requirements of the program (Amazônia 2009). One such proposal suggests modifying the Forest Code such that:

> i. All farms up to 1 fiscal module (60 hectares) would be required to restore APP
>
> ii. All farms between 1 and 2 fiscal modules (120 hectares) would be required to restore APP and maintain 20% of the property in legal reserve forest.
>
> iii. All farms greater than 2 fiscal modules would be required to restore APP and maintain 50% of the property in legal reserve forest. (de Jesus 2009)

The empirical work presented in this study illustrates how production differs across farms of 1, 2, or more fiscal modules in size and is meant to inform the decision of how this proposal should be considered as part of the LAPRO program.

The Rondônian agricultural landscape as a resilient, HOT system

As property size increases, rural economic theory predicts shifts in productivity and land-use intensity (Ellis 1993a), with smaller properties generally making more intensive use of their scarcer land resources. This prediction has borne out in empirical research within the region – in a 2008 assessment of land values on family ranches in Ouro Preto D'Oeste (which neighbors Ji-Paraná to the west), Sills and Caviglia-Harris found reported land values per hectare to be significantly negatively correlated with property size. This result reflects more productive use and a perception of land as a scarce resource on smaller properties within the study region (Sills and Caviglia-Harris 2008). Under LAPRO, taking significant land out of production will require farmers to intensify in order to maintain income; however, many of the smaller farmers in this sample are already using their land very intensively, and are limited in their capacity to intensify further. Some properties may become simply unviable as they intensify under the licensed regime; others will move closer to states described in the complexity literature as 'highly-optimized, tolerant', or HOT systems (Carlson and Doyle 1999).

Complex systems scholars have characterized several models and mechanisms to explain the behavior of complex adaptive systems (CAS) near thresholds and their response to disturbances, including HOT, self-organized criticality (SOC), and evolution to the edge of chaos (EOC), but HOT has the most potential to explain the decisions behind farm structural change. SOC focuses on the tendency of CAS to operate near some relatively stable 'attractor' state, and the pattern of responses to disturbance by the CAS in order to remain there (Newman 1996, Brunk 2002). EOC explains the behavior of CAS in terms of 'ordered chaos', emerging in a 'phase transition' between highly ordered and random, chaotic dynamics, in an analogy to the interesting physical behavior that occurs in the transition between solid and fluid states of matter, for example (Langton 1990, Kauffman and Johnsen 1991). HOT is a more relevant lens than SOC or EOC into CAS behavior in this study, however, as it explicitly focuses on the trade-offs in robustness that are made as systems (like farms) make changes to adapt to disturbances.

As Carlson and Doyle (1999) describe them, HOT systems are '*robust* to perturbations they were designed to handle, yet *fragile* to unexpected perturbations and design flaws.' As HOT systems adapt to anticipated stresses, new sensitivities or 'design flaws' are introduced – the intensification of production using fertilizers, for instance, introduces sensitivity to fluctuations in fertilizer cost. Janssen et al. (2007) refer to such shifts as 'robustness trade-offs', capturing the idea that shifting resources to adapt to one stressor necessarily leaves fewer resources to cope with other stressors. To illustrate what such a trade-off might be for many of the smaller farms in this study, I consider the case of diversification of crop production as a mode of intensification and an adaptation to a smaller property size.

Crop diversification is a means to reduce uncertainty associated with the yield of any one particular crop (Ellis 1993b). Yield is a function of a large number of factors (climate, soils, inputs, etc.), many of which average out to some extent over larger areas, making yield uncertainty a greater issue for smaller properties (Figure 3.1A). For these smaller properties, it can be beneficial to diversify production away from some revenue-maximizing product X and into other marketable commodities. In doing so, costs rise (additional seed, inputs, and labor to plant new crops in rotation or intercrop) and revenues may be reduced (new crops may be less lucrative than product X) (Figure 3.1B), so that the cash surplus for small farms above their basic needs may be reduced. However, thinking of this cash surplus as a dimension of their overall resilience to collapse, farms with diversified production become more resilient (less sensitive) to uncertainty in yield of product X, because their incomes now depend significantly upon other sources (Figure 3.1C). A similar argument as this for crop diversification may be constructed for dealing with price uncertainty in commodity X.

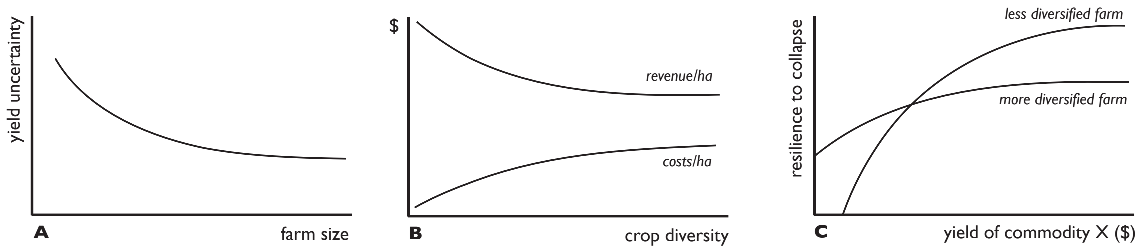

Figure 3.1: Diversification by farms to reduce vulnerability to yield uncertainty. A) Yield uncertainty is greater for smaller farms. B) Costs increase with additional inputs required for diverse crops, and revenues may drop as effort allocated away from profit-maximising product X. C) Resilience to collapse (in this case, revenues) is less sensitive to drops in yield of product X for more diversified farms.

However, this resilience to expected uncertainties in yields comes at a cost – production likely becomes more intensive, requiring additional labor and inputs, and allowing less land to lie in fallow at a given time. Thus, the intensified farm becomes sensitive to a new set of potential disturbances, such as shifts in the costs of labor or fertilizer.

The returns to intensification also have limits. Additional inputs of labor and chemicals yield diminishing returns even as costs may continue to smoothly increase (Figure 3.2A), and may eventually (as in the case of overfertilization) lead to additional costs or externalities. Further, the landscape itself may exhibit a threshold response to overuse (Scheffer et al. 2000), where degraded land must be significantly rehabilitated and intensity dropped well below previous levels of use before it can be productive again (Walker et al. 2004). Together, these economic and ecological constraints place upper boundaries on the extent to which farms can intensify. At the other end, intensity is bounded below by the household needs of the farm family. Such basic household needs can be expected to be similar across most farming households, meaning that farms with less land will need to intensify more than those with more land in order to meet those fixed minimal needs. Thusly, the lower bound on production intensity (to be a viable household) is higher for smaller properties than for larger ones.

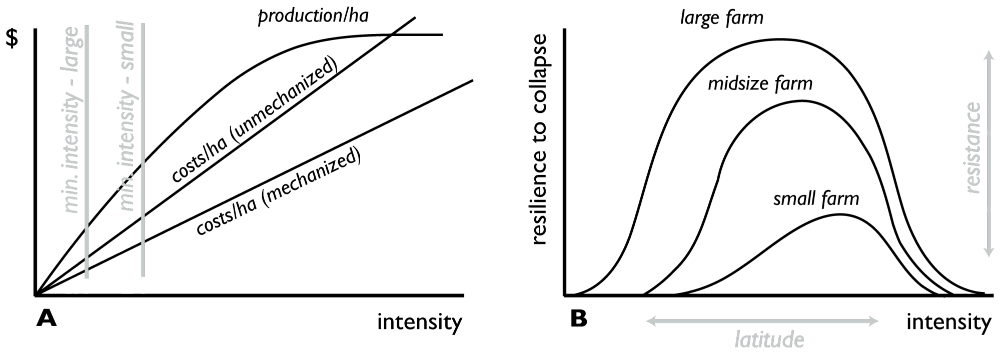

Figure 3.2: Resilience drops as a function of intensity. A) Returns to intensification (production/ha) diminish, and cost structures differ between small (unmechanized) and large (mechanized) farms. Differences in property size and costs mean that the lower bound on intensity (to meet basic household needs) will differ across farms of different sizes; Differences in costs may mean that the upper bound on intensification differs also. B) Smaller farms exhibit a narrower range of viability (latitude) with respect to intensity than larger farms, and lower resilience (resistance) to collapse.

The thrust of this argument is that not only is intensity necessarily higher for smaller properties, the range of intensities over which properties can remain viable is reduced for smaller properties and skewed toward higher intensity (Figure 3.2B). Further, the reduced surplus above basic household needs that smaller properties accumulate can mean a lower resilience to farm collapse overall relative to larger properties. In the language of Walker et al. (2004), smaller farms have both lower latitude (the width of the basin of attraction of a stable state; here, the range of intensity over which a farm can be viable) and lower resistance (the difficulty in shifting the system out of the basin of attraction; here, the financial surplus above and beyond basic household needs) to system change.

In sum, the adaptation to diversify production, to cope with expected uncertainty in yield, is one of several drivers that lock farmers into narrow ranges of production intensity. For such smaller farms, removing land from production may require them to operate in precarious positions near their upper bounds of intensity in order to meet household needs; these new conditions may in fact draw them out of the range in which their properties are viable and force them off the landscape. Intensification helps make these properties more robust to an expected set of disturbances – such as to yield uncertainty – but introduces new sensitivities to input prices (Janssen et al. 2007) while the cut in productive area simultaneously reduces their overall surplus and impacts their resilience to collapse. Thus, even where farmers are able to adapt to the licensing requirements by intensifying, their capacity to adapt to future stressors (some introduced by the intensification itself) will be reduced.

The following sections present empirical results from my sample in the Ji-Paraná River Basin that illustrate the shifts in diversity, intensity, and cost structure across farm size described above and examine their implications for rural livelihood security under LAPRO. Understanding these theoretical underpinnings of resilience and HOT on rural properties in the context of the Rondonian agricultural landscape is a critical part of any attempt to project what the outcomes of LAPRO might be.

METHODS

The study survey team conducted interviews with a sample of 234 smallholders across three municipalities – Ji-Paraná (72 interviews), Machadinho D'Oeste (88 interviews), and Cacoal (74 interviews) – in the Ji-Paraná River Basin between the months of February and April 2009. The survey was administered in partnership with the Federal University of Rondônia (UNIR) and the Rondonian agency for rural extension and technical assistance (EMATER-RO). Most interviews were solicited from smallholder producers visiting EMATER-RO local offices in each of the three municipalities, while a small number of the interviews were solicited from smallholders during EMATER public seminars and site visits. This gives a random sampling across family farm households who regularly interact with EMATER-RO, but excludes households that do not rely on rural extension services. If we can consider EMATER-RO to be important brokers of information regarding rural credit and agricultural techniques (Figure G.22), then our sample excludes family farms who have less access to this important information, skewing our sample to farms that may be slightly better off and giving a conservative estimate of how smaller farms may be negatively impacted by the licensing scheme. That is, to the extent that my arguments in this paper suggest that LAPRO will make production more difficult for smaller farmers, this will be even more true for the properties excluded from the sample that are not benefitting from EMATER-RO. Each interview took approximately one hour and respondents were asked a set of questions about their claim to their lands; their production and access to credit; their responses to climate and economic stresses; their use of information; and their understanding of various issues including global climate change as well as state and federal agricultural and water policy. Interview results were post-stratified for property size, and the results in this paper are presented in logarithmic bins for properties up to 15 ha, 30 ha, 60 ha, 120 ha, and properties larger than 120 ha in size.

Study Sites

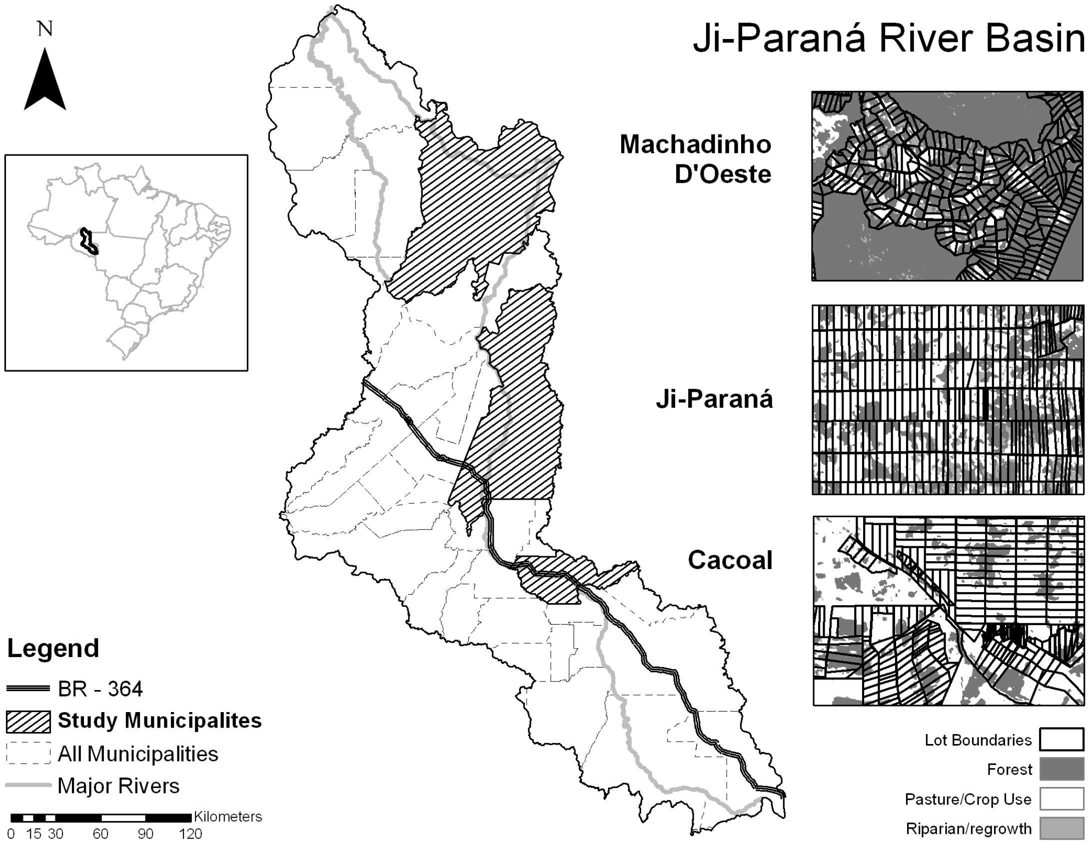

Figure 3.3: The Ji-Paraná River Basin. Study sites are indicated with a hatched pattern. Inset maps to the right illustrate lot delineation patterns characteristic of (from top to bottom) Machadinho, Ji-Paraná, and Cacoal, respectively.

The three sites were chosen to be as representative of the diversity of activities within the Ji-Paraná Basin as possible, subject to the constraint that research is not generally permitted in municipalities that lie within 150km of the border that Rondônia shares with Bolivia. The city of Ji-Paraná was founded as one of the posts for the telegraph line from Cuiabá to Porto Velho built in the period from the 1920s to 1940s (INCRA 2005). Today it is Rondônia's second most populous city and the most urbanized municipality in the basin. Ji-Parana's growth and development has been influenced both by the opening of the BR-364 highway in 1960 and by the implementation of official colonization projects beginning in the 1970s. It produces the most livestock and has the second-greatest crop production out of all municipalities in the state (IBGE 1996).

The other two sites, Machadinho and Cacoal, were the result of official colonization projects implemented both by the federal Institute for Colonization and Agrarian Reform (INCRA) and, to a lesser extent, by privately initiated colonization projects in the 1970s and 1980s (INCRA 1998). Benefiting from the existing infrastructure of the BR-364, Cacoal has grown to produce more crops – mainly coffee – than any of the other municipalities in the state, and has the second-largest livestock production (IBGE 1996).

Machadinho D'Oeste (henceforth Machadinho) lies farther from the belt of development that followed construction of the BR-364 and closer to what would be considered the Amazonian agricultural frontier. A much smaller and younger settlement than the other two sites, official colonization projects did not begin in Machadinho until 1982, as part of the World Bank-funded POLONOROESTE plan (EMBRAPA 2009).

Data Presentation

Drawing from the HOT farm model presented above, I look at a number of variables that signal farm resilience in order to understand where the Rondônia sample lies with respect to the HOT boundary. Specifically, I examine the intensity of production, cost and revenue structures, and past or future planned structural change. As indicators of intensity, I examine property size and land use, as well as the use of family and contracted labor, and the stocking density of cattle. I use herbicide costs and annual maintenance costs as indicators of cost structure, as well as the use of tractors as an indicator of mechanization. I calculate the raw value of production to indicate revenues, and as well calculate the entropy (Galtung 1980, Bailey 1983) in income as a measure of crop diversification. Finally, I examine past land sales, as well as future plans for land use change or expansion as indicators of farm structural change.

In the results that follow, I group data into logarithmically spaced bins and present them as vertical bars representing mean values or proportions. In some cases, data from each site are presented separately in groups. In other cases, several different variables are presented together on the same chart; in these cases, only the average data across all three sites is presented, for reasons of space, flow, and clarity. However, all data broken down by site along with basic statistics are tabulated in Appendix E.

The tags 'n', 'n_{JP}', 'n_{MA}', and 'n_{CA}' indicate the number of data points from which the bars across all three sites, for Ji-Paraná, for Machadinho, and for Cacoal, respectively, were derived. Where appropriate, a percentage in brackets indicates the proportion of the overall sample for that bin that was used, either because the particular question only applies to a subset of respondents, or because data were rejected. Data were rejected in cases where the response could not be understood or was missing.

Using size classes in bar charts is helpful to visualize differences in function across farm size and fits the qualitative analysis developed in the following sections, but is not statistically satisfying. In this study, I am attempting to demonstrate important shifts in farm characteristics that occur as a function of farm size, and to complement this narrative, the Pearson coefficients and p-values for the correlation between all variables presented in the following charts with property size are tabulated in Appendix F.

A complete set of results and discussion is included as Appendix G. In addition to the figures shown within this paper, Appendix G includes i) additional results not germane to the central arguments of the paper but which illustrate other interesting patterns across property size in the sample, and ii) results referenced in the main paper whose importance do not merit the space required for additional figures.

FARM CHARACTERISTICS

Property size and land use

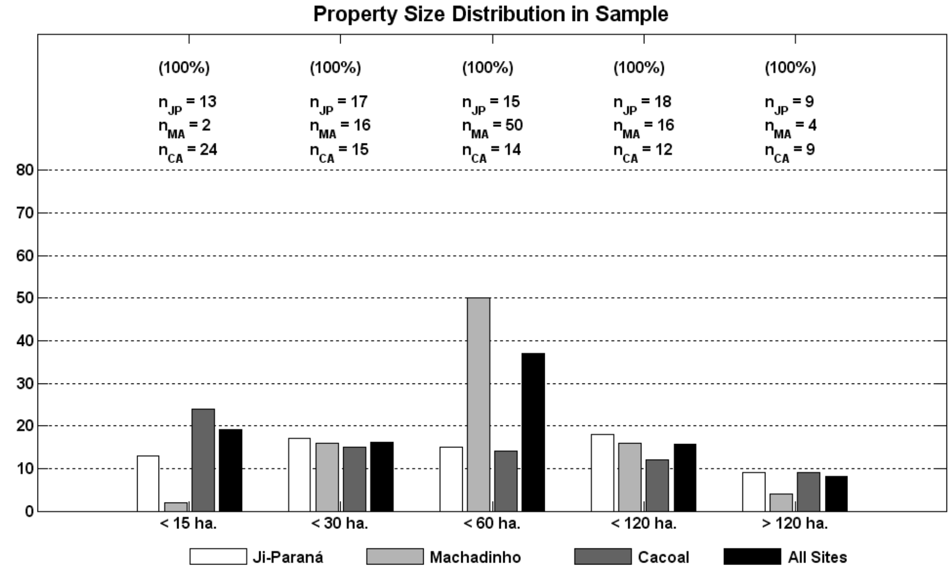

Figure 3.4: Property size distribution in sample. Bars show number of properties in each size class. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

The Ji-Paraná and Cacoal samples are fairly evenly distributed across size classes, while the distribution of the Machadinho sample is clustered much more tightly around the original lot allocation size for the Machadinho settlement of 50ha – less time has passed for land to be subdivided (Figure 3.4). Land use across scale is similar in all three sites, with cropland in smaller properties giving way to pasture land as property size increases (Figure 3.5). The amount of land in pasture across all size classes is greatest in Ji-Paraná, followed by Cacoal and then Machadinho (Appendix A). Land in forest increases with property size for all but the largest size class in the sample, and is higher in Machadinho than in the two older sites (Appendix A). Patterns of land use across the three sites fit the model of farm evolution observed by Muchagata and Brown (2003) in Marabá, Pará, with higher proportions of land in pasture and specialization in cattle on older and larger family farms.

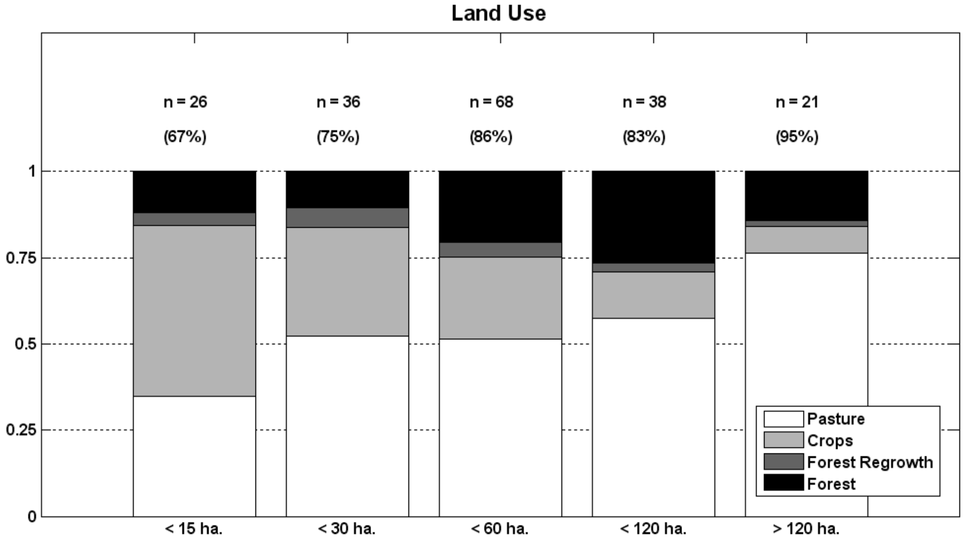

Figure 3.5: Trends in land use across property size, aggregated across all 3 sites. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

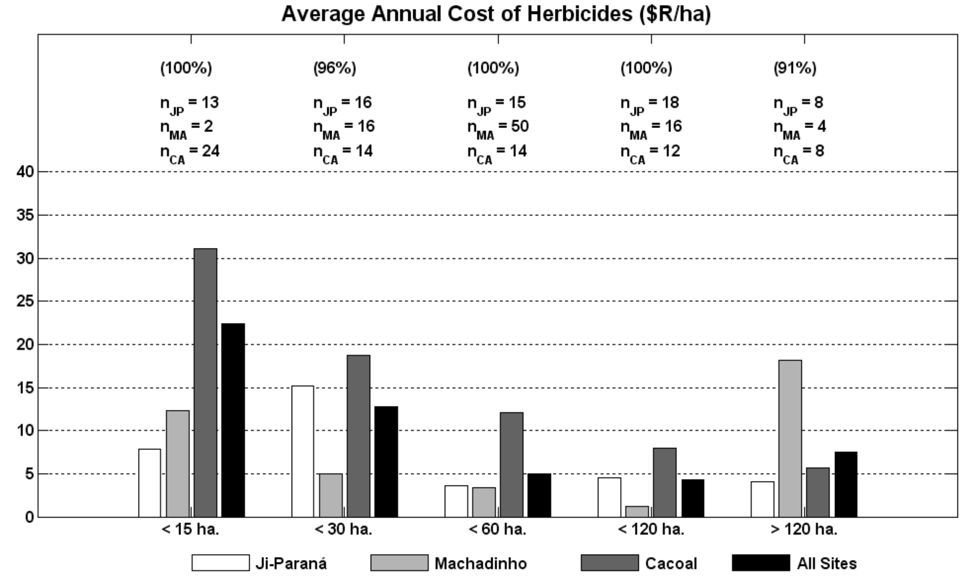

Figure 3.6: Average investment in herbicides per hectare, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Land-use intensity, measured by the per-hectare use of herbicides (whose use is most intense in coffee production in Cacoal) (Figure 3.6), and in overall annual maintenance costs (Figure 3.7), falls off as property sizes increase. The sharp rise in cost-intensity for small properties in Ji-Paraná is driven by a small number of urban chicken-rearers and horticulturalists whose capital- and input-intensive production systems are expensive to maintain.

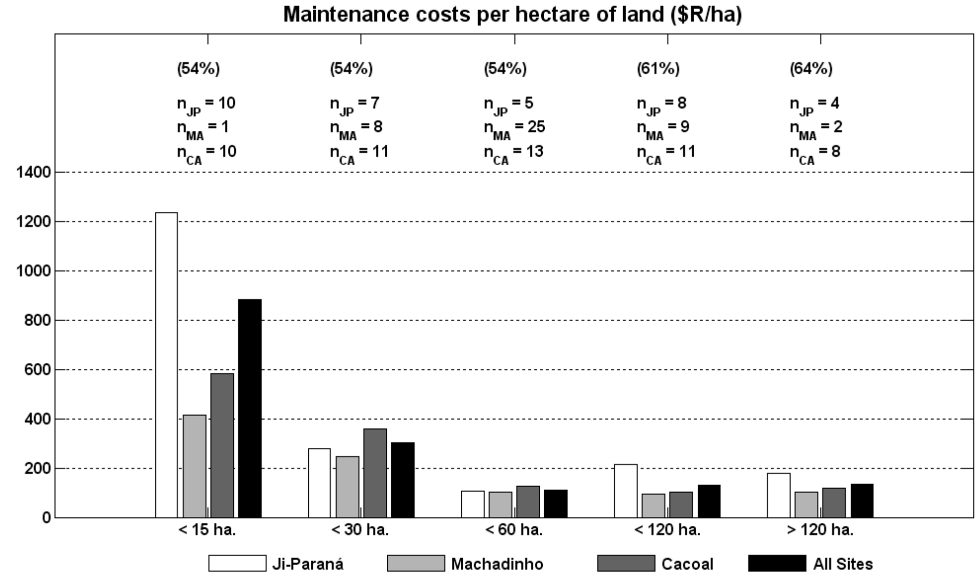

Figure 3.7: Maintenance cost per hectare, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Labor use

Labor-use intensity decreases with increasing property size (Figures 3.8, 3.9) which, together with the land-use intensity results in Figures 3.6 and 3.7, signals an underutilization of land and a shift away from it being a scarce resource for larger properties (Ellis 1993a). Comparing Figure 3.9 to Figure 3.8, the ratio of family labor to contracted labor decreases with increasing property size, reflecting the shift from peasant production toward a more market-integrated capitalist family enterprise.

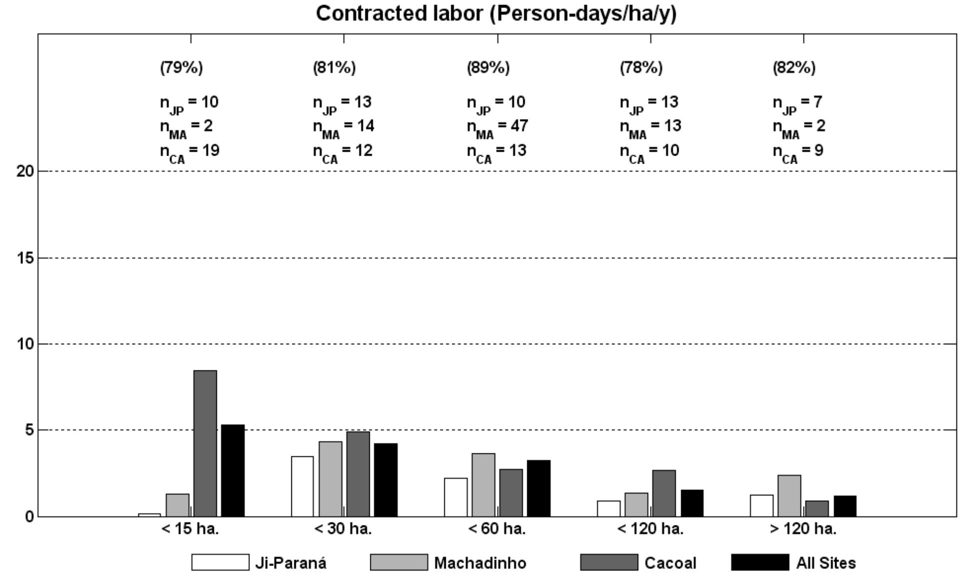

Figure 3.8: Person-days of contracted labor per hectare, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

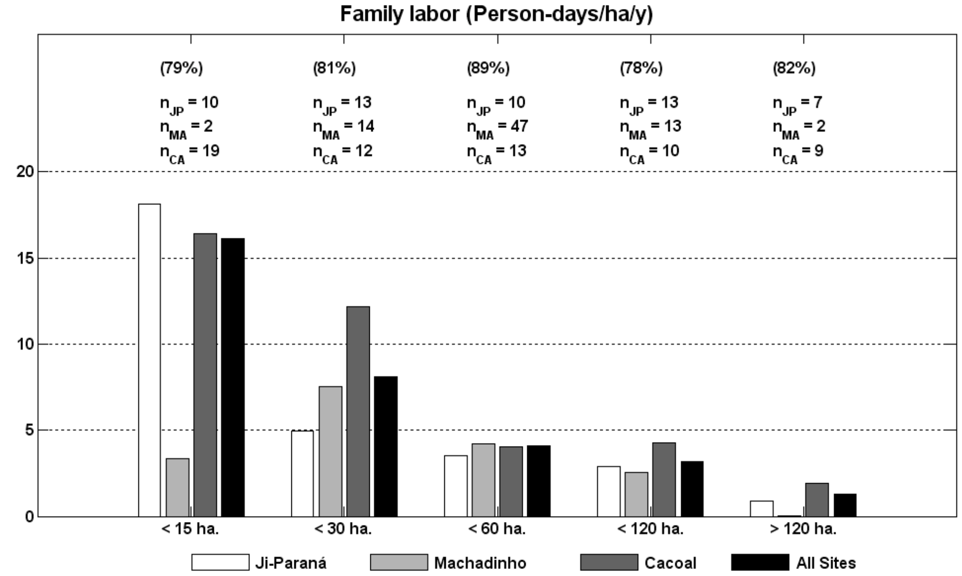

Figure 3.9: Person-days of family labor per hectare, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Farm production

The underutilization of land resources emerges again when looking at production as a function of farm size. The proportion of farms engaging in cattle ranching increases smoothly to encompass all properties above 120ha in size (Figure G.10), but the density of cattle (in head per hectare) is generally lower for larger properties (Figure 3.10). This is most clear in Ji-Paraná, where stocking densities drop from around 4 to around 2 head per hectare as property size increases.

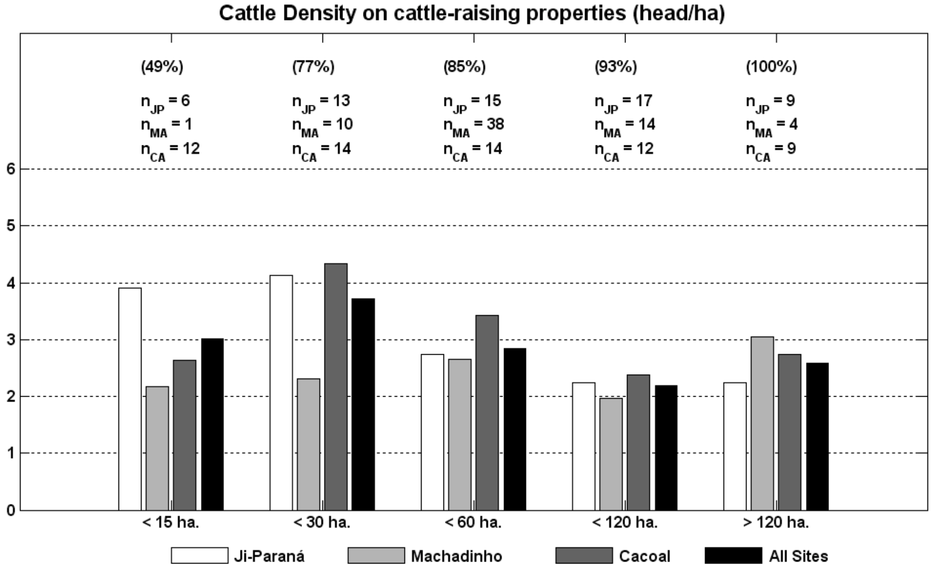

Figure 3.10: Cattle stocking density on cattle raising properties. Percent refers to the percent of surveys in each size class reporting the raising of cattle; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

In general, production intensity decreases as farms increase in size. The raw value of production (VOP) is calculated here as the sum of farm production multiplied through by each product's per-unit economic value:

$$VOP = \sum_i M_i \cdot P_i$$

where M_i and P_i are the mass produced and per-unit price for product i. The per-unit price is estimated here as the average of the stated per-unit price reported by farmers across the sample. VOP per hectare in the sample are highest for Ji-Paraná and Cacoal, with Machadinho a distant third (Figure 3.11).

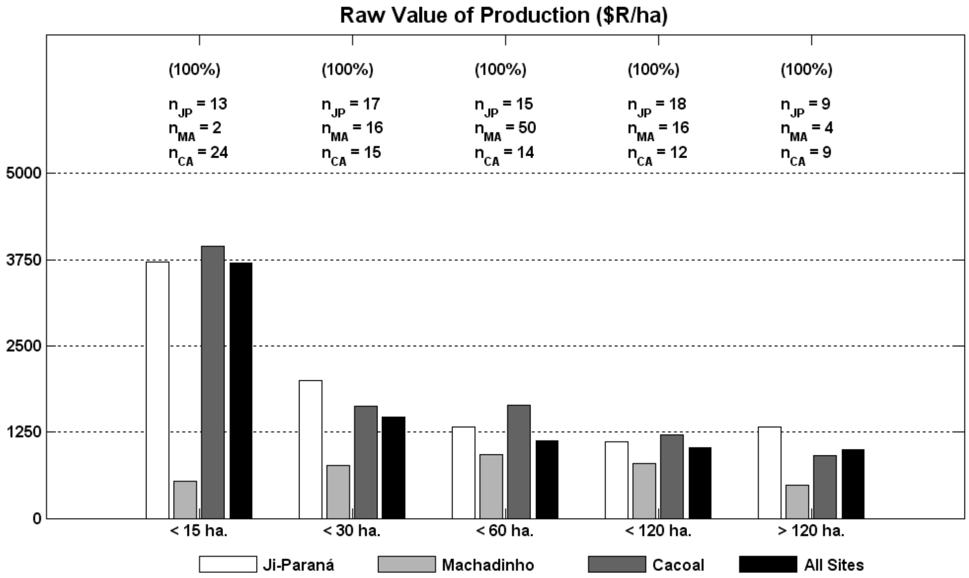

Figure 3.11: Raw value of production in $R/ha. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Income diversification

I measure diversity in farm income as the income entropy *E*:

$$E = -\sum_i f_i \cdot \ln(f_i)$$

where f_i is the fraction of farm income derived from source *i*. Borrowed from its origins in thermodynamics (Rechberger 2001, Rechberger and Graedel 2002, Kaufman et al. 2008), entropy has been used in social science research as a measure of uncertainty (Bailey 1983, Gill 2005); of flexibility (Shuiabi et al. 2005); of inequality (Allison 1978); and, as I use it here, of diversity (Galtung 1980). The income entropy measure *E* is equal to 0 when all income is derived from a single source, and is maximized when income is derived equally from a large number of sources. For example, when income is derived in equal parts from two different sources, $E = 0.69$, and when derived in equal parts from ten different sources, $E = 2.3$. Income entropy in Machadinho declines smoothly with increasing farm size, while Ji-Paraná and Cacoal both show single-peaked distributions for income entropy across farm size (Figure 3.12), and a drop in income diversity for the smallest size class. As mentioned above, some of the very small properties in these classes are urban horticulturalists, operating small, specialized operations that irrigate from river water and grow in greenhouses to supply labor- and water-intensive products like salad greens; others are capital intensive chick-hatching and chicken-raising operations. These examples of specialization at small scales highlight the departure that agriculture can take, once an area is sufficiently urban, from models like that of Muchagata and Brown (2003), where specialization follows an accumulation of property.

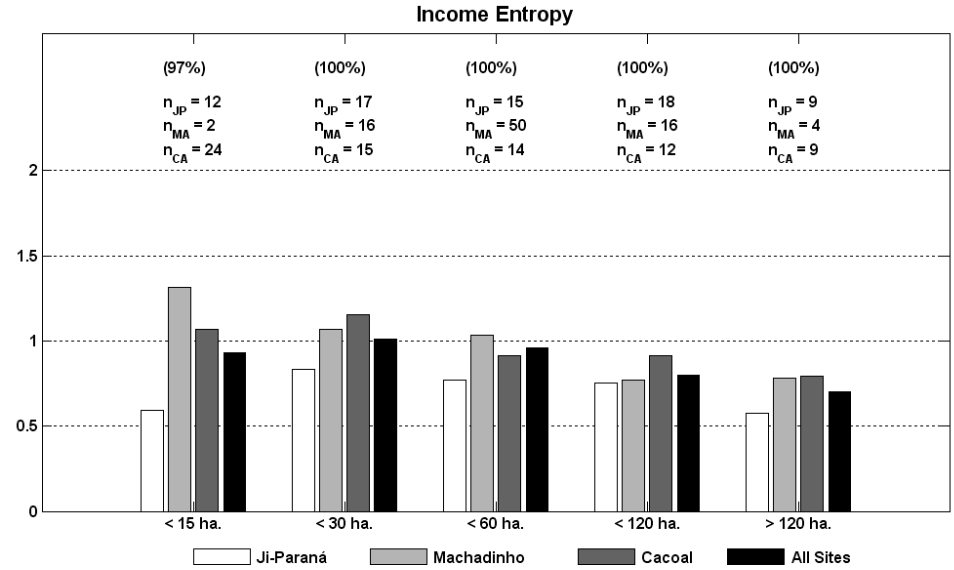

Figure 3.12: Income entropy. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Technology

I look at the use and ownership of tractors as indicators of the use of technology and capitalization on farms. Across all three sites, while ownership of tractors is largely restricted to larger landholders, use of these technologies is relatively constant across farm size for farms greater than 30ha in size (Figure 3.13). Personal relationships between farmers as well as membership in local rural associations and syndicates provide access to farmers to rent or borrow farm equipment, and help smaller farms to behave like larger properties with respect to their use of technologies such as tractors. Put differently, network ties and the ability to share equipment reduces the diseconomy associated with bringing expensive big machines to small farms (Ellis 1993a).

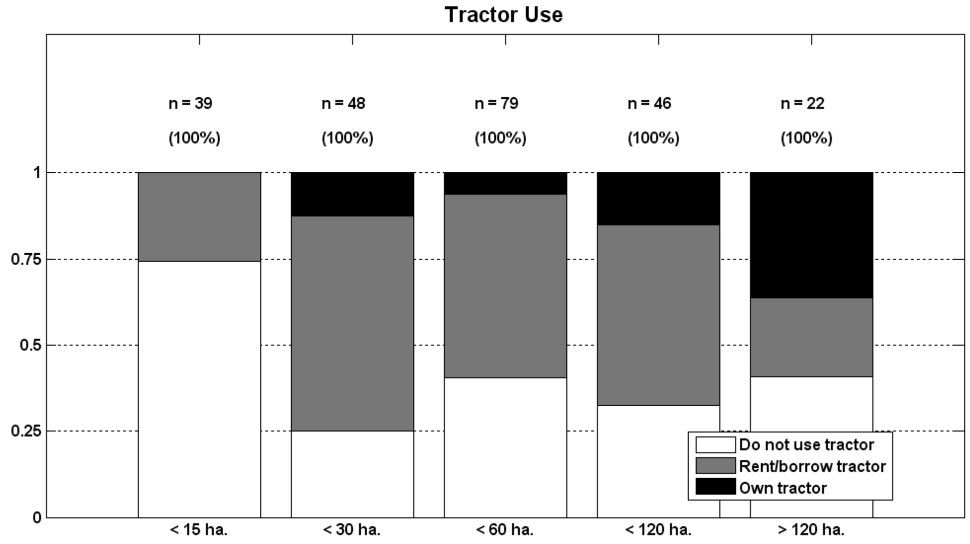

Figure 3.13: Tractor use. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

The way in which tractors affect production is a contentious topic in the rural economics literature, with two prevailing views dominating the discussion (Ellis 1993c). The substitution view argues that tractors simply substitute for animal and human labor without increasing yields or lowering costs; the net contribution view holds that tractors lead to a net increase in yields by making more land usable and allowing for more timely preparation of land, among other factors (Ellis 1993c). Ellis (1993) reviews the literature to find that tractors contribute little to net productivity in most developing countries, suggesting that the substitution view explains better the role of tractors in these areas, but this result is not borne out in these data. The minority of farmers on properties up to 60ha in size in the sample who own tractors report higher labor use as well as higher value of production relative to other farmers in the same size classes who rent, borrow, or do not report using a tractor (see Figures G.19, G.20). This paints a picture, within a size class of farm where production is already intense relative to larger farms, of a minority of well-capitalized farms where production is even more intensive.

Property division and aggregation

The purchase or sale of land holdings is an important indicator of socio-economic stratification in rural households (Browder et al. 2008). In the sample, the pattern of land consolidation suggests an archetypal 'success to the successful' behavior – the bigger the property, the more likely that it had augmented its holdings through land purchase (Figure 3.14). Few properties report having sold land, but this is misleading. Because subdivision of an already small holding is unlikely to help a farmer in the long term, we would expect land sale to often be a last resort and result in the sale of the entire property for properties in smaller size classes. Such farmers would leave the sample frame, and these transactions would not appear.

Figure 3.14: Proportion of properties in the sample having bought or sold land. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

The number of sale transactions is low (30 total) and trends across property size are not readily discernible (Figure 3.15). The reasons given for selling portions of land vary and include the need to cover a debt or pay for care during an illness (27%), the desire to invest in capital (27%) or other land holdings (10%), or the subdivision of properties within family due to inheritance or divorce (23%). In a longitudinal study from 1992 to 2002 in three other municipalities local to the BR-364 within the sate, Browder et al.

(2008) found family ‘life-cycle’ reasons to be the dominant explanation for property subdivision, indicating the passage between a first generation of frontier settlers and their children or unrelated second generation farmers. That life-cycle reasons are not the most significant factor in this study may be an indicator that this generational transition is now passing.

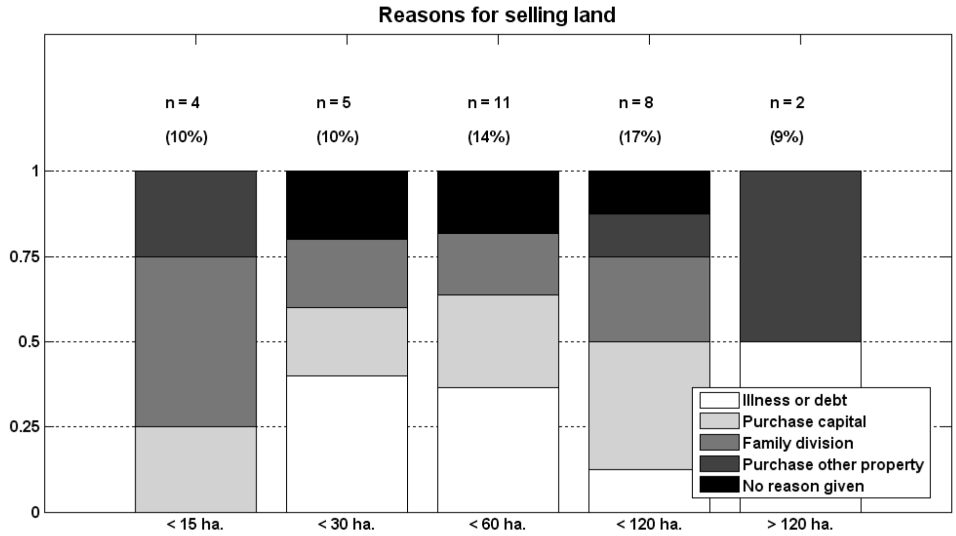

Figure 3.15: Reasons given for past sales of land. Percent refers to the percent of surveys in each size class reporting having sold land; n is the number of surveys used.

Future farm goals

Very broadly, future plans for landholdings can first be classed into plans to expand, and plans to make better or different use of currently held land (Figure 3.16). In this sample, the proportion of properties with plans to improve or intensify use of their current holdings increases smoothly with property size up to 120ha, following the same smooth decline in current land- and labor-use intensity observed earlier. Plans to intensify are markedly lower in larger properties. Plans to expand holdings are higher in very small (< 15ha) properties, suggesting a desire to move beyond a threshold endowment of land resources, and in very large (> 120ha) properties.

Taken together, these results for land-use and expansion goals suggest the existence of a 'basin of attraction' for the size of a family farm, between about 30 and 120ha in size, that reflects the scale most appropriate for a family-managed farming unit in the post-frontier region where access to new land is restricted. Smaller properties have endowments insufficient to meet household needs and attempt to grow; properties at the upper boundary in size focus more on improving existing holdings without looking to expand. The results observed for properties larger than 120ha in size suggest other basins of attraction at greater scales that reflect better scales for the operation of larger capitalist enterprises and agribusinesses. Thus, sufficiently large and prosperous family farms may find themselves in positions to choose between staying within a family production model, and leaving that attractor to transition into a larger business venture.

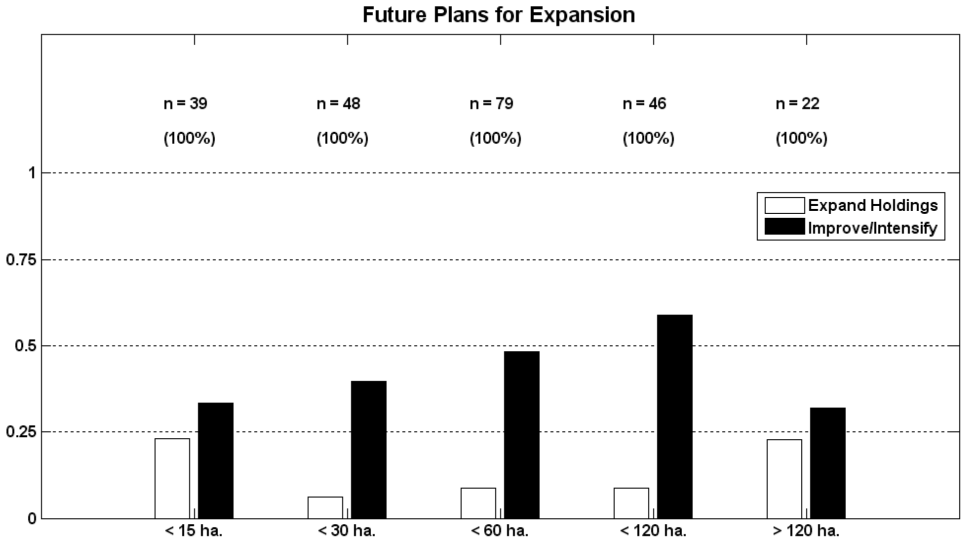

Figure 3.16: Future plans for farm expansion and improvement. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

Within plans for intensification and improvement, some clear differences across farm size can be observed (Figure 3.17). While it is a common goal among all but the smallest properties to invest more in cattle ranching, the desire to invest more into crop production drops off sharply for properties larger than 60ha in size. Only large family properties, perhaps conscious of their greater visibility in the face of the new licensing program, and belying the smaller fractions of their land that are actively held in production, express a significant desire to reforest on their properties. While few producers in the sample actively produce fish, the building of dams and reservoirs and investment in aquaculture appears to be a common goal among larger properties in the sample. Fish production may thus grow in the region as a capital-intensive, non-labor intensive, lower risk activity alongside the raising of other livestock.

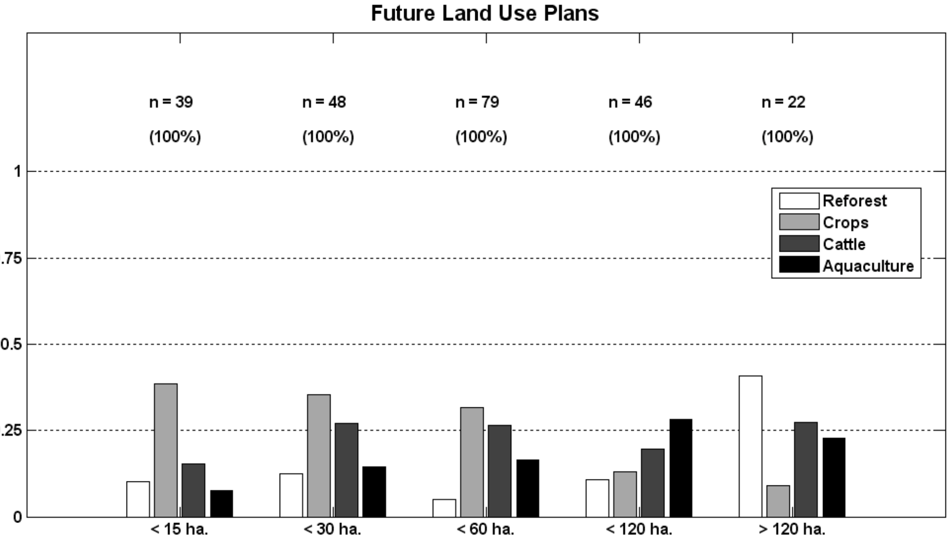

Figure 3.17: Plans for land improvement on land. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

IMPLICATIONS FOR ENVIRONMENTAL LICENSING

My results demonstrate a marked difference in farm characteristics between farms smaller than 60ha in size, and farms greater than 60ha in size. Farms smaller than 60ha in size commit more land to annuals and perennials, and maintain plans to expand these crops further. These small properties use agricultural inputs more intensively, and spend more per hectare on maintenance and labor. Cattle are herded more densely, and production is markedly higher and more diverse. Larger properties show a focus more on cattle, and plans to expand cattle and aquaculture; properties larger than 120ha in size show a notably greater interest in reforesting their land.

These results have a number of implications for the LAPRO program. Firstly, properties larger than 120ha in size self-report a greater willingness to reforest their land, while few properties smaller than 120ha in size report plans to reforest. This may reflect awareness that they cannot easily maintain their outputs on less land, since their use of land resources is already quite intensive, particularly for properties smaller than 60ha in size. Secondly, the results confirm significant shifts in production intensity for smaller properties in the sample, and across scales relevant for the licensing process (between 1 and 2 fiscal modules of 60ha).

To the extent that the current patterns across scale indicate what might happen as land is pulled out of production (e.g., the current production pattern on properties 30ha in size as indicators of how farms 60ha in size might behave as land is pulled out of production), we can speculate that production intensity will increase, and as this occurs, these farms will rely more heavily on agricultural inputs and labor, introducing greater sensitivity to shifts in input prices and bringing their land closer to ecological constraints on production. My empirical data do not show us how much further farms could potentially intensify, so I am unable to make claims about which farms would simply become unviable under LAPRO, although the increased desire to expand holdings for farms below 15ha in size may reflect a threshold below which it is quite difficult to meet basic needs. We can also note that the clear trends in production and land-use intensity across farm size tell us that all farms that remain viable will be brought closer to the HOT boundary. Given uncertainty associated with future climate change, as well as with future markets for agricultural production (beef, soy, coffee, etc.), the introduction of new sensitivities and an associated increase in the vulnerability of these rural livelihoods to stresses is an important point of consideration in the LAPRO process, worthy of further investigation and analysis.

Having examined the potential consequences of the well-implemented case, the extent to which behavior will shift under LAPRO needs to be carefully considered. Having less access to productive land does not translate directly into having a smaller farm – the structure of existing social networks as well as existing capital investments on the property will not change. Because livestock, particularly cattle, are regarded as a means of storing wealth and a step above the drudgery and risk of maintaining crops (Muchagata and Brown 2003), we would not necessarily expect farmers to re-diversify into annuals and perennials, as some of the empirical data on the use of land on smaller properties within this sample would suggest. Rather, we might expect the more labor- and input-intensive cropland to be given up and reforested, with the result being a local economy more specialized in cattle rearing than before. In this case, we would expect to see a rise in cattle density per hectare to help make up some of the lost income, and pastures pushed closer to their productive limit, introducing greater sensitivity to climate and grass production.

Environmental and social externalities

The increase in land-use intensity observed in smaller properties in our sample is accompanied by an increase in the intensity of agro-toxin application, including herbicides and chemical fertilizers (Figure 3.6); 'sustainable' farming methods are not yet typical in the region (Caviglia-Harris 2003). Increased cattle densities in pastures reduced in size will require more inputs, and any increased compaction of the soil will increase overland flow during the strong rains that characterize the region. Thus, the increase in legal reserve and riparian cover may also bring an increase in pollutant inputs to surface waters, negating some of the environmental goals the licensing scheme aims to achieve. An additional point to consider is that, looking at work in *mutirão* volunteer work groups (see Figures G.27, G.28 in Appendix G), there is a pattern that suggests larger property holders volunteer their time to assist smaller property holders. The increased demands placed on these same farmers as they intensify production may reduce their ability to contribute to *mutirão* efforts and disrupt an important exchange of labor. In general, having less land to generate an income from will make farming less profitable for many, and may make it difficult for some farms to meet household needs, leading to an increase in the sale of land parcels as farmers attempt to cover debts or opt simply to put farming behind them.

As an additional environmental externality, LAPRO has potential to causally flip the argument for land use intensification as a means to reduce deforestation rates. The validity of programs that push farmers to intensify land use to reduce deforestation has been questioned since intensification raises the productive value of farming which can attract more farmers to the region and perversely drive up deforestation (Caviglia-Harris 2005) – a hardening of demand for agricultural land. It will be interesting to observe whether the intensification driven by forced reforestation within LAPRO will draw more farmers to the region, or force resident farmers out.

Assessing real responses to licensing

Finally, it is important to be critical of our assumption implicit in the previous analysis that the licensing system will be well implemented and enforced. To be effective, the system will require 1) effective monitoring of the rural properties to ensure that land cover on the property is following the agreed-upon management plan, and 2) that there is proper incentive, available only to licensees, to encourage farmers to enroll and participate. It is not clear how the former will be accomplished; while near real-time detection of deforestation is possible in Amazonia (Shimabukuro et al. 2006), following up with rural properties on the ground would require resources that SEDAM likely does not have. The latter will be achieved initially by restricting access to rural credit only to properties in possession of a license; later, only licensees will be able to sell their production (i.e., to slaughterhouses). In this sample, less than half of properties had ever received any form of rural credit (Figure 3.18), suggesting that access to credit might not be a universal incentive. Those who receive credit, however, may be the more important targets for licensing, as access to credit has previously been linked with higher levels of deforestation (Wood et al. 2001, Caviglia-Harris 2004). At the time of the current study, only a small fraction of properties in our sample had registered for the LAPRO program, and it is not clear that the remaining properties intend to register soon, if at all. Among smaller properties, a perception that they were not required to register was common, as well as a lack of the required titling documents to do so. Both the smallest and the largest size classes in this sample cited a lack of information about the program as a reason for not registering, suggesting a lack of access to information in the case of the small properties, and possibly a lack of clear explanation on behalf of SEDAM of exactly what would be required in the case of the larger properties. While preliminary, this evidence does not indicate that the licensing program is on track to being comprehensive of rural properties in the region.

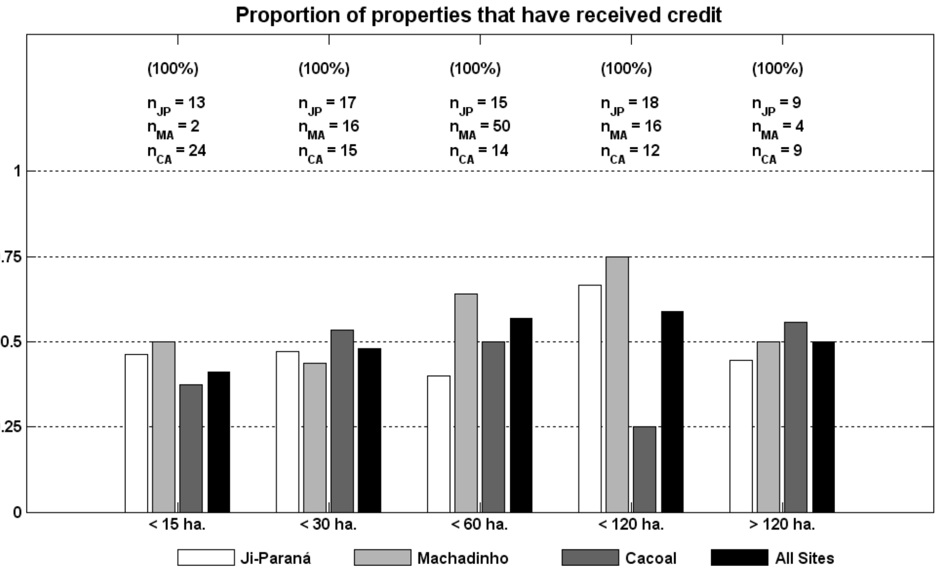

Figure 3.18: Proportion of properties in the sample having received credit in the past. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

In summary, if implemented fully, LAPRO has the potential to drive some farmers out of production, focus the local economy more on low-risk production of cattle, and intensify production in a way that may erode some of the potential gains in environmental quality. However, how fully it can be implemented remains to be seen.

The data presented in this study illustrate that the shifts in production efficiency and strategies for avoiding risk discussed in rural economics literature are relevant within the range of property sizes classed as small family agriculture in Amazonia. Some of the potential adverse impacts of LAPRO on livelihoods, particularly for smaller properties where production is already very intensive, might be avoidable through a tiered system of the type that is currently being proposed by a number of farmers' groups.

CONCLUSIONS

My primary research conducted in Ji-Paraná, Rondônia, showed that production intensity on rural properties decreased with increasing property size in the sample, coupled with decreasing contracted and family labor-use intensity, and decreased income diversification. Ownership of large equipment such as tractors rose with property size, although access to these machines was relatively constant across size classes. A pattern of land consolidation in the region is evident in the sample, with the settlement of debts or illnesses being given alongside life-cycle reasons as motivations for farmers to sell their lands.

Plans to intensify land use overshadow plans to expand in the land-scarce post-frontier, with investment in crops a common goal in smaller properties, investment in cattle a goal shared by all but the smallest properties, and the desire to reforest a luxury shared only among the larger properties in the sample. A goal more common with increasing property size is the installation of aquaculture.

For the smaller properties where production is more intense, further intensification to make up the income gap when half of the property is committed to forest may be difficult; intensification on larger properties may occur but will likely require significant additional agricultural inputs, perhaps compromising some of the environmental goals of the licensing scheme. A risk introduced by the licensing scheme is that it will impede the ability of smaller properties (less than 60ha in size) – demonstrated in the data in this study to differ markedly from those larger – to meet their basic needs; meeting the licensing requirements may lead to an increase in the sale of land parcels to cover debts and a speeding up of land consolidation in the region. Using Carson and Doyle's (1999) highly-optimized tolerance framework, these smaller farms, while resilient to expected disturbances in price and yield, may become fragile to shifts in other disturbances, such as input costs, as they intensify in response to the initially unexpected removal of significant land from production. To the extent that it could drive small farmers off of the agricultural landscape, the environmental licensing scheme will achieve environmental gains at the expense of some of the initial social goals of Amazonian colonization, to provide livelihoods to the landless. In other words, the attempt to improve the system with a policy intervention may in fact 'undermine its ability to cope with change and maintain its structure and function' (Janssen et al. 2007). In this, the Rondônian case is a good example of the challenge faced by decision makers of today and the future, armed with better understandings of socio-ecological systems and sustainability, trying to deal with the legacies of policy put in place by decision makers of the past, who had not necessarily benefited from or made use of such knowledge.

It should be noted that the outcomes of the licensing program – planned results and any adverse impacts – depend on an adequate program of monitoring and enforcement to be realized, and it is not clear from our sample that the initial incentive – access to rural credit – will reach a comprehensive majority of properties in the region. Should the scheme be implemented in such a way that farmers are motivated to follow its requirements, and if the social goals of providing livelihoods for the colonists that have come to the region remain, a tiered licensing proposal that relaxes requirements for smaller properties is worthy of consideration and further study.

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Chapter 4

Environmental Licensing and Rural Exodus: An agent-based approach to understanding ranching and land use in rural Rondônia

ABSTRACT

Agricultural development and climate change will be two of the major stressors on the Amazon natural-human system in the decades to come. Environmental licensing for rural properties is being implemented in several states in the Brazilian Amazon with the goal of restoring forests in agricultural landscapes and mediating the impacts of these stressors. We develop an agent-based model of ranching and land exchange, inform it with empirical results from social research in the Ji-Paraná River Basin, Rondônia, Brazil, and investigate the social, economic, and environmental outcomes that can be expected as a result of environmental licensing in the context of climate change. Our empirical data reveal differences in the capacities and strategies of ranches of different sizes to produce crops and raise animals. Model results informed by these data suggest that while an environmental licensing scheme with monitoring and enforcement may increase the level of forested land in ranching landscapes, it may do so at the expense of the small producer. To the extent that effective monitoring and enforcement exist, a focus on larger holdings will help to mediate this negative social impact. These results suggest that a middle ground can be found in cases where current environmental goals conflict with legacies of past colonization and resource-use regimes.

INTRODUCTION

Two major stressors on the Amazon natural-human system are an advancing frontier of agricultural development and global climate change. The agricultural frontier – driven into the Amazon by aggressive colonization policy in the 1970s, waves of migration of poor landless peasants, and growing domestic markets for beef and international markets for soy (Simon and Garagorry 2005) – threatens the Amazon system by clearing trees, destroying habitat, polluting water, and displacing indigenous peoples. In regions along the frontier, the presence of roads and land speculation are commonly cited as the major proximate drivers of land-use change (Faminow 1997, Caviglia-Harris 2004, Soares et al. 2004). Where access is created, small and large farms alike claim new land far from current markets in the expectation that further frontier expansion will drive up the land's value, though this 'dragging effect' (Fearnside 2007) has been demonstrated to be most strong when moderate levels of local infrastructure already exist (Pfaff 1999, Pfaff et al. 2007). Behind the advancing frontier, where most land parcels have been claimed or allocated, the conversion of forest into agricultural use or disuse is in the hands of the property owner. Environmental licensing for rural properties is emerging in several Brazilian Amazon states as a means of regulating land use on active agricultural properties (Lima et al. 2005, ambientebrasil 2010). However, the ability or willingness of a rural producer to maintain forested lands on his or her property may depend strongly on cost structure and the ability to turn a profit from the remaining productive land, which in turn is a function of farm size (Ellis 1993). This is a constraint for any attempts to regulate land use in the region, since for smaller properties, stringent environmental regulations may mean either an inability to comply, or an inability to remain in production.

The Amazon Region is expected to be affected in the coming decades by climate change. Simulation results from the most recent IPCC report in 2007 suggest it will be warmer, and probably drier, and there is an expected rise in the frequency of extreme weather events – longer droughts and stronger storms (Magrin et al. 2007). One impact, on large and small farmers alike, will be to make agricultural activity (like raising cattle on pasture) more expensive as vegetation growth is negatively affected. By simultaneously restricting the area of, and reducing the productivity by, active agricultural land, the joint stressors of environmental licensing and climate change have the potential to pressure production in the rural Amazon.

This study develops an agent-based model of a ranching landscape to investigate the potential social, economic, and environmental outcomes of a new environmental licensing scheme being implemented in the state of Rondônia, under the additional stressor of a change in climate. Agent-based analysis of changes in farm structure is a relatively new field of research (Zimmermann et al. 2009), and the model in this study incorporates features of particular relevance to the Amazonian context – land sale by struggling farmers, and climate variability – that have not appeared in other agent-based approaches to farm change. The coupled model of ranching and climate asks whether the joint pressures of licensing and a changed cost structure due to climate change will act to force producers on small properties off of their land, and whether this social impact can be mediated while still achieving landscape-scale land-use goals.

I find that environmental goals *can* be harmonized with social and economic goals in the ranching landscape, but that this will require particular care in implementation, with monitoring programs that emphasize larger properties. We expect the current work to be of value both to the nascent literature on agent-based approaches to analyzing rural policy, and to the broader discussion within natural resource management of how, in a socially just manner, to match today's goals for environmental and ecological services with the legacies of colonization and resource-exploitation regimes of the past.

BACKGROUND

Ranching and Environmental Licensing

This study focuses within the agricultural community on ranching, the dominant agricultural land use in Rondônia (5,000,000 ha of pasture compared to only 500,000 ha of cropland in 2006 (IBGE 2006)). The rates of land-use change across properties of different sizes in Amazônia tends to be different, with smaller plots needing to deforest proportionally more of their lots than larger plots in order to meet needs (Aldrich et al. 2006, D'Antona et al. 2006). There is a broad distribution of property size in Rondônia, with nearly 30 properties greater than 2000 ha in size declared in the 1996 Census, along with more than 15,000 properties smaller than 100 ha and hundreds in between (IBGE 1996). There is also a slow process of land aggregation in the Amazon, with many smaller ranchers selling land to meet financial obligations (D'Antona et al. 2006). If climate change affects the profitability of ranching activity, it is reasonable to expect that there will be some impact on the extent of land sale among ranchers. To the extent that ranchers operating at different scales of production deforest at different rates and maintain their land in different ways (Ewers and Laurance 2006), it is reasonable to expect that changes in land distribution will affect environmental outcomes beyond the direct impacts brought about by an increase in storms and droughts.

To confront the environmental problems brought about by land-use change, the state environmental secretary SEDAM-RO is following other states in the Amazon region in implementing a program of environmental licensing for rural properties (LAPRO) (SEDAM-RO 2008). At present, in order to obtain any form of rural credit from Brazilian banks, properties must obtain an environmental license, or for some smaller properties, simply declare that their properties are in accordance with law. Eventually, SEDAM-RO plans to close off access to markets for those properties not licensed. To obtain a license, rural properties must generate a management plan for recuperation of forests over a 30-year period in areas of permanent preservation (APP) – including riparian buffer strips along all watercourses and forests on all steep hill slopes – and legal reserve (LR).

The requirements for LR are a point of tension for SEDAM-RO – under LAPRO, properties with less than 50% of land in LR prior to 1998 must recuperate up to 50% within the 30-year period. In contrast, properties wishing to clear new land on properties that was forested as of 2005 must maintain 80% of the land as LR, a move that clearly favors those who have already committed infractions. Further, to many, the requirements of LAPRO feel like a complete reversal by the state – while on paper the Federal Forest Code has long required rural properties to maintain 50% of their land as LR, in practice, colonization policies that brought many farmers to the region in the 1970s and 80s rewarded those who added value to their land by clearing it (Hecht and Cockburn 1989, Fearnside 2001). For large cattle ranchers not currently possessing 50% LR, licensing will mean a big drop in income; for many smaller family properties, licensing that requires proportionally the same from them as from large properties may mean their properties will become unviable as the sole sources of income to maintain the household. While a number of activities implementing agroforestry systems (SAF) are permitted within APP and LR – including rubber, açai palm, and coffee – there is no guarantee that many of these small farmers have the resources or skills to switch to these activities, or that markets will support them.

A number of proposals have arisen recently to try to minimize the way in which LAPRO will affect the small farmer (Amazônia 2009). One proposal being put forward by several organizations in the state proposes a modification to the Forest Code such that:

i. All farms up to 1 fiscal module (60 hectares) in size would be required to restore riparian forests along watercourses.

ii. All farms between 1 and 2 fiscal modules (120 hectares) in size would be required to restore riparian forests along watercourses and maintain 20% of the property in legal reserve forest.

iii. All farms greater than 2 fiscal modules in size (>120 hectares) would be required to restore riparian forests along watercourses and maintain 50% of the property in legal reserve forest (de Jesus 2009).

The goal of this paper is to investigate the ways in which climate change and LAPRO will affect environmental quality, measured through the fraction of land that is forested; the profitability of ranching in the region, measured by the average profit earned per hectare of property per year; and social equity, measured by distribution of land among farmers. Additionally, this paper will investigate the ways in which modification of the

Forest Code or LAPRO may shift how small farmers are affected by licensing requirements. While programs like LAPRO may help to restore critical environmental services in rural areas, it is important to consider in detail the burdens that they place on rural production.

This paper tests the following hypotheses, regarding the impacts of climate change and environmental licensing on the rancher-water coupled natural-human system:

H1: Decreases in precipitation will drive increased rates of land aggregation

H2: Environmental licensing will lead to better environmental outcomes

H3: Reduced access to markets through environmental licensing will drive increased rates of land aggregation

H4: Reduced licensing requirements for small properties will lead to lower rates of land aggregation

Agent-based modeling in agriculture – filling a current gap

Agent-based approaches to looking at farm production and change are yet relatively uncommon, and there is only one model in the literature that has specifically been applied to looking at the kinds of farm structural change that are a focus of this paper (Zimmermann et al. 2009). The AgriPoliS model of Happe et al. is a sophisticated agent-based approach to rural economics problems that allows farmer agents to make technological and structural change to their farms by purchasing equipment and renting additional plots, and to make land-use choices in response to shifts in policy, prices and costs (Happe et al. 2006). Developed to look at European (with particular attention to German) agriculture, AgriPoliS has been applied to several policy-relevant issues in common with the current study – the effect of a switch in policy regime on farm structure (Happe et al. 2005), and the factors that may cause farmers to leave the agricultural landscape (Happe et al. 2009).

However, AgriPoliS lacks the capacity to model several of the features that characterize the Amazonian frontier and post-frontier agricultural landscapes. Firstly, while land rental does occur, land purchase and aggregation under successful farmers is much more common than in the European context for which AgriPoliS was developed. Secondly, climate variability (one of the focal stressors in the current study) is an important decision-making factor for local farmers, and strongly shapes the productive capacity of pastures for cattle. Most ranchers in our sample reported using pasture conditions rather than market prices as the primary decision factor in stocking pasture. A model of the Rondônian post-frontier ranch landscape must incorporate the local practice of selling off land parcels to cover financial needs, as well as the link between climate, pasture productivity, and rancher decision-making. The model developed for this study fills this particular gap.

METHODS

This study employs an agent-based model of a ranching landscape, informed by and validated through survey data collected as part of the project "Águas Limpas num Clima Incerto" (Clean Waters in an Uncertain Climate) from February to April 2009. The survey was applied to a sample of 241 small to medium cattle producers (up to 320 hectares in size) from three municipalities (Ji-Paraná, Cacoal, and Machadinho do Oeste) in the Ji-Paraná River Basin in Rondônia, Brazil (Figure 4.1). The sample was generated by interviewing farmers as they visited local offices of the state agency for rural extension services, EMATER-RO, and was post-stratified for size. Rondônia boasts the most intensive agricultural production of the Amazonian states with 37% of its land committed to pasture and cropland (IBGE 2009). Within Rondônia, the Ji-Paraná Basin is the most developed – most of the length of the BR-364 in Rondônia passes through the basin – and is an ideal site to investigate cattle ranching.

Our survey research yielded important baseline data with which to inform and calibrate the agent-based model. Specifically, data on the use and ownership of tractors (as an indicator of mechanization), on the rate of recuperation of pasture and the annual maintenance costs incurred, on the annual costs to supplement cattle diets during drought, and on the kinds of information used to decide how many cattle to stock in pastures were obtained. These data, and the role they played in informing model development, are given in the full model description (Appendix H) and the section on calibration and validation (Appendix J). Where available, other data to parameterize the model were obtained from literature sources; these data are summarized in Appendix I.

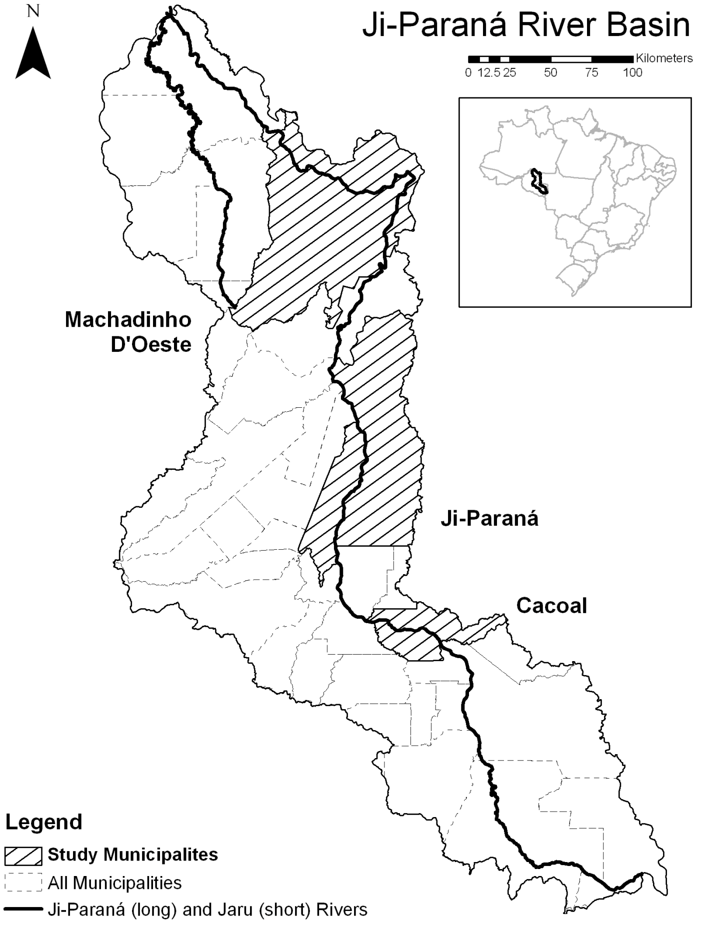

Figure 4.1: Ji-Paraná River Basin

Model Summary

Full source code for the following model, implemented in MATLAB, is available by request from the corresponding author. The following is a summary of model logic; the complete description of model mechanisms and state equations, along with data on land use and mechanization from our sample by which the model is informed, can be found in Appendix H.

Rancher agents raise cattle on an *n x m* grid of land representing a rural Amazon watershed. Each agent begins with an allocation of grid cells, with land in each cell allocated entirely to pasture, the source of grass for cattle growth. Cattle consume grass to meet their dietary needs when grass growth is sufficient to support them; when grass growth is insufficient (such as during a drought), ranchers must purchase supplements to meet cattle needs.

At each time period, rancher agents choose to modify a portion of their land (clearing forest for pasture, restoring degraded pasture to pasture or pasture to forest), to stock their land with cattle, and to purchase or sell land from their neighbors. Land use change decisions are made based on the present value of land under the particular use with a discount rate *d*, and conversion is limited by both the financial and time resources of the agent. Ranchers who fall into financial deficit sell cattle and land in order to attempt to remain solvent. Parcels of land put up for sale are auctioned to the highest bidder among neighbors of the property from which the parcel is being taken. The cattle stocking rate is a function of the grass growth rate.

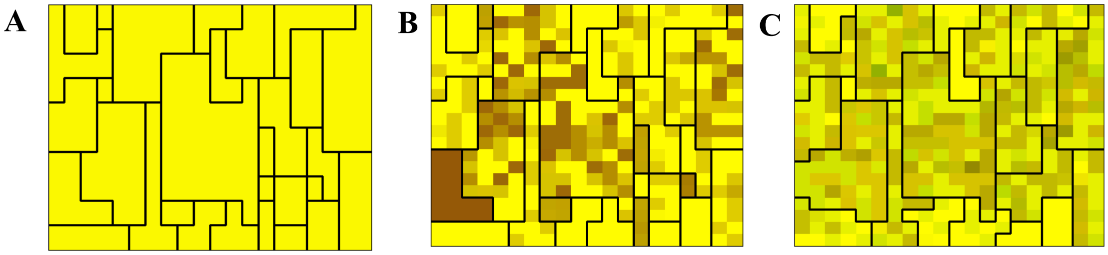

Figure 4.2 - Land use for a typical model run ($\Delta_{Prec} = 0$; $\Delta_{EI} = 0.25$; Tiered Environmental Licensing). Green indicates forest, yellow pasture, and brown degraded pasture. A) Time = 1 year B) Time = 10 years C) Time = 30 years. Note that land owned by a failing ranch at year 10 (brown L-shape in B) has been bought out by neighboring farms by year 30.

After an initial spin-up period of 10 years, an environmental licensing program is implemented for the remaining 30 years of the simulation (Figure 4.2). Under the license, ranchers must achieve a set level of reforestation each year to maintain their licenses and enjoy the premium market price that is given only to license holders. A random selection of agents is monitored at each time step, and those ranchers that are far off from meeting their licensing obligations may lose their licenses. The selection of agents is made by a uniform random selection of grid cells, so that larger properties are more likely to be fined. Agents are informed of the monitoring of other ranchers by communicating with other ranchers in the landscape, which in turn informs their expected incomes when calculating the present value of each land use. The strength of communication among agents is thus a determinant of how well ranchers can predict the expected costs of clearing forest. All ranchers share a network link with all other ranchers (they are a 'clique', in the network sense); the strength of each link (the likelihood that a rancher will communicate with another particular rancher in a time period) is normally distributed.

Daily precipitation is drawn from exponential distributions of mean λ_i, with a different λ_i for each month i of the year. Climate change is treated as an equal, fractional decrease in all λ_i and thus, in overall annual precipitation. The direct impact of climate change is to increase supplement costs for cattle diets during drought periods.

In the experiments discussed below, ranchers are granted an initial allocation of land based on the distribution of properties observed in our field sample from the Ji-Paraná Basin, with random divisions of land among forest and pasture in each grid cell. During an initial spin-up period of 10 years, no charges are levied or land sales permitted while ranchers stock their land and clear away forest to make room for more pasture. At the 10-year mark, land sales are permitted, monitoring and enforcement for licenses begins, and the model is run for an additional 30-year period. Ranchers must continually reforest their property, at a rate that allows them to meet the established goals by the end of the 30-year period, to keep their licenses. The outcome for each experiment at the end of this period is measured by the forested fraction of the landscape, the average profit per hectare of property per year, and the distribution of land among all ranchers originally present on the land.

EXPERIMENTS

We performed a set of experiments across 12 scenarios: 4 sets of assumptions about the structure and value of rancher networks and communication for each of 3 policy scenarios.

Experiment Structure

For each of the 12 scenarios, a set of n=10 replicate model runs with different seeds was performed across the values of our independent variables Δ_{EI} and Δ_{Prec} to generate a response surface (Table 4.1). The dimension Δ_{EI} represents the fractional change in expected income from the sale of cattle when not in possession of a license, and is a signal of how strictly market access for those without licenses is controlled. The price ranchers without licenses obtain for cattle is simply $(1-\Delta_{EI})$ times the market price. The dimension Δ_{Prec} represents the change in overall precipitation relative to the base case; in month i, precipitation is drawn from an exponential distribution with mean $(1-\Delta_{Prec})\lambda_i$.

Table 4.1: Values for independent variables Δ_{EI} and Δ_{Prec} in response surfaces for policy scenarios 1 and 2

Variable	**Values**
Proportional Change in Income Δ_{EI}	0 to 0.5 in increments of 0.05
Change in Precipitation Δ_{Prec}	0 to -0.1 in increments of 0.01

The total number of runs for each response surface is 11x11x10 = 1210 runs.

Policy Scenarios

The first two scenarios investigate the interaction of the Δ_{EI} and Δ_{Prec} stressors across two different implementations of environmental licensing. The goals of the licensing are treated in terms of a target fraction of forest cover at the end of the 30-year licensing period, $f_{targ,final}$, so that the two approaches are:

1) Constant licensing requirements for all properties ($f_{targ,final} = 0.5$ for all property sizes)

2) A tiered licensing system favoring the small producer. We assume that riparian forest along watercourses takes up about 10% of properties up to 120 ha in size, and can totally be contained within the 50% legal reserve for larger properties, so that the tiered licensing described earlier becomes:

   $f_{targ,final} =$ 0.1 for properties smaller than or equal to 60 ha,

   $f_{targ,final} =$ 0.3 for properties less than or equal to 120 hectares but greater than 60 hectares, and

   $f_{targ,final} =$ 0.5 for properties larger than 120 ha

The third scenario investigates trading off effort in monitoring and enforcement. In both of the first two experiments, p_{mon} (the probability of a grid cell being selected and the corresponding property monitored) was set to 0.075, meaning that a property composed of 10 cells, for example, had a 7.5% chance of being monitored in a given year. In the third scenario, we varied Δ_{EI} and p_{mon} to investigate the way in which these two parts of the monitoring and enforcement process (site monitoring and the control of market access) may substitute for one another, under the basic, non-tiered licensing scenario:

Table 4.2: Values for independent variables Δ_{EI} and p_{mon} in response surfaces for policy scenario 3

Variable	Values
Proportional Change in Income Δ_{EI}	0 to 0.5 in increments of 0.05
Probability of selection for monitoring p_{mon}	0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.08, 0.16, 0.24, 0.32, 0.48

Rancher Scenarios

There are two major assumptions to be made about how ranchers interact in the system – firstly, that they interact to exchange information (about costs, practices, or having their site monitored, etc.), and secondly, that they interact to share labor and equipment, thus cutting their costs and allowing them to act like larger, more mechanized farms. Over 75% of our sample reported membership in local rural syndicates and producers associations, and many reported that this membership gave them access to equipment and discounts they would not otherwise have. However, our survey did not otherwise shed much light on the extent to which these assumptions of information, labor, and equipment sharing might be true in the region. Thus, in each policy scenario we evaluate our outcomes across four scenarios of rancher networks, based on the two dimensions of communication strength and size effect (Table 4.3).

Table 4.3: Values for independent variables q and p_{base} in rancher network scenarios

	Low Size Effect	**High Size Effect**
Low Communication	Network links are weak, so that risks of being monitored as well as information about costs is poorly communicated. Network links confer little advantage in the way of reducing costs.	Network links are weak, so that risks of being monitored as well as information about costs is poorly communicated. Where they do exist, network links significantly help reduce costs, such that some small properties experience costs and limitations similar to larger properties.
High Communication	Network links among ranchers are strong so that the risk of being monitored is well communicated and understood. Network links confer little advantage in the way of reducing costs.	Network links among ranchers are strong. Network links also help farmers significantly reduce their costs (i.e., through shared labor and equipment) making their effective farm sizes much larger. In this scenario, small ranches experience costs and limitations similar to larger properties, so that there is no real economy of scale.

Communication strength refers to the mean strength of connections among ranchers in the system (and thus the probability that a given pair of ranchers will share information, such as about land values or levied fines). Size effect refers to the extent to which ranchers who share a strong connection also share resources – labor, tractors, etc. – and is thus a measure of how well smaller farms are able to act (from a cost and land-use perspective) like larger farms. The mathematical details of these scenarios are presented in the model description in Appendix H.

Because we lack precise knowledge of how well networked ranching communities may be, or how costs may vary across scale, exploring these alternative scenarios shed insight into the ways that communication and economies of scale may affect the trajectories of land aggregation and environmental quality throughout the simulations.

The complete set of experiments – 4 rancher network scenarios within each of 3 policy scenarios, and 1210 experimental runs to generate the surfaces in each experiment – results in a total number of 3x4x1210 = 14520 experimental runs.

EXPERIMENTAL RESULTS

Figures 4.3 through 4.6 present the three outcomes of 1) fractional forest cover, 2) average profit per year per hectare of land, and 3) property GINI for the rancher scenario of low communication and low size effect; the complete set of results across all rancher scenarios is included as Appendix K.

The state of land aggregation in the basin is expressed as a 'GINI' coefficient in the model results. The formula for the property size distribution GINI is:

$$GINI_{property} = \frac{2\sum_{i=1}^{n} iA_i}{n\sum_{i=1}^{n} A_i} - \frac{n+1}{n}$$

where A_i is the size of a ranch and n is the total number of ranches. This coefficient ranges from close to 0, implying a more even distribution of land among ranchers, to 1, signifying most or all land concentrated under a single or small number of ranchers.

Joint Pressures of Environmental Licensing and Climate

In the non-tiered environmental licensing scenario, we find some support for hypothesis H2, that licensing can in fact bring about better forest outcomes (forested fraction initially rises as Δ_{EI} increases from 0 in all scenarios and for all tested levels of Δ_{Prec}) (Figure 4.3). However, this comes at the expense of revenue – average per hectare profits strictly decrease as the market price available to non-licensed properties drops. Above some threshold value of Δ_{EI}, profits on average drop below 0, and ranchers do not have the resources to commit to forest restoration or even their own ranching. Forested fraction peaks and then decreases as the stricter environmental licensing makes ranching unviable.

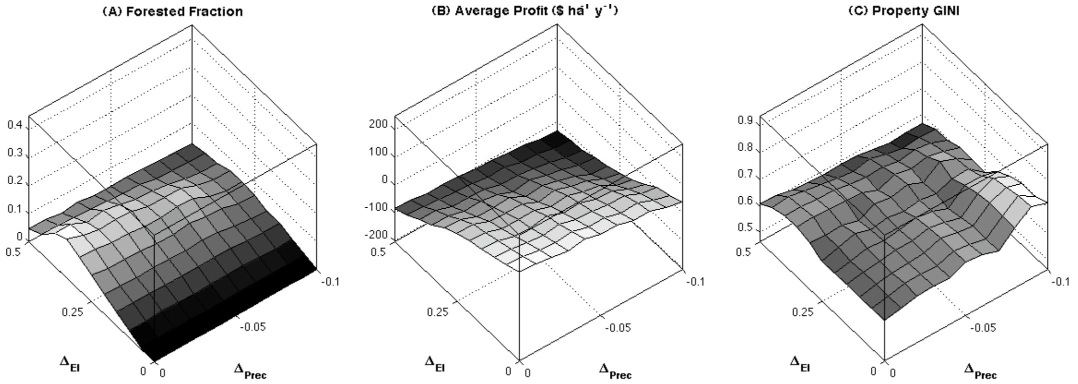

Figure 4.3: Response surfaces for Policy Scenario 1 (non-tiered environmental licensing), Rancher Scenario 1 (low networking, low size effect) showing sensitivity to change in expected income Δ_{EI} and in precipitation Δ_{Prec}. A) Average forested fraction across the landscape; B) Average profit per hectare of property per year; C) Level of land aggregation measured by the property GINI coefficient. Response surfaces for Rancher Scenarios 1-4 are shown in Appendix D, as are surfaces for the standard deviations across repetitions.

Moving along the dimension of decreasing precipitation, the peak forested fraction that is achieved drops, suggesting a lack of resources to commit to forest restoration, which in turn is reflected by the smooth decrease in average profits per hectare as Δ_{Prec} drops further.

Overall, higher forested fractions are achieved when network connectivity is high – when ranchers are better able to assess the risk of having a license stripped and their perceived opportunity cost of losing the license is much higher (Figure K.1). Put simply, for a policy to be effective, those it is meant to govern must be well informed. When size effect is high, meaning that strong network connections allow smaller ranches to behave much like larger ranches, the peak and drop in forested fraction is much less pronounced

– small and large ranches alike are more able to turn a profit since their costs are lower, reflected in higher average profits per hectare.

In all network scenarios except for the high communication/high size effect scenario, both Δ_{EI} and Δ_{Prec} act as drivers of land aggregation, measured as an increase in the property GINI, which provides some support for hypotheses H1 and H3 (see also Appendix K). However, as was also the case for forested fraction, these relationships have a single peak, beyond which they decrease. The explanation is that while all ranches are impacted by stricter licensing or by drier weather, smaller ranches have less of a financial buffer once their basic needs and costs are met, and will be the first to need to sell cattle or land in order to make up for an expensive year. Larger ranches will be in a position to buy up this land and, initially at least, increases in Δ_{EI} and Δ_{Prec} lead to higher property GINI values. However, as these stressors increase further, the profit margin for even larger properties disappears, leaving them unwilling or unable to purchase neighboring plots, and the property GINI peaks or drops off. If an incremental increase in either stressor makes smaller ranches more willing to sell *faster* than it makes larger ranches less willing to buy, it leads to a net increase in property GINI. In general, across the four rancher scenarios, the peak in property GINI is diminished when the two stressors are acting jointly – along the back edges of each of the surfaces. When size effect is high and all ranches have similar cost structure, any effect on land aggregation from Δ_{EI} is minimal, which is to be expected since the smaller ranches share similar cost structure and mechanization to larger ranches in this scenario.

Tiered Environmental Licensing

The tiered environmental licensing option leads to several distinct outcomes relative to the un-tiered case (Figure 4.4). The shapes of the curves remain similar, however, so that these distinctions may be better viewed by looking at the difference in environmental, economic, and social outcomes between the two experiments (Figure 5).

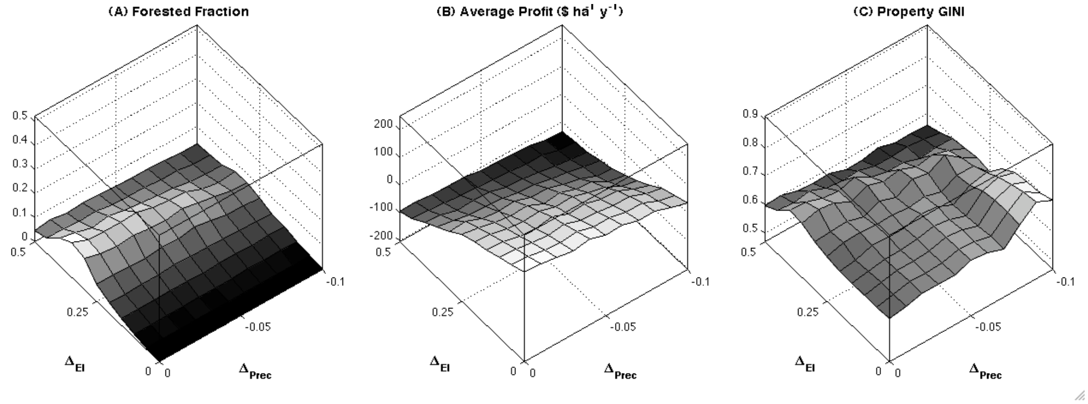

Figure 4.4: Response surfaces for Policy Scenario 1 (tiered environmental licensing), Rancher Scenario 1 (low networking, low size effect) showing sensitivity to change in expected income Δ_{EI} and in precipitation Δ_{Prec}. A) Average forested fraction across the landscape; B) Average profit per hectare of property per year; C) Level of land aggregation measured by the property GINI coefficient. Response surfaces for Rancher Scenarios 1-4 are shown in Appendix D, as are surfaces for the standard deviations across repetitions.

Firstly, the forested fraction achieved is lower across all conditions relative to the un-tiered case, as would be expected. The effort to improve equity across ranch scale requires that smaller ranchers be held to a looser environmental standard, and the overall area of restored forest is reduced. The difference in average profits in the tiered case rises with Δ_{EI}, reflecting the relative ease that the lower environmental standard gives to the ranching landscape; this difference is less significant under conditions of lower precipitation, suggesting that the additional climate stress helps to equalize any differences between the two approaches.

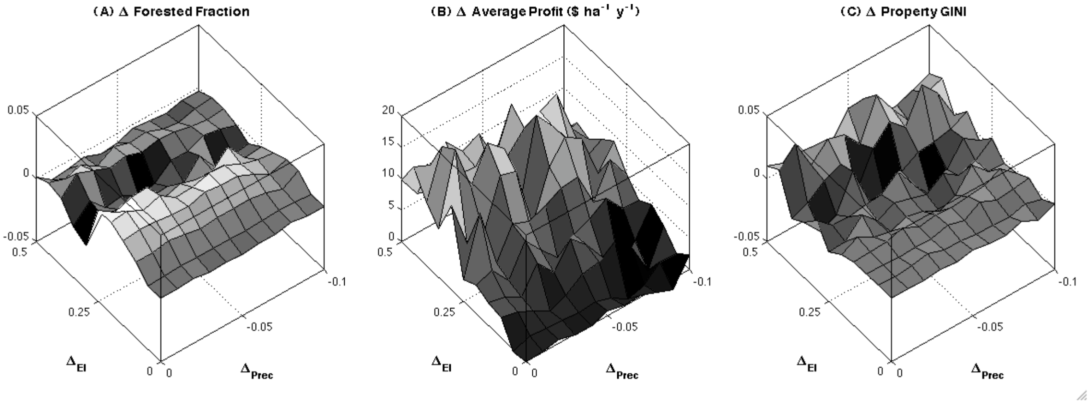

Figure 4.5: Response surfaces for the differences between Policy Scenarios 1 and 2, given as (Outcome in Policy 2 – Outcome in Policy 1), for Rancher Scenario 1 (low networking, low size effect). A) Average forested fraction across the landscape; B) Average profit per hectare of property per year; C) Level of land aggregation measured by the property GINI coefficient. Response surfaces for Rancher Scenarios 1-4 are shown in Appendix D.

The major result is that under a small range of conditions, the tiered approach to licensing does result in lower rates of land aggregation (as Δ_{EI} initially increases from 0). The effect is most pronounced where communication is high and size effect is low, meaning that ranchers are very well informed of the risk of being monitored and the costs those in their network are incurring, but gain little else through their network connections (Figure K.3). Conversely, the effect is least pronounced in the case where both communication and size effect are high – where smaller ranches are able to act much like larger ranches and thus are less disproportionately affected by environmental licensing (Figure K.3).

There is at best mixed support for hypothesis H4 however, since as conditions worsen (Δ_{EI} and Δ_{Prec} increase further) the tiered case appears to lead to higher levels of land aggregation than the non-tiered case (the initial dips in Figure 4.5 in property GINI as Δ_{EI} increased from 0 now rise). The implication is that, rather than eliminating the problem of land aggregation, the tiered approach simply shifts the domain in which Δ_{EI} and Δ_{Prec} act as drivers of land aggregation farther out. That is, under moderate climate or policy stress, the tiered approach can ameliorate some of the pressure on small properties, but if the stressors intensify, the same issue may return. This is even clearer when looking at the relative standard deviations across replications (Figures K.5, K.6). As ranches begin to fail, the variance in profitability across the landscape increases (some farms are doing well while others are failing) and then falls off as conditions worsen (all farms are failing). The sharp ridge on the surface for profitability in Figures K.5 and K.6 marks the threshold, as a function of both climate and licensing stressors, where ranches begin to fail. Comparing the two figures, these ridges move farther out from the origin ($\Delta_{EI} = \Delta_{Prec} = 0$) in the tiered case.

Another approach to achieving a socially equitable outcome

The tiered licensing proposal is unpopular among those who do not stand to benefit, so that it may be worthwhile to look for other means of achieving more equitable results under licensing. Rather than creating explicit tiers that may or may not map well onto functional groups of ranchers it should be possible to design a monitoring and enforcement scheme that implicitly lessens the burden that licensing places on smaller ranchers.

The monitoring and enforcement process in this model has two parts – 1) monitoring of land use on individual properties and allocation or stripping of licenses, and 2) verification of licenses at the point of sale of cattle (such as at a slaughterhouse). In the model, properties are selected for monitoring based on size – a fraction of the cells in the grid is selected randomly, and the properties to which they belong are selected. In this way, larger properties are at a higher risk of being caught. This is a reasonable representation, since any real agency with limited (and perhaps minimal) resources would likely choose to target a smaller number of relatively large targets over a large number of smaller targets. However, all ranchers in the simulation forfeit the same proportion of their revenue Δ_{EI} when they lose their licenses. If we interpret Δ_{EI} as a measure of the difficulty of unloading cattle, this too is reasonable, since all truckloads of cattle present themselves to slaughterhouses in much the same way, regardless of how large the property from which they come.

The agency tasked with monitoring and enforcement must choose how to divide effort between the two parts of the process described above to maximize some objective function. The monitoring of individual properties would likely involve the use of real-time satellite imagery of the property in question, as well as a site visit and consultation with the property owner regarding his or her management plan. The verification of licenses at the point of sale would require the stationing of an agent at a slaughterhouse or the provision of incentives to the slaughterhouse to require licenses as a part of the sale. Considering these processes for monitoring and enforcement together, the implication is that if the objective is to make equitable the burden placed by licensing on ranches, more effort should be allocated to site monitoring, and less to point-of-sale verification of licenses.

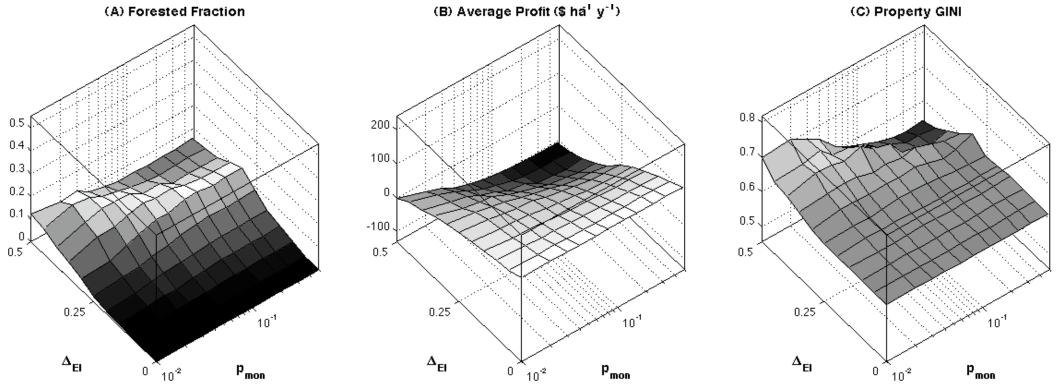

Figure 4.6: Response surfaces for Policy Scenario 3 (non-tiered environmental licensing), Rancher Scenario 1 (low networking, low size effect) showing sensitivity to change in expected income Δ_{EI} and in probability of monitoring p_{mon}. A) Average forested fraction across the landscape; B) Average profit per hectare of property per year; C) Level of land aggregation measured by the property GINI coefficient. Response surfaces for Rancher Scenarios 1-4 are shown in Appendix D, as are surfaces for the standard deviations across repetitions.

This implication plays out in the experimental results. Figure 4.6 shows a set of outcome surfaces generated by varying both Δ_{EI} and p_{mon}. Forested fraction increases along both Δ_{EI} and p_{mon} dimensions until it peaks, so that curves of equal forested fraction – 'isoforest'curves – can be drawn that show how monitoring effort (p_{mon}) can substitute for control over market access (Δ_{EI}) to give equivalent forest outcomes. Per-hectare profit strictly decreases along both Δ_{EI} and p_{mon}, so that similar isoprofit curves can be drawn. In general, the isoforest and isoprofit curves map closely onto each other, which is to be expected – similar areas in forest should indicate similar areas in pasture, and thus similar levels of revenue generated on average across the landscape. However, the same relationship does not hold for the property GINI.

With the notable exception of the high communication, high size effect case, the property GINI is generally higher when Δ_{EI} is high and p_{mon} is low, and downward sloping as Δ_{EI} decreases and p_{mon} increases (Figure K.4). Thus, moving along the isoprofit and isoforest curves associated with the peak forested fraction from higher Δ_{EI} toward higher p_{mon}, the property GINI decreases, implying lower rates of land aggregation and a social outcome that is more favorable for smaller ranches (Figure 4.7). This effect is most pronounced in the low communication, low size effect case – where ranchers on small properties are the least informed of the risks they face and where their costs are considerably higher than those for larger properties, they have the most to gain by shifts in policy that place more burden on larger properties.

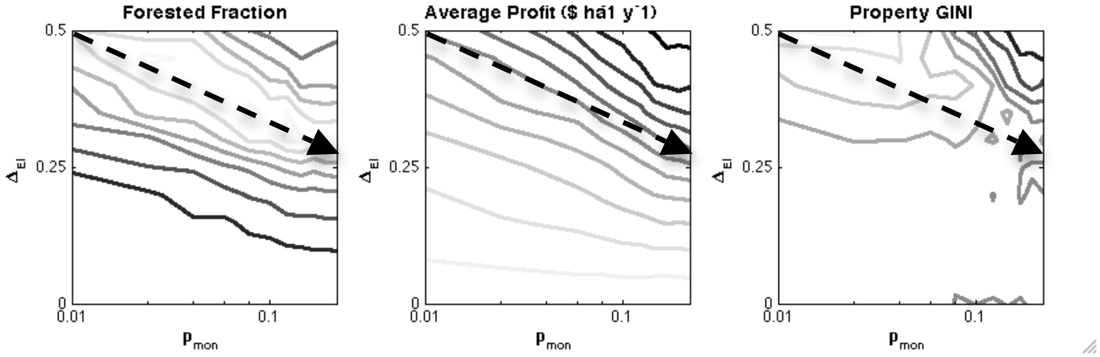

Figure 4.7: Contour curves for the Low Network, Low Size Effect case shown in Figure 4.6; darker curves indicate lower values. A vector (dashed line) drawn along the ridge of nearly constant peak forested fraction corresponds closely with an isoprofit contour, but also with a nearly strictly decreasing property GINI.

Because site monitoring is likely to be the more resource intensive component of the monitoring and enforcement process, it is important that this social equity benefit be emphasized. Figure 4.7 shows that site monitoring and point-of-sale enforcement can substitute for one another to preserve forest cover and average profit levels, but that site monitoring will not simultaneously preserve the capacity for smaller ranches to produce.

So what? Linking model results back to reality

A key process in making insights derived from modeling results useful to real-world situations is to step back through the set of simplifying assumptions upon which the model is built and understand how these insights change as the assumptions are relaxed. In this model, a number of simplifying assumptions were made regarding land market structure, the monitoring and enforcement of fines, and land-use decisions, and we now discuss how the more complex, real-world versions of these processes might modify our results.

First, only parcels offered by ranches in deficit entered the land auction in our model. This is certainly a major component of land that gets sold in real ranching landscapes, but is incomplete – successful ranchers may also be aggressively attempting to buy up local properties in an effort to grow. This mechanism is excluded here to avoid introducing further assumptions about how ranchers choose to invest their money; the impact of excluding this mechanism is likely to be a more conservative estimate of land aggregation, since only some of the means through which successful ranchers can buy up neighboring land are included.

Another important simplification in the model is that there are no wholly unexpected costs borne by the ranchers. In reality, the failure of equipment as well as illnesses and injuries among family members are unpredictable shocks and can drive the need to sell off cattle or land in a pinch. It is reasonable to assume that the risk of injury or illness is uniform across the population (if not higher among poorer ranchers), and that richer ranchers will be better prepared to weather these shocks. Again, this simplifying assumption likely leads to a more conservative estimate of the rate of land aggregation.

The mechanism through which changes in climate influence production in this model is simple – a decline in precipitation results in decreased grass growth, which in turn increases the cost to the rancher to supplement cattle diets during dry periods. While such a relationship has a basis in the literature (Svoray et al. 2008), it is certainly not the only way climate might affect the growth of grass or other crops. In reality, shifts in the mean levels as well as the temporal distribution of precipitation and temperature may have positive or negative effects on grass growth depending on whether they pull conditions toward or away from what is optimal for the plant. Thus, it is worth interpreting the climate effects more loosely, as in, to the extent that changes in temperature or precipitation inhibit grass growth, they may act as drivers of land aggregation in the Rondônian ranching landscape. Integrating more sophisticated relationships between vegetation growth and climate into models focused on social processes, like this one, is an important direction for future work.

The other major assumptions that steer model results relate to monitoring and enforcement. It is assumed in this model that all ranchers will have the same difficulty marketing their product without a license, and thus the same Δ_{EI} is applied to all ranchers. In reality, it would not be unreasonable that larger, more powerful ranches would be better positioned to circumvent rules and obtain good prices than might smaller ranches – another effect that might tip outcomes in favor of larger ranches.

In sum, this first set of assumptions in this model provide what is likely a conservative assessment of the role that environmental licensing in Rondônia could play, in concert with expected climate stresses, in driving rates of land aggregation, given some non-trivial capacity for monitoring and enforcement of the licensing scheme. Relaxing these assumptions, we could expect more severe impacts on smaller property holders in the real system, and further aggregation of land holdings. In terms of the study hypotheses, this means a stronger case for our findings for H1, H3, and H4 (Table 4.4).

The last major assumption of the model is that effective monitoring and enforcement occurs at all. This is a key assumption because strong evidence exists to suggest that little enforcement of policy does take place. IBAMA, the federal environmental protection agency, recently estimated that they collected only a small fraction (less than 5%) of the fines that they levied (Hall 2008, Economist 2009). In our sample, only a small fraction (less than 20%) of properties reported even having their properties visited by members of a public agency for the purposes of observing environmental quality. It is clear that under such conditions the real impact that environmental licensing may have is trivial to evaluate – little will happen; reports from licensing schemes elsewhere in Amazônia do not yet suggest much success elsewhere in the region (Lima et al. 2005). This reality means that our findings with respect to H2 must be interpreted with caution (Table 4.4). The model developed in this study is not the appropriate tool to investigate why such monitoring and enforcement does not occur, nor how it might be encouraged. The value of this study is in highlighting the benefits that can arise from effective implementation of environmental licensing, and in examining how the social impacts of licensing can be managed, under the assumption of some real capacity for effective implementation.

The Rondônia case is just one of many where land-use practices established through colonization or resource exploitation are in conflict with present-day goals for environmental preservation, but are depended upon to preserve livelihoods. Beyond POLONOROESTE (through which much of Rondônia's settlement was funded), the World Bank funded projects in the 1980s in Indonesia, Asia, and the Congo that included as goals the transmigration of peoples and the liquidation of forest assets as a means to economic development (Fearnside 1997, Ekoko 2000, Rachman et al. 2009). As long as legacies of these projects remain, they will continue to present conflict among environmental, economic and social goals. The results presented in this study should offer some hope that these dissonant goals may be harmonized, and that tools like agent-based models allow explicit study of the tensions among them.

Table 4.4: Evidence summary for hypotheses

	Hypothesis	**Support**
H1:	Decreases in precipitation will drive increased rates of land aggregation	Strong, given real constraints on smaller properties
H2:	Environmental licensing will lead to better environmental outcomes	Strong, if licensing implemented effectively; weak, otherwise
H3:	Reduced access to markets through environmental licensing will drive increased rates of land aggregation	Strong, if licensing implemented effectively, given real constraints on smaller properties
H4:	Reduced licensing requirements for small properties will lead to lower rates of land aggregation	Weak to Fair, depending on how licensing is implemented

CONCLUSIONS

This study developed an agent-based model of cattle ranching and land exchange and applied it to the context of the Ji-Paraná Basin in Rondônia, Brazil, using data derived from standardized surveys conducted with local producers on small to medium properties. The model was used to evaluate some of the social, environmental, and economic outcomes that might result from the joint stresses of an environmental licensing scheme, in the context of possible reduced precipitation due to climate change. This study contributes to what is still a small body of agent-based models tied to empirical data (Berger and Schreinemachers 2006), and an even smaller body that examine structural change in farms (Zimmermann et al. 2009), by tying rancher decision-making in with climate and representing the set of conditions particular to the Amazonian frontier and post-frontier.

The model results suggest that while environmental licensing can improve environmental outcomes, as measured here by increased forest cover, this benefit can disproportionately impact smaller properties and drive up rates of land aggregation. Proposals currently under consideration to tier the requirements of environmental licensing for smaller properties have potential to mediate this effect, but are politically unpopular, and may only push the problem of land aggregation further away – as conditions worsen, the problem may return. Rather than an explicit tiered structure, our results suggest that to the extent that more focus is placed on site monitoring, and that this site monitoring (limited by resources) focuses on larger properties, some of the pressure on smaller properties can be mediated and lower rates of land aggregation may occur.

This said, the achievement of any non-trivial outcomes at all from environmental licensing will require effective monitoring and enforcement, which in this case will mean site monitoring of properties as well as point-of-sale enforcement of the requirement to have an environmental license to sell cattle. An effectively implemented scheme is the goal of the state environmental secretary for Rondônia, SEDAM-RO, but it is not the aim of this study to evaluate the different cultural and institutional constraints that will govern whether such monitoring and enforcement will happen. Rather, it is hoped that the results may contribute to the body of evidence of the potential benefits of effectively implemented regulation programs and encourage effort into the careful construction of monitoring and enforcement schemes.

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Chapter 5

Conclusions

The three parts of this dissertation looked at different aspects of the issue of securing clean water resources in the agricultural landscape of the Brazilian Amazon, with a specific focus on the intensively developed State of Rondônia. Chapter 2 focused on the comparison of the efficacy of two different governance mechanisms (bulk water charges and land-use fines) to address agricultural pollution under multiple stressors. Chapters 3 and 4 focused on environmental licensing and the characteristics of the Rondônian agricultural landscape and community that may constrain the success of the licensing program. The following sections summarize the findings of these three chapters.

River basin councils in the Amazon?

Chapter 2 investigated the potential for decentralized river basin councils to govern the issue of non-point-source pollution in rural Amazônia.

The chapter presented a simple set of climate, hydrological, ecological, and rational actor models in a systems dynamics framework to evaluate the potential differences between two different approaches to sanctioning ranchers as a means to regulate agricultural erosion impacts on water quality. A bulk water charge brought strong reductions in erosion by pushing the rational actor to both plant buffer zones and to restore degraded pasture, but laid a strong financial burden on the rancher. In contrast, the land-use fine calculated solely on the presence of buffer zones brought more modest erosion reductions, since it placed no additional emphasis on the maintenance of pasturelands, but also placed less of a burden on the rancher. Both policies showed similar robustness with respect to erosion reduction under changes in precipitation volume and variability, while the bulk water charge placed progressively higher burdens on the rancher with increased precipitation and climate variability. These results fail to show a particular advantage of bulk water charges in confronting the agricultural impact of erosion and sediment loading to surface waters over sanctions tied by proxy to these agricultural impacts via land use and the maintenance of vegetated buffer zones.

Stake is part of the explanation as to why approaches tied to land use may be superior to the tools of the river basin councils for the region. Stake has been a major driver for participation in basins where water reform is most advanced, manifested as the need to claim a share of scarce water resources or stand up to a major industrial polluter. The absence of such conditions in Amazônia has meant that efforts at implementing councils have been sparse and localized (the basin feeding the industrial center in Manaus, or the small catchment supplying drinking water to the municipality of Ouro Preto). The general abundance of water, prevalence of extensive agriculture, and reliance on groundwater on most rural properties in Rondônia do not suggest much incentive in the region to mobilize around water issues. However, the attention paid in recent decades to deforestation and land-use change have mobilized many around an assortment of projects and regulations aimed at improving forest cover on rural properties – effectively the same goals of any initiative aimed at reducing non-point-source pollution and improving water quality in rural areas. While, like most government programs in Amazônia, they are poorly funded and have limited capacity, these initiatives may be in a better position to protect the future of Amazônia's water resources. The greater relevance of land use to farmers and ranchers, and the greater ease in understanding targets for land rather than for water quality may make initiatives tied to land use a superior focal point for environmental action in the region. Voluntary BMP programs in the US that include the maintenance of riparian buffers have had some success in rationalizing land use and in doing so protecting water quality (Prokopy et al. 2008); success observed in Amazônia could point toward more generalizability of the BMP approach across different institutional and cultural contexts.

Basin councils and the decentralized approach to water management may indeed have a role in managing water distribution and industrial water pollution, as it is coming to have in other areas in Brazil, though this study suggests it is not likely that it will be the means to govern the agricultural impacts to water quality which dominate human water impacts at the regional scale in Amazônia.

HOT Farms in Rondônia

The social survey research conducted in Ji-Paraná, Rondônia, and presented in Chapter 3 showed that production intensity on rural properties decreased with increasing property size in the sample, coupled with decreasing contracted and family labor-use intensity, and decreased income diversification. Ownership of large equipment such as tractors rose with property size, although access to these machines was relatively constant across size classes. A pattern of land consolidation in the region is evident in the sample, with the settlement of debts or illnesses being given alongside life-cycle reasons as motivations for farmers to sell their lands.

Plans to intensify land use overshadow plans to expand in the land-scarce post-frontier, with investment in crops a common goal in smaller properties, investment in cattle a goal shared by all but the smallest properties, and the desire to reforest a luxury shared only among the larger properties in the sample. A goal more common with increasing property size is the installation of aquaculture.

For the smaller properties where production is more intense, further intensification to make up the income gap when half of the property is committed to forest may be difficult; intensification on larger properties may occur but will likely require significant additional agricultural inputs, perhaps compromising some of the environmental goals of the licensing scheme. A risk introduced by the licensing scheme is that it will impede the ability of smaller properties (less than 60ha in size) – demonstrated in the data in this study to differ markedly from those larger – to meet their basic needs; meeting the licensing requirements may lead to an increase in the sale of land parcels to cover debts and a speeding up of land consolidation in the region. Using Carson and Doyle's (1999) highly-optimized tolerance framework, these smaller farms, while resilient to expected disturbances in price and yield, may become fragile to shifts in other disturbances, such as input costs, as they intensify in response to the initially unexpected removal of significant land from production. To the extent that it could drive small farmers off of the agricultural landscape, the environmental licensing scheme will achieve environmental gains at the expense of some of the initial social goals of Amazonian colonization, to provide livelihoods to the landless. In other words, the attempt to improve the system with a policy intervention may in fact 'undermine its ability to cope with change and maintain its structure and function' (Janssen et al. 2007). In this, the Rondônian case is a good example of the challenge faced by decision makers of today and the future, armed with better understandings of socio-ecological systems and sustainability, trying to deal with the legacies of policy put in place by decision makers of the past, who had not necessarily benefited from or made use of such knowledge.

It should be noted that the outcomes of the licensing program – planned results and any adverse impacts – depend on an adequate program of monitoring and enforcement to be realized, and it is not clear from our sample that the initial incentive – access to rural credit – will reach a comprehensive majority of properties in the region. Should the scheme be implemented in such a way that farmers are motivated to follow its requirements, and if the social goals of providing livelihoods for the colonists that have come to the region remain, a tiered licensing proposal that relaxes requirements for smaller properties is worthy of consideration and further study.

Stemming exodus under LAPRO

Chapter 4 presented an agent-based model of cattle ranching and land exchange and applied it to the context of the Ji-Paraná Basin in Rondônia, Brazil, using data derived from standardized surveys conducted with local producers on small to medium properties. The model was used to evaluate some of the social, environmental, and economic outcomes that might result from the joint stresses of an environmental licensing scheme, in the context of possible reduced precipitation due to climate change. This study contributes to what is still a small body of agent-based models tied to empirical data (Berger and Schreinemachers 2006), and an even smaller body that examine structural change in farms (Zimmermann et al. 2009), by tying rancher decision-making in with climate and representing the set of conditions particular to the Amazonian frontier and post-frontier.

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The future for clean water in the rural Amazon

The findings of this work suggest that management of water at the river basin scale may happen slowly in the Amazon, if at all, but that there are other means through which the availability of clean water resources for the region may be maintained. Initiatives focused on land use that encourage farmers to maintain riparian cover have potential to address the issue of agricultural pollution, but there is a need to be sensitive to the way in which the region was settled and the capacity of smaller property holders to comply with the conditions of any public policy. Incentives exist that can improve forest and riparian cover, while still keeping the region economically productive and preserving the social goals of the original settlement projects, but care must be taken in the design and implementation of such incentives to ensure that burdens are distributed appropriately.

Limitations and Future Work

The results presented are limited on the one hand by a relatively small sample size for the survey data and exclusion of properties not connected to EMATER-RO, and on the other hand by a lack of high-fidelity treatment of natural system processes in the models developed. As the state of the art of coupled natural human systems modeling advances, and clearer sets of standardized assumptions allow more sophisticated processes to be included and understood within a project, it will be a worthy area for future work to revisit the same problems investigated in this dissertation. Natural system processes that are a truer fit to the Amazonian context (climate and drought cycles derived from real system data, soil and pasture grass models that better represent real system heterogeneity) as well as more sophisticated treatment of rancher decision making (beyond simple economics) may draw out important nuances of the Amazonian ranching problem under LAPRO that have not emerged in the current study. Further, integration of the results collected in this study with other social data sets for the region, as well as additional data collection efforts, would improve understanding not only of how production shifts across scale, but also across the transition from frontier to post-frontier and the shifts in climate, ecology, and culture that occur across the broad Brazilian Amazon Region.

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Appendix A

Systems Dynamics Model Description

The first part of this study implements a model of rancher land use as a systems dynamics model (SDM) in STELLA 9. While numerous studies exist in the literature that explore simple scenarios of human behavior within detailed spatial models of natural systems (Marshall and Randhir 2008, van Roosmalen et al. 2009), in this study we use SDM to develop a model that, with comparable simplicity across both human and natural system components, facilitates the treatment of truly 'coupled' behavior and natural responses. In SDM, or stock-and-flow modeling, the system of interest is treated as a set of stocks (state variables) with material flowing among them (rates of change). To the extent that mean values of the state variables matter (i.e. 'land in agriculture' or 'total rancher population'), and interactions among individuals (such as between ranchers with different opinions) do not, SDM can provide valuable insight into the ways systems behave. These kinds of models have previously been applied to issues in the Brazilian Amazon to gain insight into the impacts of land-cover change (Evans et al. 2001) and loss of ecosystem services (Portela and Rademacher 2001). Rather than making detailed point predictions, SDM are useful for exploring more qualitatively how different stressors impact system characteristics like resilience or vulnerability (Young et al. 2006). In particular, as simple, accessible models, SDM are valuable in exposing existing gaps in knowledge about systems (to help guide the needs of new inductive research, for example) (Young et al. 2006); in their ability to expose counterintuitive system behavior (Sterman 2004); and to communicate to broad stakeholder audiences in participatory approaches to system governance (Voinov and Gaddis 2008). For the study of coupled natural-human SES, SDMs are a valuable component of a portfolio of analytic approaches to improve understanding, their validity deriving from their ability to structure debate and integrate different forms of knowledge (Young et al. 2006).

Causal Model

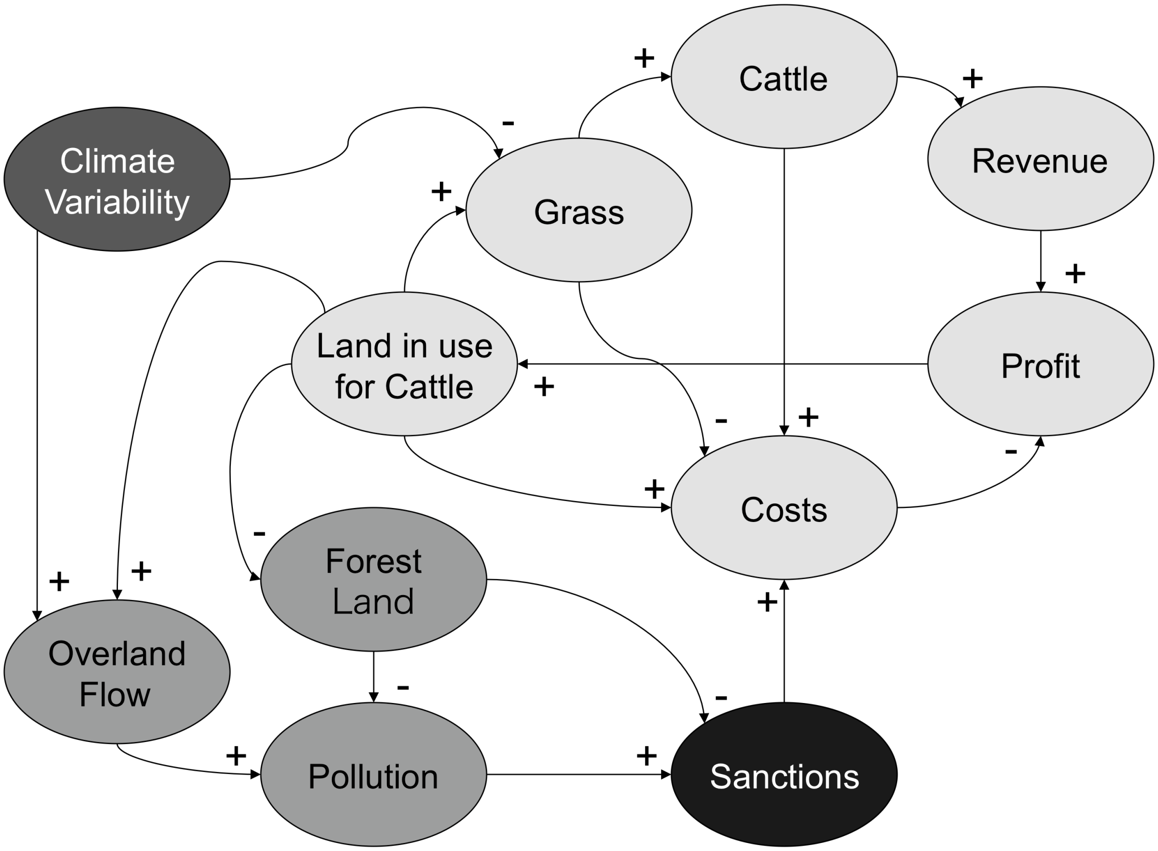

Figure A.1 - Causal Model for Ranching/Water Pollution Coupled Natural-Human System

The causal model that is the basis for the SDM implemented in this study begins with the variable ‘Land in use for Cattle’ (Figure A.1). The rancher puts more land into use for cattle, making available more grass and raising a greater number of cattle. This brings in more revenue, and raises profits – profits that encourage the rancher to reinvest in the land and develop more pasture (a reinforcing loop). At the same time, changing the land use and raising cattle both incur costs, mediating the rancher’s profits (a balancing loop).

Land use for cattle means that land is taken out of forest or riparian buffer. It also means more overland flow, as the pastures soils get compacted. These two factors lead to more sediment load and pollution in surface waters. In this model, there are two possible sanctions to minimize this pollution – fines for insufficient forest/buffer, and charges for cleaning polluted volumes of water (both balancing loops).

Finally, climate variability affects how well grass is produced, and can augment the volume of overland flow, leading to increased pollution and sanctions. Less grass means that our rancher needs to pay more to supplement the cattle diet, and together with augmented pollution, these effects diminish profitability of the ranch.

Modeling Hydrology

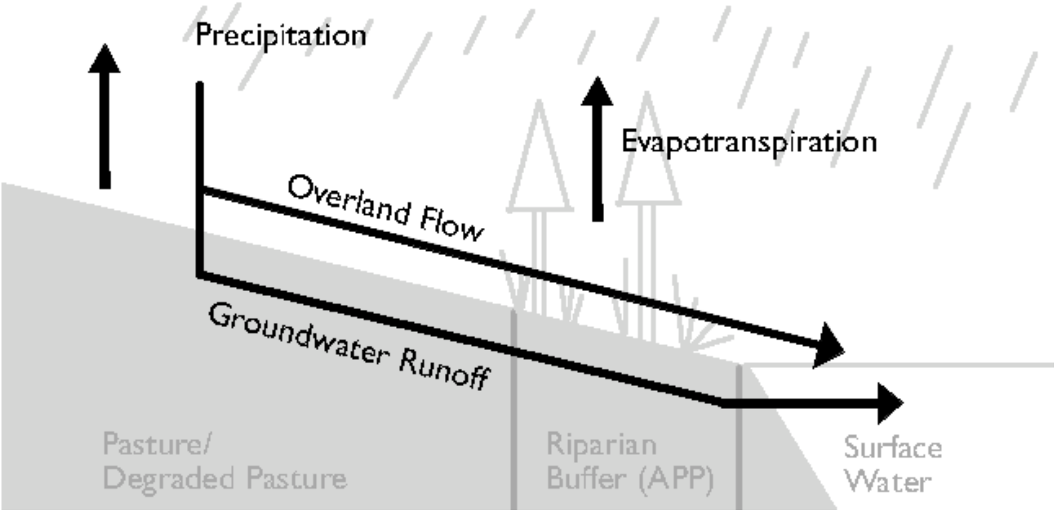

Figure A.2 - Ranch plot and model hydrology

The hydrological submodel is a non-spatial adaptation of the hydrological model developed in the SWAT software package (Neitsch et al. 2005), with the exclusion of the base flow/shallow aquifer recharge component of flow (Figures A.2, A.3). The processes governing this component of flow occur at a scale outside the unit of analysis, the ranch. Since the primary role of the base flow component in the model would be to provide a constant diluting factor along the annual cycle (which would shift the absolute position of sanction responses but not affect the comparative analysis), this component is excluded for simplicity and all water entering the ground is allowed to travel through to surface waters.

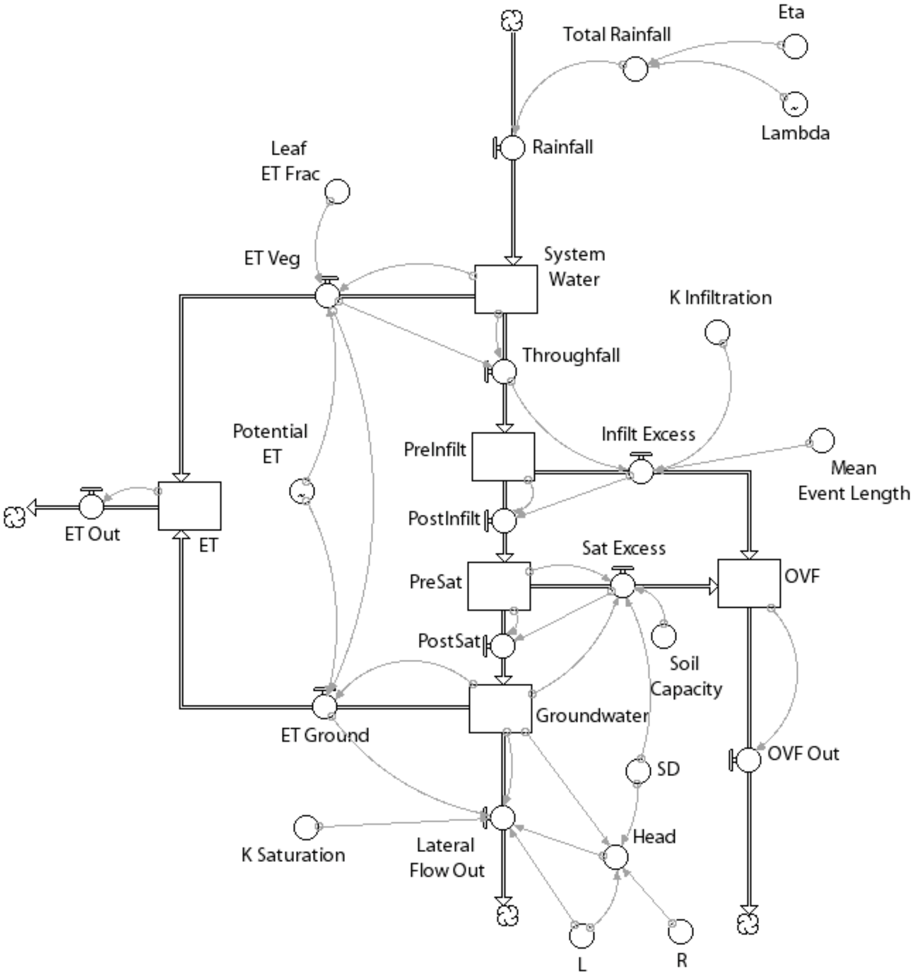

Figure A.3 - SDM Implementation of Hydrology

The state variables in this submodel are given by:

$$System\ Water = Rainfall + ET\ Veg - Throughfall \tag{A.1}$$

$$PreSat = PostInfilt - Sat\ \ Excess - PostSat \tag{A.2}$$

$$PreInfilt = Throughfall - InfiltExcess - PostInfilt \tag{A.3}$$

$$Groundwater = PostSat - Lateral\ Flow\ Out - ET\ Ground \tag{A.4}$$

$$ET = ET\ Veg + ET\ Ground - ET\ Out \tag{A.5}$$

$$OVF = Infilt\ Excess + Sat\ Excess - OVF\ Out \tag{A.6}$$

where the flows are given by:

$$Rainfall = Total\ Rainfall \tag{A.7}$$

$$ET\ Veg = \min\left(Leaf\ \ ET \cdot System\ Water, Potential\ ET\right) \tag{A.8}$$

$$ET\ Ground = \min\left(Groundwater, Potential\ ET - ET\ Veg\right) \tag{A.9}$$

$$Throughfall = System\ Water - ET\ Veg \tag{A.10}$$

$$Infilt\ \ Excess = \max\left(0, Throughfall - Mean\ \ Event\ \ length \cdot K\ \ Infiltration\right) \tag{A.11}$$

$$PostInfilt = Preinfilt - Infilt\ \ Excess \tag{A.12}$$

$$Sat\ \ Excess = \max\left(0, \mathrm{Pr}\,eSat - \left(Soil\ Capacity \cdot SD - Groundwater\right)\right) \tag{A.13}$$

$$PostSat = PreSat - Sat\ \ Excess \tag{A.14}$$

$$Lateral\ Flow\ Out = \min\left(\frac{Head}{L} \cdot K\ \ Saturation, Groundwater - ET\ Ground\right) \tag{A.15}$$

$$Sat\ \ Excess = \max\left(0, PreSat - \left(Soil\ Capacity \cdot SD - Groundwater\right)\right) \tag{A.16}$$

$$Head = \frac{R}{\sqrt{R^2 + L^2}} \cdot \frac{\dfrac{SD \cdot L}{2 \cdot R} - SD + \sqrt{SD^2 + 2 \cdot L \cdot \left(\dfrac{L}{R} + \dfrac{R}{L}\right) \cdot Groundwater}}{\dfrac{L}{R} + \dfrac{R}{L}} \tag{A.17}$$

Potential evapotranspiration is defined for both pasture and forest to be around 4mm/day, though pasture evapotranspiration dips significantly during the dry season (Figure A.4). The shape of this annual pattern is based on modeled and measured results in (Costa and Foley 2000).

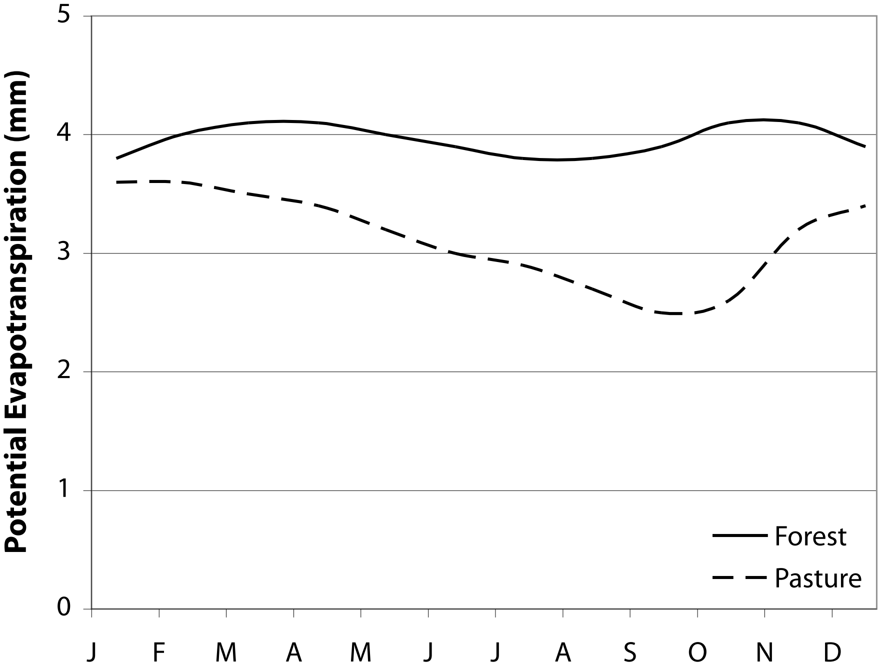

Figure A.4 - Daily Potential Evapotranspiration Curves

Modeling Climate

In the model, daily precipitation is drawn from the distribution:

$$Total\ Rainfall = X \sim Exp\big(\lambda(1-\eta) + X \sim Exp(\eta\lambda)\big) \tag{A.18}$$

Here, X~Exp(a) denotes an exponential distribution with mean a. Exponential distributions are commonly applied to model precipitation (Gao 1997, Wan et al. 2005) as they have the property of being highly skewed toward 0 as in real distributions of precipitation. In this study they are chosen for their simple, one-parameter definition. Integer values for each month have been chosen that preserve rainy-dry season structure (Table A.1) and an average rainfall for the region of about 1800-2200 mm per year (), consistent with actual field measurements for Rondônia (von Randow et al. 2004). The parameter η scales the variance of λ to increase the frequency of extreme precipitation events, one of the anticipated impacts of climate change in the region, while maintaining the same annual precipitation. The parameter ν scales the overall precipitation without affecting distribution. Thus, the modified three-parameter (λ,η,ν) model allows us to capture several of the major anticipated impacts of climate change in the region – increases in wet and dry season precipitation, and increases in the frequency of droughts and extreme storms – in a simple and straightforward way.

Table A.1 - Monthly λ Values for Exponential Distribution

Month	**λ**	**Month**	**λ**	**Month**	**λ**
January	10	May	2	September	6
February	6	June	1	October	8
March	5	July	1	November	9
April	4	August	2	December	10

Modeling Erosion

The erosion model used here is extremely simple. Soil erodes from pasture and degraded pasture at rates linearly proportional to the amount of overland flow, and is retained by the buffer at a rate linearly proportional to the width of the buffer:

$$\begin{aligned} e_{net} &= e_{total} - e_{atten,Buffer} \\ &= e_{total} - \min\left(e_{total}, e_{atten,APP}^{potential}\right) \end{aligned} \tag{A.19}$$

where

$$\begin{aligned} e_{total} &= \left(\frac{H_{OVL}}{H_{OVL,0}}\right)^{c} \cdot \left(e_{0,past} \cdot A_{past} + e_{0,dpast} \cdot A_{dpast}\right) \\ e_{atten,APP}^{potential} &= e_{0,atten,Buffer} \cdot \left(\frac{A_{Buffer}}{A_{0,Buffer}}\right)^{a} \cdot \left(\frac{H_{OVL,0}}{H_{OVL}}\right)^{b} \end{aligned} \tag{A.20}$$

Here, H_{OVL} is the overland flow in mm and $H_{OVL,0}$ is the mean overland flow under normal (η=0) conditions, resulting in nominal erosion values $e_{0,past}$ and $e_{0,dpast}$ per unit area; and $A_{0,Buffer}$ is the width of buffer for which the nominal erosion attenuation $e_{0,atten,Buffer}$ is defined. The exponents a, b, and c allow the relationship between erosion or sediment trapping and buffer depth or overland flow to be non-linear or linear; the definition of these exponents is discussed in the Experiments section. While simple, this model retains the important behaviors that erosion is augmented by overland flow, and can be attenuated by riparian buffers.

Modeling Ranching

The ranch in this model is a 1-dimensional plot, with three land types – pasture, degraded pasture, and forest buffer (Figure A2). The rancher is a simple profit maximizer, with two decisions to make in each period – whether and how to stock cattle, and how to change land use. All cattle on the land that reach three years of age are slaughtered, and this is the sole source of revenue for the rancher. Ranching costs include the supplementing of cattle diets during drought periods when grass growth is not sufficient to support cattle growth, costs for land-use changes, and costs incurred through sanctions.

Cattle Stocking

The rancher decides whether to stock the land with cattle based on the present value (PV) of beef (over a 3-year cattle lifetime) on a mass basis:

$$PV_{beef} = \frac{p - \frac{c_{annual}}{T}}{(1+d)^2} - \frac{\frac{c_{annual}}{T}}{(1+d)} - \frac{c_{annual}}{T} \qquad \text{(A.21)}$$

where p is the market price for beef, c_{annual} is the total annual cost for the ranching operation, d is the discount rate, and T is the current cattle stock in kg. When this value is positive, the rancher performs a simple estimate of the rate at which the land can be stocked:

$$
\begin{aligned}
dT &\sim \left(pasture\ capacity\ \ for\ cattle\right)\cdot\frac{\left(cattle\ stocking\ interval\right)}{\left(cattle\ slaughter\ age\right)}\\
&= f\cdot S\cdot\frac{dt}{3}\\
&= f\cdot\frac{k_{grass,\max}\cdot A_{Past}}{U_{daily,kg}\cdot\left(\dfrac{W_{calf}+W_{2\,year}+W_{3\,year}}{3}\right)}\cdot\frac{dt}{3}\\
&= f\cdot\frac{k_{grass,\max}\cdot A_{Past}}{U_{daily,kg}\cdot\left(W_{calf}+W_{2\,year}+W_{3\,year}\right)}\cdot dt
\end{aligned}
\tag{A.22}
$$

where W_{calf}, $W_{2\ year}$, and $W_{3\ year}$ are the weights of calves, 2-year, and 3-year old heads of cattle; $k_{grass,max}$ is the maximum observed grass growth rate per hectare; $U_{daily,kg}$ are the daily nutrient requirements of cattle per kg of body weight; A_{Past} is the area of pasture; dt is the cattle stocking interval; and f is a unitless scalar term. The pasture capacity S, as can be seen above, is simply the maximum observed grass growth rate, divided by the average daily needs per head of cattle. The scalar f is an important part of the rancher decision-making process. Since $k_{grass,max}$ is an imperfect signal of how well grass can grow, and the average cattle weight used is also simple, the equation above gives an imperfect estimate of the actual maximal stocking rate. The scalar f provides a means both to correct for imperfections in this estimate, and to distinguish behaviors among ranchers. A higher f implies riskier behavior with respect to exceeding the production capacity of the land; a lower f implies more conservative, risk-averse behavior.

Land-Use Change

At each decision interval the rancher is able to change up to a_{change} hectares of land in one of three ways:

i. Restore degraded pasture to pasture
ii. Restore pasture to forest
iii. Clear new forest

The rancher looks at the present value (PV) per hectare of each of these decisions, and undertakes them in order of decreasing PV until a_{change} ha have been changed or there is no further change that would result in a positive PV. The PV calculations for each land use change are given by:

$$PV_{r,dp}(\$/ha) = -C_{r,dp} + PV\left(I_{e,p}\right) - PV\left(C_{e,n}\right) + PV\left(C_{e,wc}^{dp}\right) \tag{A.23}$$

$$PV_{r,fb}(\$/ha) = -C_{r,fb} - PV\left(I_{e,p}\right) + PV\left(C_{e,n}\right) + PV\left(C_{e,wc}^{p}\right) + PV\left(C_{e,fb}\right) \tag{A.24}$$

$$PV_{c,fb}(\$/ha) = -C_{c,fb} + PV\left(I_{e,p}\right) - PV\left(C_{e,n}\right) - PV\left(C_{e,wc}^{p}\right) - PV\left(C_{e,fb}\right) \tag{A.25}$$

where C indicates a cost, and I indicates income. The subscripts e, r, and c denote expected, restore, and clear, respectively. The sub- and superscripts p, dp, fb, n, and wc denote pasture, degraded pasture, forest buffer, nutrient, and water charge, respectively. The individual present value terms are given by:

$$PV\left(I_{e,p}\right) = \sum_{i}^{n} \frac{w_{3\,year} \cdot S \cdot p}{(1+d)^{i}} \tag{A.26}$$

$$PV\left(C_{e,n}\right) = \sum_{i}^{n} \frac{S \cdot c_{nutrients}}{(1+d)^{i}} \tag{A.27}$$

$$PV\left(C_{e,wc}^{p}\right) = \sum_{i}^{n} \frac{q_{eros} \cdot e_{past}}{(1+d)^{i}} \tag{A.28}$$

$$PV\left(C_{e,wc}^{dp}\right) = \sum_{i}^{n} \frac{q_{eros} \cdot \left(e_{dpast} - e_{past}\right)}{(1+d)^{i}} \tag{A.29}$$

$$PV\left(C_{e,fb}\right) = \begin{cases} \displaystyle\sum_{i}^{n} \frac{q_{fb}}{(1+d)^{i}} \\ 0 \quad \left(A_{fb} > A_{fb,req}\right) \end{cases} \tag{A.30}$$

where p is the unit price for beef, S is the pasture capacity, and $w_{3\ year}$ is the weight fraction of 3-year old cattle in the stock; q_{eros} is the average sanction (collected per unit contaminated water) that accrues per unit erosion and q_{Buffer} is the unit sanction collected per hectare of land below the required $A_{\text{Buffer, req}}$; e_{past} and e_{dpast} are the observed erosion loads from pasture and degraded pasture, respectively; $c_{\text{nutrients}}$ is the average annual cost of nutrient supplement; and d is the discount rate. The number of periods n for the PV calculation is the expected lifetime of the pasture before it degrades, which is a function of the rate at which it is grazed:

$$n = \left(\frac{G_0}{G} \cdot n_0 \right) \tag{A.31}$$

where G is the grazing rate, and G_0 is the nominal grazing rate for which the nominal pasture lifetime n_0 is defined (Appendix B).

These calculations assume the rancher has a thorough understanding of economic value – knowledge about how land value is affected directly by erosion and cattle prices may be more limited in reality. Since economic knowledge here allows the rancher to optimize the use of land, the model can reasonably be expected to produce conservative estimates of the pollution and lost profitability that could actually occur in reality.

One important note is that this model does not evaluate processes at a landscape scale. The rancher has access only to the plot of land in the model, and cannot expand his holdings. While significant literature points to land-grabbing and speculation as a major driver of land-use change in Amazonia (Hecht and Cockburn 1989), other researchers question the role of this mechanism (Faminow 1998). Sills et al. (2008) found that in Ouro Preto do Oeste, a typical established ranching region in Rondônia, relatively secure land tenure and low rates of absentee ownership suggest that land speculation is not important in the area (Sills and Caviglia-Harris 2008); therefore it is not included as a mechanism in this model.

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Appendix B

Systems Dynamics Model Parameters for Reference Mode

Where available and appropriate, literature values informed the parameter choices used in this model, with deviations from literature values noted below.

Name	**Parameter Description**	**Value**	**Literature Values/Justifications**
W_{calf}	Calf Weight	50 kg	Based on an adult weight of about 410kg (Mattos and Uhl 1994)
$W_{2\ year}$	Two-year Weight	200 kg	
$W_{3\ year}$	Three-year Weight	400 kg	
p	Price, Beef	\$3/kg	\$R80-90/@ (15kg) (Pecuária.com.br 2009)
$C_{r,p}$	Pasture Restoration Cost per hectare	\$300	\$116-234/ha in 1991 (Smith et al. 1995) \$260/ha in 1994 (Mattos and Uhl 1994)
$C_{r,f}$	Forest Restoration Cost per hectare	\$1,000	\$2000/ha in São Paulo State (GEF 2005) \$800/ha in Amazonia (Fearnside 2001)

$C_{c,f}$	Forest Clearing Cost per hectare	$50	Assumed
$c_{nutrients}$	Cost per kg Nutrient Supplement	$0.08	Based on assumed grain prices of $2-3/bushel
$U_{daily,kg}$	Nutritional Needs, Cattle	7 kg/100kg/d	20-25kg/animal/d (NRC 2001)
a_{change}	Maximum Land Use Change Rate	10 ha/y	Assumed
$A_{0,Buffer}$	Nominal Width for minimal erosion	30-60 m	Required width for rivers < 10m across (Brasil 1965)
Soil Capacity	Soil Water Capacity	40 cm/m	Assumed. Reasonable values estimated from SIGTERON Soil Profile database (Cochrane and Cochrane 2006)
SD	Soil Depth	0.5-2m	
R/L	Slope Grade	5%	
$K_{Infilt,f}$	Soil Infiltration Rate, Forest	1500 mm/h	1533 mm/h (Zimmermann et al. 2006)
$K_{Infilt,p}$	Soil Infiltration Rate, Pasture	120 mm/h	122 mm/h (Zimmermann et al. 2006)
$K_{sat,f}$	Saturation velocity, Forest	200 mm/h	206 mm/h (Zimmermann et al. 2006)
$K_{sat,p}$	Saturation velocity, Pasture	20 mm/h	26 mm/h (Zimmermann et al. 2006)
l	Mean Rain Event Length	1 h	An operational variable to generate realistic hourly rainfall intensities from modeled daily rainfall distributions.

			Estimated from precipitation data for Ji-Paraná (ANA 2009)
$e_{0,p}$	Nominal Erosion, Pasture	5 t/ha/y	Based on erosion rates of 30 t/ha/y (Martinelli and Filoso 2008) up to 200 t/ha/y (da Silva et al. 2007) for fields with exposed soils in São Paulo State, and erosion rates as low as 2 t/ha/y for maintained pastures (Martinelli and Filoso 2008)
$e_{0,dp}$	Nominal Erosion, Degraded Pasture	30 t/ha/y	
$k_{grass,\ max}$	Nominal Maximum Grass Growth Rate	70 kg DM/ha/d	Chosen to give a capacity of about 1.5-2.0 head/hectare. Average stocking rates for Amazonia range from 0.5-1 (Mattos and Uhl 1994, Smith et al. 1995) head/hectare up to 6 head/hectare (Butler 2008)
G_0	Nominal Annual Grazing Rate	60 kg/ha/d	
n_0	Nominal Pasture Lifetime	10 years	5-10 years (Mattos and Uhl 1994)
A_{plot}	Plot Size	200 ha	Assumed
w	Plot Width	500 m	Assumed
dt	Decision Interval	1 y	Assumed
r	Discount Rate	10%	Assumed

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Appendix C

Full Systems Dynamics Model Results

Typical Runs – BWC and LUF

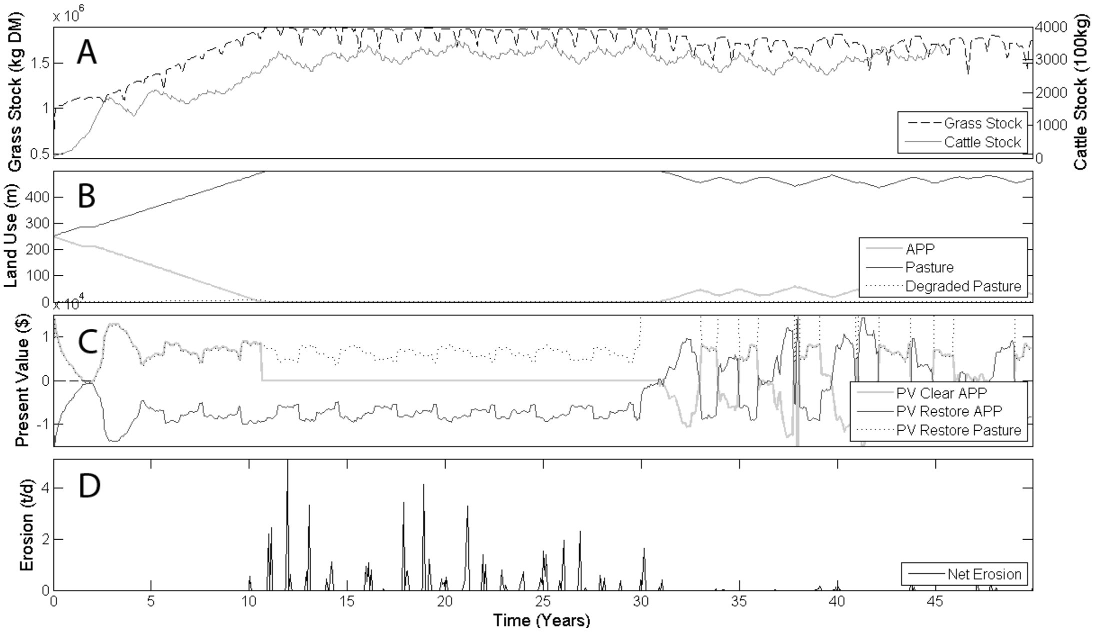

Figure C.1 - Typical Run for BWC with $L_R = 0.0001$ t/m^3 and $S_{BW} = \$0.12$/m^3

In each simulation, the model is run for a startup period of 20 years, during which time the ranching operation grows to a pseudo-steady state, and an additional 10 years at this pseudo-steady state. At 30 years, the fine is imposed, and the simulation continued for a further 20 years. All average results reported in this study are from the final 10 years of the simulation, where the rancher has had opportunity to respond to the imposed sanction.

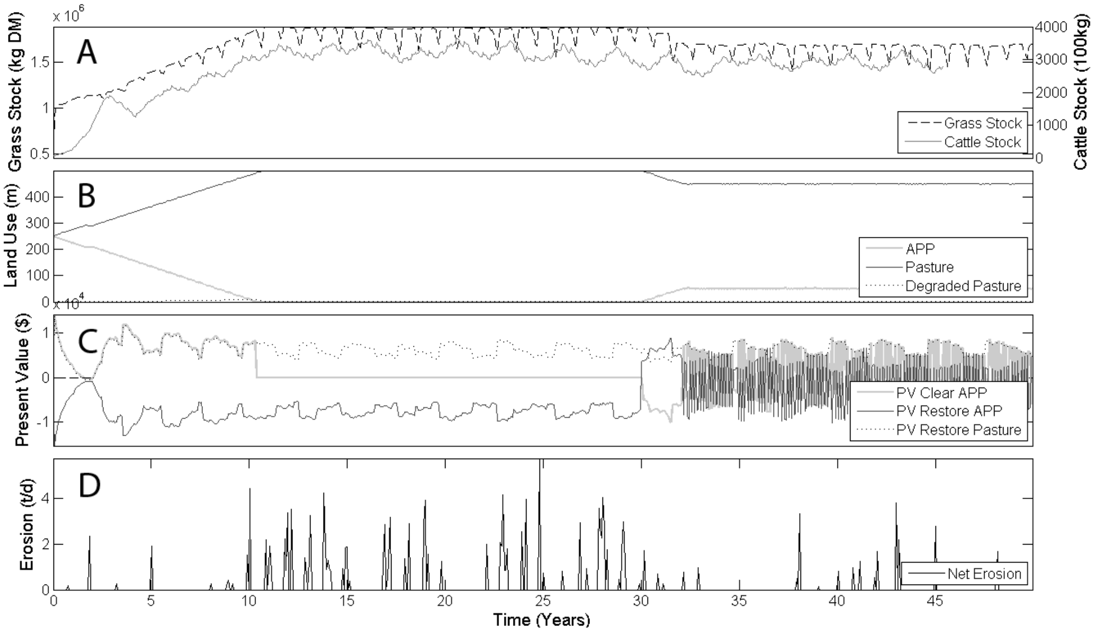

Figure C.2 - Typical Run for LUF with W_R = 50m and S_{LU} = $3000/ha

During the startup period, the present value for pasture is consistently positive (Figure C.1B and Figure C.2B) and that for forest is negative, leading it to be completely converted to pasture by around year 10 (Figure C.1C and Figure C.2C). Without any forest, significant erosion occurs (Figure C.1D and Figure C.2D) – this can be thought of as the expected steady state result without any sanction in place. With the fine in place at year 30, the value of forest buffer land shifts, inducing the rancher to maintain more forest, and in turn reducing erosion (Figure C.1D and Figure C.2D). The high variability observed in the LUF run for the value of forest land, as compared with the BWC run, is due to the dramatic shift in the marginal value of forest as the width of the buffer hovers around W_R. The modeled land values, taken as the PV calculations in Figure C.1C and Figure C2C, are consistent with measured land values for the basin. Sills and Caviglia-Harris found land values per hectare across the basin to vary from $150 to $10,000 per hectare (Sills and Caviglia-Harris 2008).

Approach 1 – Bulk Water Charges (BWC)

Increases to both unit sanctions for bulk water (S_{BW}) and the sanction threshold (L_R) cause smooth declines in profitability, although while S_{BW} is low this does not immediately shift practices and lead to reduced erosion rates (Figure C.3A, Figure C.3B). Above about S_{BW} = \$0.04/m^3 in the simulation, the rancher begins to respond and both increases in unit sanction levels as well as decreases in sanction thresholds lead to smoothly decreases in net erosion (Figure C.3B). These smooth shifts are the clear result of a rise in the average buffer width over the course of the simulation (Figure C.3C) and significant pasture restoration such that levels of degraded pasture remain low across all cases (Figure C.3D).

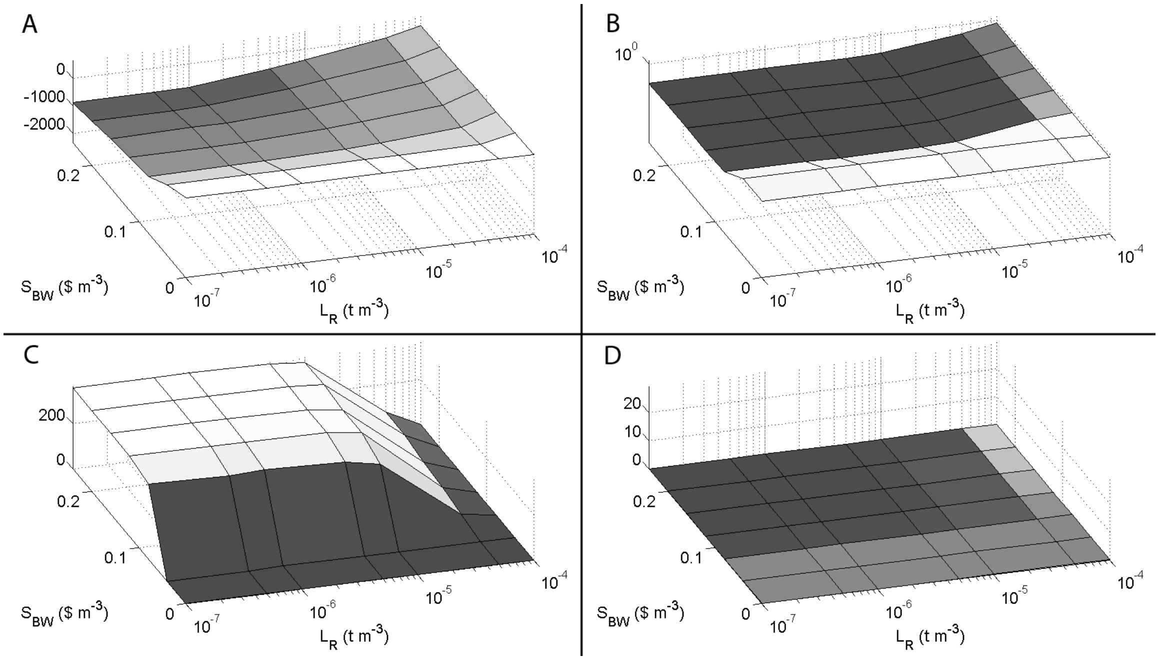

Figure C.3 – Response surfaces for BWC across sanction threshold L_R and unit sanction S_{BW}. A) Profit (\$/ha/y) B) Erosion (t/ha/y) C) Buffer Width (m) D) Degraded Pasture (m). Each point on the surface represents the mean profit per hectare over the final 10 years of the simulation, averaged across 100 Monte Carlo runs.

Approach 2 – Land Use Fines (LUF)

As in the case for bulk water charges, low sanction (S_{LU}) levels do not initially cause a change in behavior, and erosion levels do not shift (Figure C.4B). However, above about

S_{LU} = \$1000/ha, an abrupt 'tipping point' effect occurs as the rancher rapidly shifts his behavior to meet the target buffer width (W_R) (Figure C.4C). Further increases to S_{LU} above this value do not lead to further changes in the buffer width as the target W_R is already met; this target value appears to be achieved at the same value of S_{LU} across the set of simulations. Increases to W_R appear to lead to smooth decreases in net erosion in all cases where S_{LU} is above the 'tipping point.'

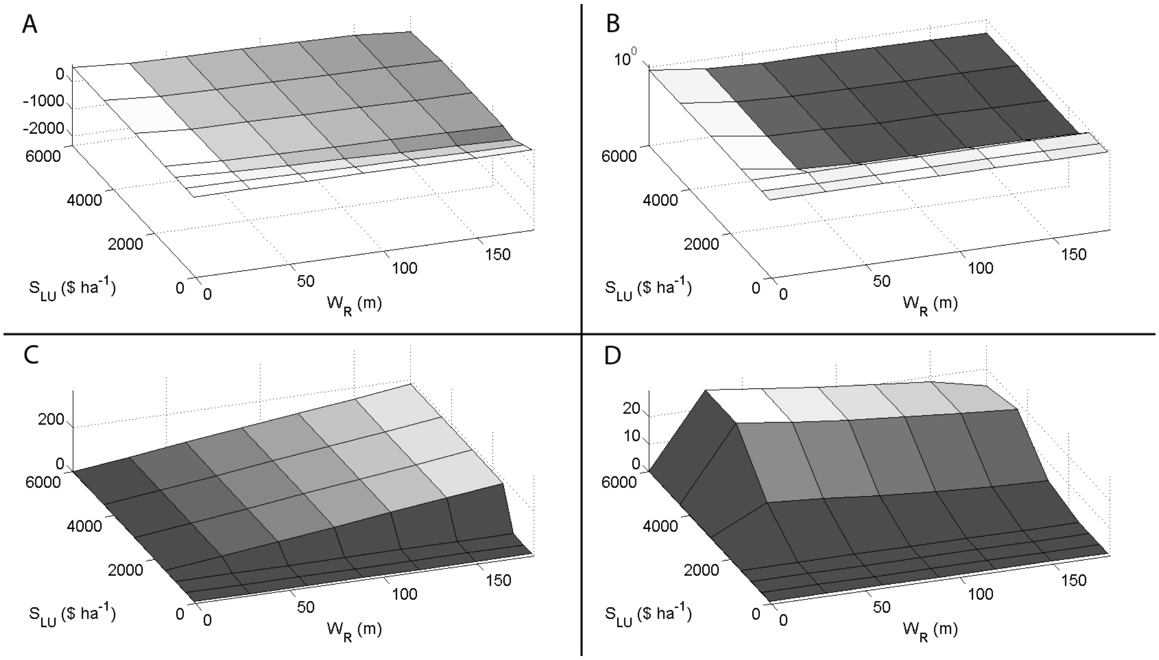

Figure C.4 - Response surfaces for LUF across sanction threshold L_R and unit sanction S_{BW}. A) Profit (\$/ha/y) B) Erosion (t/ha/y) C) Buffer Width (m) D) Degraded Pasture (m). Each point on the surface represents the mean profit per hectare over the final 10 years of the simulation, averaged across 100 Monte Carlo runs.

Contrasting BWC and LUF

A first key difference in the LUF case from the BWC approach is that increases in both W_R and S_{LU} from zero initially lead to significant rises in the amount of degraded pasture on the property (Figure C.4D). Degraded pasture width peaks at about 25m (or about 5% of the property), and then declines with further increases in W_R as the total amount of pasture that can degrade declines. Since the LUF does not specifically reward reduction in pollution, only the maintenance of required buffer widths, the value of restoring pasture relative to its value in the BWC case is lower, and it accumulates. This occurrence is not unrealistic; Fearnside summarized estimates of pasture degradation in Amazonia ranging from 17% to 54% of total pasture area as recently as 1986 (Fearnside 1986), and more recently estimated an equilibrium point for Amazonia of about 10% of pasture land in degradation (Fearnside 1997).

An important dynamic difference between the BWC and LUF scenarios in this simulation is the way in which buffers are maintained over time. In the LUF scenario, the required buffer width W_R is achieved quickly after the policy is implemented (Figure C.2) and remains stable for the remainder of the simulation, such that the standard deviation of the buffer width across time late in the simulation is very low (Figure C.5B). In contrast, the buffer widths in the BWC simulation are much more dynamically variable, leading to higher standard deviations over the final 10 years of the simulation (Figure C.5A). Since climate and the rate of generation of overland flow, as well as the effectiveness of buffers in trapping eroded sediment are variable and not perfectly known to the rancher, a consistent and stable ‘optimal’ buffer width does not emerge within the simulation. The rancher ends up maintaining land more dynamically, planting wider buffers to reduce pollution charges and removing them as the opportunity cost for raising cattle rises.

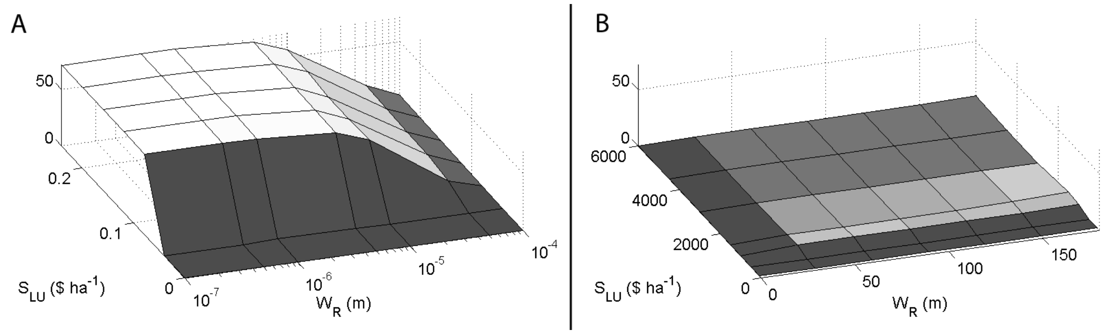

Figure C.5 - Standard Deviation in Buffer Width Over Time (m) for A) BWC and B) LUF across sanction threshold L_R and unit sanction S_{BW}. Each point on the surface represents the standard deviation in buffer width over the final 10 years of the simulation, averaged across 100 Monte Carlo runs.

Comparisons between these approaches is hampered by the fact that the policy dimensions are different in each case, and by the difficulty in viewing how these different outcomes – principally profitability and net erosion – co-vary within and across scenarios. To make comparison easier, we adopt the 'sanction response curve' as a means of representing components of the response surfaces shown above. Sanction response curves are explained in full in Appendix D.

Sanction Response Curve – BWC

Looking along the curve of decreasing L_R at S_{BW} = \$0.24/m^3, a profile of the form in Figure D.3 is clear (Figure C.6A). Since the constant high fine per unit of contaminated water along the entire curve creates some incentive to change behavior even at higher erosion thresholds, we do not observe a flat region A. A smooth drop occurs in region B, bottoming out in region C.

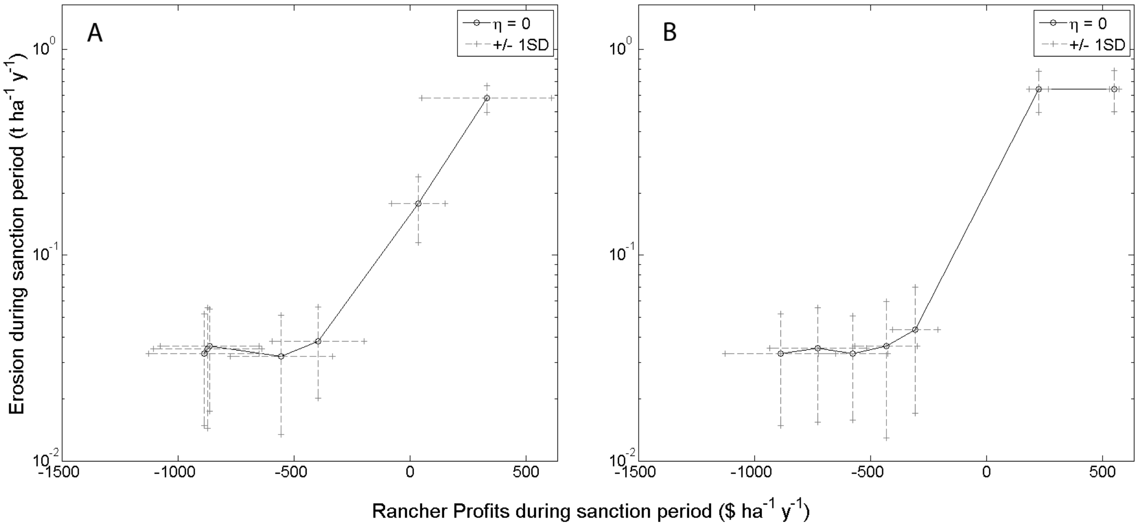

Figure C.6 - Sanction Response Curve across A) Constant Unit Sanction of S_{BW} = \$0.24/m^3 and B) Constant Sanction Threshold of L_R = 1e-6 t/m^3 for BWC. Grey dashed lines indicate the range of values observed in the Monte Carlo analysis; solid black circles indicate mean values across Monte Carlo runs.

The ranges observed in both profitability and erosion in the Monte Carlo analysis (grey dashed lines in both Figure C.6 and C.7) reflect the significant environmental differences between runs in the Monte Carlo analysis and give confidence that we are evaluating these policy approaches over a truly rugged landscape – where high overland flow is coupled with ineffective riparian buffers in some instances, or where deep soil and thick riparian buffers keep erosion low in others. Even with these ranges, there is a clear statistical difference between the endpoints of the curves in Figures C.6 and C.7 for both erosion and profit outcomes, demonstrating the existence of distinct regions A and C, and implicitly, the regions B that are the transitions between them.

The curve of increasing S_{BW} at a constant low threshold of L_R = 1e-6 t/m^3 is more similar to that observed in Figure D.3 (Figure C.6B). A clear flat region A is present, showing that at low unit sanction levels, there is not a strong enough signal to influence behavior – that is, when the unit fine is low, the rancher prefers to pay the sanction rather than changing his practice.

Sanction Response Curve – LUF

The LUF curves are distinctly different from those for BWC. First looking along the curve of increasing W_R at S_{LU} = \$9000/ha, like in the BWC constant S_{BW} case, erosion levels begin to drop immediately as W_R increases since with high S_{LU} there is a clear signal for the rancher to follow (i.e., it is always worthwhile for the rancher to try to change his practice) (Figure C.7A).

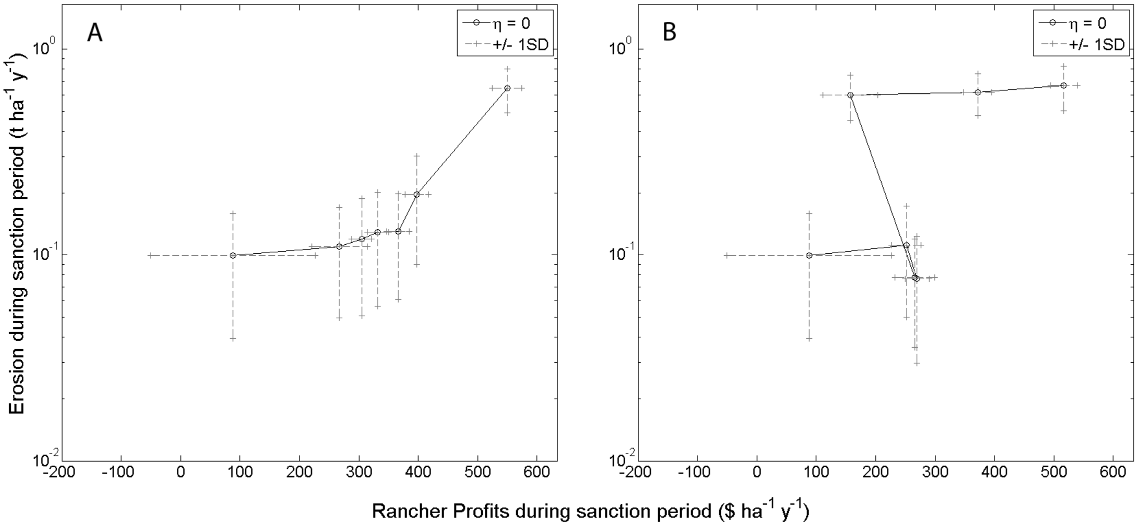

Figure C.7 - Sanction Response Curve across A) Constant Unit Sanction of S_{LU} = $9000/ha and B) Constant Target Buffer Width of W_R = 180m for LUF. Grey dashed lines indicate the range of values observed in the Monte Carlo analysis; solid black circles indicate mean values

The curve for constant W_R = 180m at increasing S_{LU} is distinct from the previous curves in that it shows the clearest ‘tipping point’ behavior of the group. A smooth decline in profitability without a change in erosion levels is then followed by a rapid drop in erosion and bump in profitability as S_{LU} crosses the threshold that moves the rancher from complete noncompliance to near complete compliance (Figure C.7B). In other words, the high target buffer width is onerous enough that it takes a fairly significant sanction to encourage the rancher to adhere to it. Once he does, he experiences a bump in profitability as the drop in sanctioning outweighs the lost revenue. Several of the subsequent increases in S_{LU} bring about neither changes in profitability nor erosion, since the rancher is in complete compliance with regulations and does not change their behavior further. Beyond this point however, in region C, both profitability and environmental performance decline. This is a result of the higher rate at which the rancher acts to comply with the regulations when the sanction is particularly onerous. Since in the model the rancher does not sell cattle until they are 3 years of age, the turnover of land into buffer or degraded pasture crowds cattle into a smaller pasture area. A high enough cattle density causes the grass supply to be critically drained, and the production of cattle crashes. This model does not treat the re-establishment of ranching operations following a crash, so that profitability drops, and large tracts of degraded pasture are left, resulting in poorer environmental outcomes. This particular outcome may not have a clear analog in reality – ranchers are likely to sell cattle early or otherwise adjust their behavior more radically to avoid crashing their pastures – and may simply be an artifact occurring at the limit of the model's useful range. However, that it does occur does draw attention to the interaction between policy and dynamic systems – the severity of a sanction and the timescale over which it is implemented need to respect the capacity of sanctionees to adapt and react.

Contrasting BWC and LUF

Comparing the absolute performance of the BWC and LUF along the sanction response curve, it is easily seen that BWC achieves better reduction of erosion, but at a much higher cost to the rancher (compare Figure C.6 with Figure C.7). Variability in climate and the relationships between soil, overland flow, and buffer effectiveness make it much more difficult for the rancher to minimize erosion than it is to comply with a simple land use regulation. By specifically targeting erosion outcomes, the BWC achieves better erosion reduction; however, by targeting an imperfect proxy for low erosion outcomes, a standardized buffer width, the LUF achieves a more modest reduction in erosion but preserves the livelihood of the rancher.

BWC and LUF as adaptations to Climate Change

As climate grows more variable, ranchers are less able to judge how well grass will grow and thus how much cattle their land will support. Further, peak profits for ranchers are lower with higher climate variability, as the costs for nutrient supplements and other inputs during dry periods rise. When erosion is considered as well, the effects are more pronounced – greater overland flow brought about by severe storms (Bonell et al. 1993) and by increased conversion to agricultural use (Scanlon et al. 2007) leads to greater erosion into surface waters and greater effects on downstream aquatic and human systems.

In the following sections, we investigate how the performances of BWC and LUF shift under changes in the climate, as measured through the social dimension of profitability and the environmental dimension of net sediment loading. Each of the curves in Figure C.8 and Figure C.9 shows the policy response curves under 6 scenarios for climate – high ($\eta = 1$) and low ($\eta = 0$) variability cases for each of runs with lower ($\nu = -10\%$), normal ($\nu = 0$), and higher ($\nu = +10\%$) precipitation. Scenarios corresponding to low and high variability are marked with circles and triangles, respectively, and scenarios corresponding to lower, normal, and higher precipitation are marked with dashed, solid, and dotted lines, respectively. Each curve within a figure is generated using the same policy parameters.

While the choice of $\nu = \pm 10\%$ is based on the IPCC findings summarized in (Magrin et al. 2007), the choice of $\eta = (0, 1)$ is more arbitrary, since the expected change in the frequency of extreme weather events is less well known or reported, and is made for reasons of clarity and simplicity. Thus, it is important to emphasize that the two effects (η and ν) are not necessarily expected to scale against each other as they do in these simulations, and that these results should not imply that the change in variability will have a more or less severe impact on ranching than the change in precipitation.

Response to Climate Change – BWC

The striking result from the curves in Figure C.8, across constant S_{BW} and L_R, is that as both overall precipitation and variability increase, the performance of the BWC degrades. Specifically, for a given set of policy parameters net erosion rises, and profitability for the rancher falls. Moving along the sanction response curves from region A to region C, the spread between any two given curves in the figure increases, indicating that the policy is more effective in one scenario than in the other. Further, this shows that the impacts of changes in precipitation and climate variability manifest themselves more under strong sanctions than under weak sanctions.

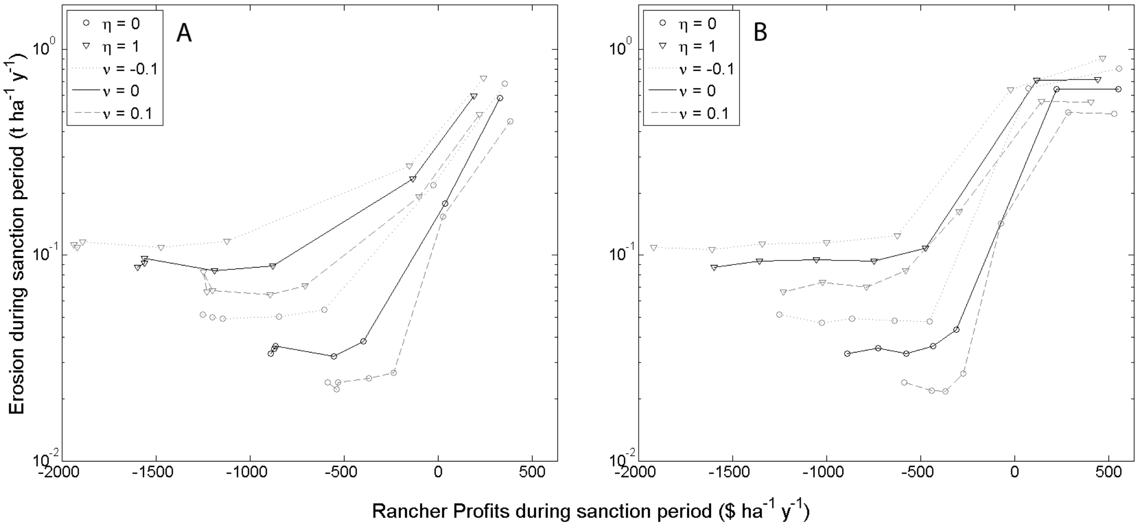

Figure C.8 - Sanction Response Curves over Climate Scenarios across A) Constant Unit Sanction S_{BW} = \$0.24/m^3 and B) Constant Threshold of L_R = 1e-6 t/m^3 for BWC. Curves associated with low climate variability are marked with circles, those with high climate variability are marked with triangles. Increased precipitation is marked by a dashed line; decreased precipitation by a dotted line.

It is important to note at this point that the only growth impact of climate change incorporated into this simple model is a linear effect of precipitation on grass productivity (Svoray et al. 2008), so that the shifts in profitability here are dominated by the imposed sanctions. To the extent that the growth rate of pasture grass is affected in more complicated ways by changes in climate, these profiles would be different.

Response to Climate Change – LUF

Where the effect of climate on BWC was to elongate the sanction response curve along the profitability axis, the effect on LUF appears, if anything, to be to compress the curve. Across both constant S_{LU} and W_R, increases in variability and in precipitation appear to shift the sanction response curves directly up along the erosion dimension with little movement along the profitability dimension (Figure C.9). This is not entirely surprising, since the sanction requirements for the rancher (to maintain a buffer width of W_R) are invariant across changes in climate, and any shifts in profitability in the model would be expected to arise from the changing capacity of the pasture grass to support cattle. What is worth noting is that the magnitude of the upward shift due to increasing variability and precipitation appears similar to the magnitude of the upward shifts seen for BWC. That is, while the LUF demonstrates overall lower performance in reducing erosion in this model, it demonstrates an equivalent robustness against climate change, as compared to the BWC.

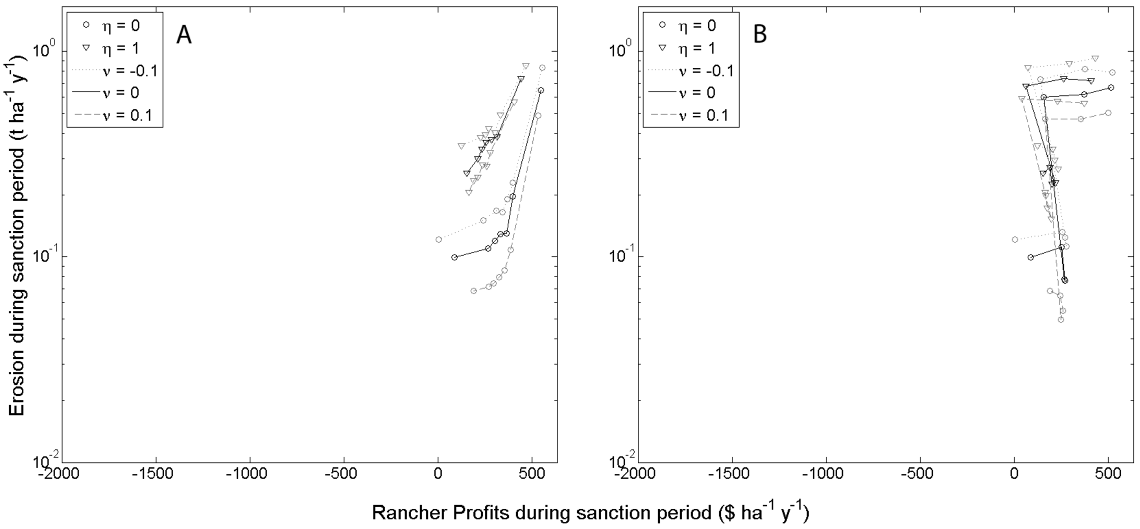

Figure C.9 - Sanction Response Curves over Climate Scenarios across A) Constant Unit Sanction of S_{LU} = \$9000/ha and B) Constant Target Buffer Width of W_R = 180m for LUF. Curves associated with low climate variability are marked with circles, those with high climate variability are marked with triangles. Increased precipitation is marked by a dashed line; decreased precipitation by a dotted line.

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Appendix D

Sanction Response Curves

To make comparisons across the different policy approaches and climate scenarios in this study, we propose the following set of curves as archetypal economic and environmental responses to sanctioning. This archetype assumes that enforcement of the sanction is uniform across different sanctioning strengths, and that the sanctionee is behaving optimally – that is, acting to maximize profitability – before sanctions are levied.

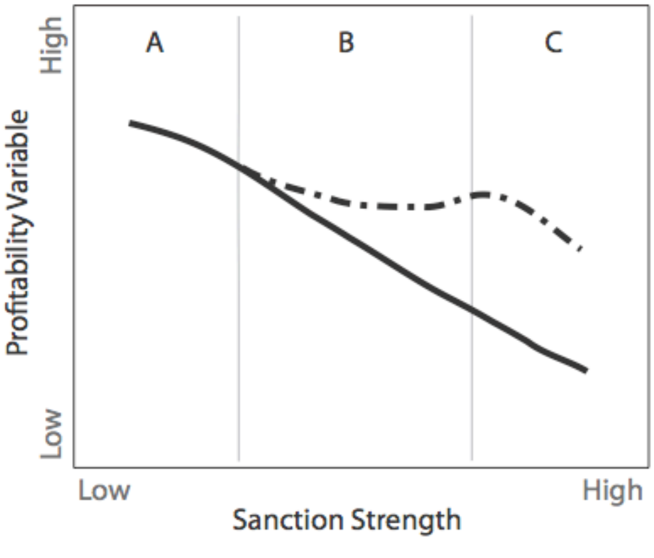

Figure D.1 - Profitability as a function of Sanction Strength

In the most basic case, as sanctions are levied and become more severe, profitability will decline (Figure D.1, solid line). At low strengths, sanctions may not be effective at shifting behavior and simply increase costs for the sanctionee (Figure D.1, solid line, region A); at higher strengths, they may force the sanctionee to change practices and the pollutant variable of interest may begin to decline (Figure D.2, solid line, region B). As sanctions become even stronger, the sanctionee may reach the limit of changes that can be made, and further increases in sanction strength simply increase the cost burden without further environmental improvement (Figures D.1 and D.2, solid line, region C).

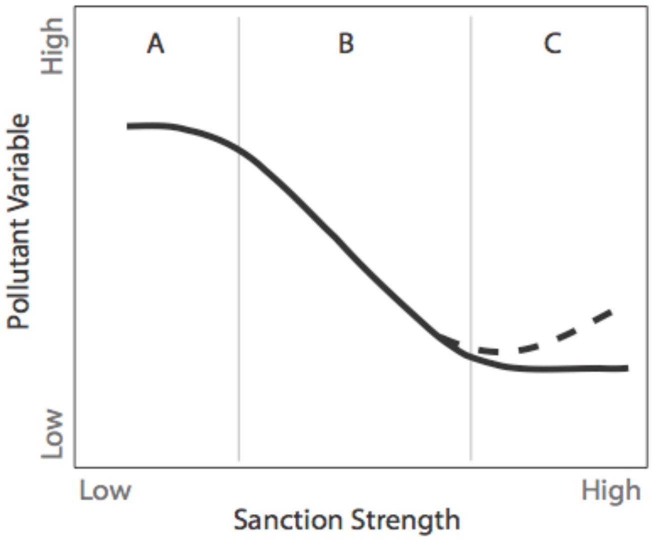

Figure D.2 - Pollution as a function of Sanction Strength

However, there are important ways in which a sanction response may differ from this most basic case. In the first, an incremental increase in sanction strength may lead to a relative increase in profitability, if it causes the sanctionee to make some discrete change in practice that reduces pollution in such a way that the total sanctions levied are now lower than before (e.g., an addition to a chemical process that reduces generation of a harmful toxic byproduct to very low levels, but which is fairly expensive to install) – a threshold effect (Figure D.1, dash-dotted line). In the second, sanctions that become too onerous may affect the ability of the sanctionee to maintain practices, leading to environmental degradation and a net increase in the pollutant variable with incremental increases to sanction strength e.g., the maintenance of wide riparian buffer zones such that the remaining pasture land can not support enough cattle to cover costs) (Figure D.2, dashed line).

In our analysis, we are not focused on what pollution and profit outcomes are at particular sanction strengths. Across different policy approaches, sanction strengths cannot really be compared meaningfully, and the low-fidelity modeling approach of this paper means that calibration of sanction strengths should not be a goal. Instead, we are more interested in how the ranges of pollution and profit outcomes vary with each other and across scenarios. Thus, we propose in this paper to combine the information in Figure D.1 and Figure D.2 into a single 'sanction response curve' that plots pollution outcomes on the vertical axis against profitability outcomes on the horizontal axis (Figure D.3).

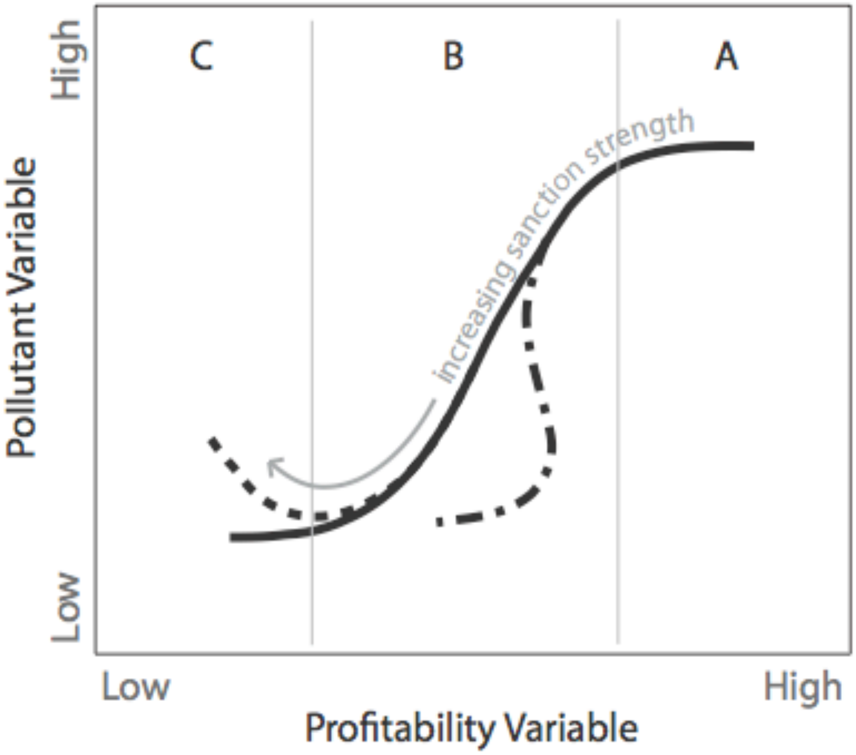

Figure D3 - Sanction response curve across pollutant and profitability variables

In this distinctively sigmoidal or 'S'-shaped curve, sanction strengths increase from right to left in the figure, corresponding to the same regions A, B, and C as in Figure D.1 and

Figure D.2. Rises in profitability due to threshold shifts in behavior brought about by increased sanction strength manifest as inflection points on the horizontal axis (Figure D.3, dash-dotted line); rises in pollution brought about by overly onerous sanctions and reduced capacity to manage pollution manifest as inflection points in the vertical axis (Figure D.3, dashed line).

We propose this sanction response curve as a means of clearly representing the following properties of a sanction response on a single curve: 1) threshold behavior changes (such as discrete jumps in compliance or changes in technology that lead to improved profitability) as inflections in profitability variables, 2) overly onerous sanctions (such as a sanction that leaves ranchland unprofitable and in degradation) as inflections in pollution variables, as well as 3) the change in profitability over the effective behavior-changing range of the sanction (Region B in Figures D.1-D.3). We apply it in this study to compare responses across approaches and climate scenarios.

To reduce the data and make it more tractable in the main article, we selected slices of the previously shown response surfaces to generate the sanction response curves. We selected the most stringent slices along each dimension, holding the other dimension constant (S_{LU} = \$9000/ha and W_R = 180m for the LUF case, L_R = 1e-6 t/m^3 and S_{BW} = \$0.24/m^3 for the BWC case). In other words, these slices are the model results along the back edges of the response surfaces in Figure C.3 and Figure C.4 (Appendix C). They represent extreme values for the policy dimensions where the burden of the sanction is particularly onerous and responses can be expected to be strong; finding results in region 'C' shown in Figure D.3 along both of these slices, where no further improvements to environmental outcomes is occurring, gives some confidence that the simulations have covered the regions in the possibility space defined by the two dimensions of the policy approach with the best erosion outcomes.

Appendix E

Tabulated Size Class Mean Values and Proportions for all Study Variables

Tabulated results begin in landscape layout on the following page.

		Average across all sites		Ji-Paraná		Machadinho		Cacoal	
Value (M/P: Mean or Proportion; SE: Standard Error)		**M/P**	**SE**	**M/P**	**SE**	**M/P**	**SE**	**M/P**	**SE**
Average Size of Property	< 15ha	8.77	6.4	7.92	4.81	13	1.41	8.87	3.98
	< 30ha	22.91	6.93	23.33	3.67	24.59	3.9	20.64	4.4
	< 60ha	44.35	14.15	44.73	8.96	44.59	6.99	43.08	8.44
	< 120ha	82.78	22.85	94.16	14.6	73.88	12.8	77.59	12.05
	> 120ha	197.04	115.12	175.39	44.23	227.07	56.03	205.35	90.32
Proportion of Property in Pasture	< 15ha	0.35	0.49	0.47	0.4	0	0	0.26	0.28
	< 30ha	0.52	0.55	0.68	0.33	0.37	0.34	0.48	0.27
	< 60ha	0.51	0.38	0.74	0.22	0.4	0.24	0.62	0.19
	< 120ha	0.58	0.45	0.67	0.25	0.46	0.28	0.58	0.25
	> 120ha	0.76	0.29	0.85	0.05	0.66	0.22	0.73	0.17
Proportion of Property in Crops	< 15ha	0.5	0.46	0.43	0.38	0.83	0	0.53	0.27
	< 30ha	0.31	0.5	0.28	0.32	0.31	0.31	0.35	0.22
	< 60ha	0.24	0.31	0.11	0.13	0.29	0.23	0.21	0.17
	< 120ha	0.13	0.29	0.13	0.18	0.11	0.09	0.16	0.2
	> 120ha	0.08	0.33	0.03	0.03	0.17	0.32	0.08	0.08
Proportion of Property in Regrowth	< 15ha	0.04	0.17	0	0	0	0	0.08	0.17
	< 30ha	0.06	0.24	0	0.01	0.08	0.15	0.09	0.19
	< 60ha	0.04	0.13	0.01	0.04	0.05	0.1	0.05	0.08
	< 120ha	0.03	0.13	0.04	0.12	0.04	0.05	0	0.01
	> 120ha	0.02	0.06	0	0	0.03	0.03	0.02	0.05
Proportion of Property in Forest	< 15ha	0.12	0.27	0.1	0.22	0.17	0	0.13	0.16
	< 30ha	0.1	0.23	0.03	0.05	0.23	0.21	0.08	0.07
	< 60ha	0.21	0.28	0.14	0.15	0.26	0.2	0.11	0.12

	< 120ha	0.27	0.38	0.17	0.13	0.4	0.27	0.26	0.22
	> 120ha	0.14	0.19	0.12	0.07	0.14	0.11	0.17	0.14
Raw VOP	< 15ha	22363.78	42500.83	16824.46	18239.75	7448.83	8508.87	26607.17	37433.02
	< 30ha	32471.11	40519.64	45388.02	34058.49	18201.71	15043.32	33052.64	15986.21
	< 60ha	49261.45	115461.6	59451.4	60117	39024.46	62566.24	74904.35	76176.06
	< 120ha	88225.05	165041.55	109773.53	123716.24	59686.15	73325.57	93954.19	80971.39
	> 120ha	217760.1	474361.26	279847.5	383010.66	118622.47	140826.8	199733.8	241845.51
Raw VOP Per Hectare	< 15ha	3693.5	10150.85	3715.92	8185.07	540.58	595.72	3944.1	5974.06
	< 30ha	1471.55	1978.47	2002.9	1704.26	768.14	659.79	1619.64	757.97
	< 60ha	1129.05	2569.99	1322.38	1149.65	926.46	1727.9	1645.44	1515.76
	< 120ha	1026.88	1807.32	1108.65	1206.88	801.58	932.52	1204.64	969.66
	> 120ha	1000.06	1786.42	1319.27	1513.35	475.84	450.46	913.84	835.56
Income Entropy	< 15ha	0.93	0.83	0.6	0.39	1.31	0.53	1.07	0.52
	< 30ha	1.01	0.78	0.83	0.49	1.07	0.44	1.16	0.4
	< 60ha	0.96	0.85	0.77	0.53	1.03	0.43	0.91	0.5
	< 120ha	0.8	0.83	0.75	0.42	0.77	0.6	0.91	0.39
	> 120ha	0.7	0.61	0.58	0.42	0.78	0.17	0.79	0.42
Cattle Density	< 15ha	3.02	1.68	3.91	1.13	2.17	0	2.64	1.24
	< 30ha	3.72	4.29	4.14	3.23	2.31	1.66	4.33	2.28
	< 60ha	2.84	3.38	2.74	1	2.66	1.61	3.43	2.8
	< 120ha	2.19	1.6	2.25	0.99	1.97	0.92	2.38	0.86
	> 120ha	2.59	3.1	2.25	0.94	3.05	2.44	2.74	1.66
Average Cost of Fungicide per Hectare	< 15ha	33.19	182.67	0	0	0	0	53.93	182.67
	< 30ha	0.31	3.51	0	0	0	0	1.01	3.51
	< 60ha	0.23	2.37	0.13	0.5	0.14	0.64	0.62	2.22
	< 120ha	0.42	3.06	0.92	2.99	0	0	0.23	0.63
	> 120ha	1.58	16.67	0.13	0.4	8.33	16.67	0.02	0.05
Average Cost of Herbicide per Hectare	< 15ha	22.36	46.51	7.79	13.46	12.32	0.25	31.08	44.51
	< 30ha	12.73	27.79	15.18	15.86	5.02	5.51	18.75	22.15
	< 60ha	5.01	21.95	3.63	3.9	3.43	5.14	12.12	20.97
	< 120ha	4.26	15.01	4.54	9.28	1.15	1.62	7.98	11.68

	> 120ha	7.51	34.1	4.01	4.88	18.17	32.36	5.67	9.57
Average Cost of Chemical Fertilizer per Hectare	< 15ha	36.46	229.72	63.35	218.47	0	0	24.92	71.02
	< 30ha	4.03	19.86	3.94	12.86	1.54	3.48	6.79	14.73
	< 60ha	1.05	6.13	0.54	1.28	1.21	4.66	1.01	3.77
	< 120ha	3.35	16.4	3.12	7.06	0.64	2.33	7.02	14.61
	> 120ha	11.55	116.77	2.03	4.81	58.33	116.67	0.29	0.87
Maintenance Costs per Hectare	< 15ha	885.42	1872.44	1236.33	1650.59	416.67	0	581.38	884.07
	< 30ha	302.02	500.01	276.69	263.17	246.06	296.53	358.83	304.67
	< 60ha	109.05	160.96	104.75	107.9	101.82	61.85	124.6	102.18
	< 120ha	131.68	195.63	215.98	143.51	94.77	83.82	100.56	103.18
	> 120ha	133.12	123.97	176.76	54.44	102.7	50.96	118.9	99.04
Proportion of Pasture Recuperated per Year	< 15ha	0.73	NaN	0.62	0.53	0	NaN	0.83	0.24
	< 30ha	0.59	0.91	0.38	0.35	0.6	0.57	0.87	0.63
	< 60ha	0.2	0.62	0.18	0.14	0.1	0.09	0.58	0.6
	< 120ha	0.38	1.47	0.77	1.44	0.25	0.3	0.08	0.04
	> 120ha	0.43	1.12	0.06	0.04	0.37	0.42	0.83	1.03
Average Importance of Local Extension Services as a source of Information Regarding Prices	< 15ha	2.82	3.02	3	2.2	0	0	2.96	2.07
	< 30ha	2.53	3.74	3.12	2.26	1.88	1.93	2.57	2.28
	< 60ha	2.45	3.42	2.87	2.23	2.08	1.99	3.38	1.66
	< 120ha	2.85	3.4	3.33	2.09	2	1.79	3.25	2.01
	> 120ha	2.45	3.35	2	2.12	2	1.83	3.11	1.83
Average Importance of Local Extension Services as a source of Information Regarding Agricultural Techniques	< 15ha	3.08	4.06	3.38	2.14	2	2.83	3	1.98
	< 30ha	3.17	3.61	3.53	1.97	2.56	1.9	3.4	2.35
	< 60ha	3.32	3.12	3	2.24	3.16	1.91	4.21	1.05
	< 120ha	3.41	3.21	4	1.68	2.94	2.02	3.17	1.85
	> 120ha	3.41	3.18	3.11	2.15	4	1.41	3.44	1.88
Average Importance of Local Extension Services as a source of Information	< 15ha	1.9	3.5	1.23	1.92	1.5	2.12	2.29	2.01
	< 30ha	2.12	3.64	1.53	2.18	1.69	1.78	3.27	2.31
	< 60ha	2.03	3.6	2	2.33	1.7	1.82	3.21	2.04
	< 120ha	2.35	3.23	3.17	2.26	1.56	1.46	2.17	1.8

Regarding Climate	> 120ha	1.77	2.67	1.78	1.79	0.75	0.5	2.22	1.92
Average Importance of Local Extension Services as a source of Information Regarding Credit	< 15ha	2.85	3.58	2.62	2.02	1.5	2.12	3.08	2.06
	< 30ha	3.12	3.43	3.24	2.02	2.62	1.82	3.53	2.1
	< 60ha	3.2	3.24	3.8	2.04	2.88	2.07	3.71	1.44
	< 120ha	3.5	3.31	4.06	1.63	3.31	2.06	2.92	2.02
	> 120ha	3	2.26	1.67	1.22	4.25	0.96	3.78	1.64
Average Importance of Neighbors as a source of Information Regarding Prices	< 15ha	1.9	3.41	1.92	2.06	1.5	2.12	1.92	1.69
	< 30ha	2.79	3.34	2.29	2.26	3.06	1.61	3.07	1.87
	< 60ha	3.34	3.09	3.2	1.86	3.56	1.36	2.71	2.05
	< 120ha	2.54	3.16	2.72	2.11	2.75	1.61	2	1.71
	> 120ha	2.14	2.96	2	1.58	2.5	1.91	2.11	1.62
Average Importance of Neighbors as a source of Information Regarding Agricultural Techniques	< 15ha	1.54	3.31	1.54	1.85	1.5	2.12	1.54	1.74
	< 30ha	2.15	3.52	1.53	2.12	2.62	1.78	2.33	2.16
	< 60ha	2.57	3.17	2.07	2.09	2.84	1.57	2.14	1.79
	< 120ha	2.2	2.89	2.22	2.07	2.25	1.18	2.08	1.62
	> 120ha	1.73	2.58	1.44	1.94	2.25	0.96	1.78	1.39
Average Importance of Neighbors as a source of Information Regarding Climate	< 15ha	1.31	2.88	1.23	1.96	1	1.41	1.38	1.56
	< 30ha	1.94	3.31	0.94	1.64	2.19	1.72	2.8	2.31
	< 60ha	2.08	3.22	1.67	2.06	2.36	1.76	1.5	1.74
	< 120ha	1.48	2.73	1.56	1.95	1.44	1.09	1.42	1.56
	> 120ha	1.36	2.53	1.56	1.94	1.5	1	1.11	1.27
Average Importance of Neighbors as a source of Information Regarding Credit	< 15ha	1.59	3.07	1.46	2.07	1	1.41	1.71	1.78
	< 30ha	1.83	3.27	1.12	1.69	1.75	1.44	2.73	2.4
	< 60ha	2.62	3.41	2.07	2.22	2.72	1.7	2.86	1.96
	< 120ha	2.02	3.34	2.22	2.26	2.12	1.59	1.58	1.88
	> 120ha	1.77	3.12	1.89	2.2	2	1.15	1.56	1.88
Average Importance of Associations as a source of Information Regarding Prices	< 15ha	2.82	4.53	2.69	2.02	2.5	3.54	2.92	2
	< 30ha	2.38	3.72	2	2.32	1.75	2.08	3.47	2.03
	< 60ha	2.57	3.25	3.53	1.85	1.92	1.98	3.86	1.79
	< 120ha	2.87	3.29	3.67	1.64	2.19	2.14	2.58	1.88
	> 120ha	2.64	3.2	2.33	1.94	1	2	3.67	1.58

Average Importance of Associations as a source of Information Regarding Agricultural Techniques	< 15ha	2.56	3.82	2.54	2.26	1.5	2.12	2.67	2.24
	< 30ha	2.21	3.67	2	2.21	1.81	1.91	2.87	2.23
	< 60ha	2.57	2.96	3.2	2.01	1.88	2.05	4.36	0.74
	< 120ha	2.8	3.59	3.39	2.23	2.25	2.02	2.67	1.97
	> 120ha	2.5	3.24	2.33	1.87	1	2	3.33	1.73
Average Importance of Associations as a source of Information Regarding Climate	< 15ha	1.92	3.63	1.38	2.22	1.5	2.12	2.25	1.94
	< 30ha	1.49	3.24	0.94	1.85	0.75	1.18	3	2.39
	< 60ha	1.63	3.08	1.8	2.01	1.3	1.8	2.64	1.5
	< 120ha	1.89	3.33	2.33	2.2	1.56	1.71	1.67	1.83
	> 120ha	1.68	2.68	1	1.32	0.75	1.5	2.78	1.79
Average Importance of Associations as a source of Information Regarding Credit	< 15ha	2.62	3.31	2.54	2.22	1	1.41	2.79	2
	< 30ha	2.27	3.57	2.18	2.24	1.69	1.82	3	2.1
	< 60ha	2.34	3.39	2.47	2.26	1.8	2.13	4.14	1.35
	< 120ha	2.74	3.66	3.17	2.36	2.06	2.14	3	1.81
	> 120ha	2.09	2.51	1.44	1.59	0.75	1.5	3.33	1.22
Average Importance of Passersby as a source of Information Regarding Prices	< 15ha	1.49	3.43	1.69	2.06	1.5	2.12	1.38	1.74
	< 30ha	1.79	3.17	0.94	1.82	2.88	1.71	1.6	1.96
	< 60ha	2.04	3.08	1	1.56	2.5	1.67	1.5	2.07
	< 120ha	2.09	2.91	2.11	1.94	2.38	1.45	1.67	1.61
	> 120ha	1.41	3.3	1.33	1.66	2.5	2.38	1	1.58
Average Importance of Passersby as a source of Information Regarding Agricultural Techniques	< 15ha	0.77	4.16	0.92	1.89	2.5	3.54	0.54	1.1
	< 30ha	0.56	1.94	0.12	0.49	0.88	1.15	0.73	1.49
	< 60ha	1.22	2.51	0.33	1.05	1.72	1.85	0.36	1.34
	< 120ha	1.02	2.57	0.94	1.73	1.25	1.13	0.83	1.53
	> 120ha	0.59	1.86	0.44	0.88	1.5	1.29	0.33	1
Average Importance of Passersby as a source of Information Regarding Climate	< 15ha	0.61	2.07	0.42	1.44	0	0	0.75	1.48
	< 30ha	0.73	2.19	0.18	0.73	1	1.15	1.07	1.71
	< 60ha	0.8	1.77	0.27	1.03	1.18	1.44	0	0
	< 120ha	0.78	2.05	0.78	1.59	1.12	1.02	0.33	0.78
	> 120ha	0.64	2.34	0.44	1.33	0.5	0.58	0.89	1.83
Average Importance	< 15ha	0.85	2.38	1.15	1.95	0	0	0.75	1.36

of Passersby as a source of Information Regarding Credit	< 30ha	0.65	2.03	0.18	0.53	0.88	0.96	0.93	1.71
	< 60ha	1.14	2.69	0.8	1.7	1.46	1.79	0.36	1.08
	< 120ha	1.09	2.41	1.17	1.76	1.19	1.05	0.83	1.27
	> 120ha	0.73	2.33	0.67	1.32	0.5	0.58	0.89	1.83
Average Importance of Radio, Television, and Newspapers as sources of Information Regarding Prices	< 15ha	3.79	2.37	4.08	1.5	4.5	0.71	3.58	1.69
	< 30ha	3.94	2.61	3.88	1.93	3.38	1.59	4.6	0.74
	< 60ha	3.86	2.02	4.2	1.08	3.58	1.58	4.5	0.65
	< 120ha	4.13	2.11	4.17	1.5	3.94	1.18	4.33	0.89
	> 120ha	3.91	1.86	3.67	1.41	4.5	0.58	3.89	1.05
Average Importance of Radio, Television, and Newspapers as sources of Information Regarding Agricultural Techniques	< 15ha	2.69	3.87	3.38	1.61	2	2.83	2.38	2.1
	< 30ha	3.29	3.39	3	2.4	3.19	1.6	3.73	1.79
	< 60ha	2.94	3.34	3.13	1.88	2.96	1.84	2.64	2.06
	< 120ha	3.33	2.93	3.61	1.94	3.12	1.63	3.17	1.47
	> 120ha	3.5	1.88	2.22	1.56	4.5	0.58	4.33	0.87
Average Importance of Radio, Television, and Newspapers as sources of Information Regarding Climate	< 15ha	2.9	3.29	3.69	1.55	1.5	2.12	2.58	1.98
	< 30ha	3.52	3.57	3.18	2.43	3.5	1.86	3.93	1.83
	< 60ha	3.08	3.44	3.27	2.02	2.86	2.04	3.64	1.91
	< 120ha	4.07	2.67	4.17	1.62	4.56	0.81	3.25	1.96
	> 120ha	3.41	1.86	2.44	1.51	4.75	0.5	3.78	0.97
Average Importance of Radio, Television, and Newspapers as sources of Information Regarding Credit	< 15ha	2.36	3.52	2.15	1.95	1.5	2.12	2.54	2.02
	< 30ha	2.9	3.47	2.59	2.29	2.38	1.86	3.8	1.82
	< 60ha	2.67	3	2.53	2.07	2.34	1.91	4	1.04
	< 120ha	2.98	3.51	3.17	2.18	2.81	1.72	2.92	2.15
	> 120ha	2.91	1.66	1.33	1.22	4.75	0.5	3.67	1
Average Importance of the Internet as a source of Information Regarding Prices	< 15ha	0.26	1.72	0.38	1.39	0	0	0.21	1.02
	< 30ha	0.44	2.45	0.59	1.66	0.38	1.26	0.33	1.29
	< 60ha	0.18	1.94	0.6	1.4	0	0	0.36	1.34
	< 120ha	0.3	1.72	0.22	0.94	0.06	0.25	0.75	1.42
	> 120ha	0.73	3.31	0.78	1.72	1.25	2.5	0.44	1.33
Average Importance	< 15ha	0.26	1.72	0.38	1.39	0	0	0.21	1.02

of the Internet as a source of Information Regarding Agricultural Techniques	< 30ha	0.52	2.71	0.59	1.66	0.62	1.71	0.33	1.29
	< 60ha	0.18	1.94	0.6	1.4	0	0	0.36	1.34
	< 120ha	0.3	1.82	0.17	0.71	0.19	0.75	0.67	1.5
	> 120ha	0.45	2.01	0.44	0.88	0.75	1.5	0.33	1
Average Importance of the Internet as a source of Information Regarding Climate	< 15ha	0.21	1.52	0.38	1.39	0	0	0.12	0.61
	< 30ha	0.44	2.45	0.59	1.66	0.38	1.26	0.33	1.29
	< 60ha	0.11	1.4	0.6	1.4	0	0	0	0
	< 120ha	0.35	2.07	0.17	0.71	0.31	1.25	0.67	1.5
	> 120ha	0.64	2.59	1	2	0.75	1.5	0.22	0.67
Average Importance of Neighbors as a source of Information Regarding Credit	< 15ha	0.26	1.72	0.38	1.39	0	0	0.21	1.02
	< 30ha	0.5	2.61	0.59	1.66	0.56	1.55	0.33	1.29
	< 60ha	0.19	2.01	0.67	1.5	0	0	0.36	1.34
	< 120ha	0.3	1.72	0.28	1.18	0.06	0.25	0.67	1.23
	> 120ha	0.36	2.26	0.33	1	1	2	0.11	0.33
Person-days of Contracted Labor per Year	< 15ha	40.02	165.83	1.45	3.08	18.25	25.81	62.61	163.78
	< 30ha	85.74	243.01	73.61	126.13	93.79	146.78	89.5	146.97
	< 60ha	138	419.35	109.56	278.99	149.12	215.37	119.69	227.23
	< 120ha	115.68	313.85	86.54	133.62	91.37	103.08	185.15	264.61
	> 120ha	253.14	931.06	189.79	172.31	697.5	880.35	203.67	249.32
Person-days of Family Labor per Year	< 15ha	110.49	227.84	115	154.02	42.25	18.03	115.31	166.92
	< 30ha	171.04	299.04	108.85	110.04	165.75	202.66	244.58	190.38
	< 60ha	169.73	272.39	158.2	166.11	172.37	163.63	169.04	140.81
	< 120ha	240.55	464.24	268.85	227.71	173.65	149.43	290.74	375.95
	> 120ha	253.08	471.73	141.21	121.17	1.5	2.12	396	455.9
Person-days of Contracted Labor per Hectare per Year	< 15ha	5.32	22.92	0.14	0.25	1.3	1.84	8.47	22.84
	< 30ha	4.22	13.52	3.49	6.78	4.31	7.34	4.9	9.11
	< 60ha	3.25	9.28	2.21	5.53	3.62	5.67	2.71	4.83
	< 120ha	1.54	4.59	0.89	1.4	1.34	1.53	2.65	4.09
	> 120ha	1.19	3.22	1.22	1.28	2.39	2.84	0.91	0.81
Person-days of Family Labor per Hectare per	< 15ha	16.13	31.07	18.12	21.67	3.35	1.75	16.43	22.2
	< 30ha	8.11	14.73	4.96	5.27	7.53	9.92	12.18	9.52

Year	< 60ha	4.07	6.69	3.5	3.64	4.21	4.75	4.03	2.99
	< 120ha	3.16	6.63	2.92	2.56	2.55	2.14	4.26	5.73
	> 120ha	1.31	2.05	0.89	0.77	0.01	0.01	1.92	1.91
Proportion of Property Intercropped	< 15ha	0.23	NaN	0.15	0.01	0	NaN	0.25	0.17
	< 30ha	0.21	NaN	0.26	0.31	0	NaN	0.19	0.13
	< 60ha	0.1	0.25	0.04	0.04	0.4	0.25	0.04	0.02
	< 120ha	0.04	0.04	0.04	0.03	0.1	0	0.03	0.01
	> 120ha	0.02	NaN	0.02	0	0	NaN	0.02	0.01
Proportion of Properties Producing Milk	< 15ha	0.38	0.85	0.38	0.49	0.5	0.5	0.38	0.48
	< 30ha	0.69	0.79	0.76	0.42	0.56	0.5	0.73	0.44
	< 60ha	0.7	0.74	0.87	0.34	0.64	0.48	0.71	0.45
	< 120ha	0.67	0.77	0.72	0.45	0.5	0.5	0.83	0.37
	> 120ha	0.82	0.64	0.67	0.47	0.75	0.43	1	0
Proportion of Properties Raising Cattle	< 15ha	0.46	0.86	0.46	0.5	0.5	0.5	0.46	0.5
	< 30ha	0.73	0.76	0.76	0.42	0.62	0.48	0.8	0.4
	< 60ha	0.85	0.43	1	0	0.76	0.43	1	0
	< 120ha	0.91	0.49	0.94	0.23	0.88	0.33	0.92	0.28
	> 120ha	1	0	1	0	1	0	1	0
Milk Production per Hectare Pasture per Day	< 15ha	50.81	57.59	3.3	0.97	78.26	0	74.15	57.58
	< 30ha	62.99	86.98	19.79	29.99	62.22	44.31	114.67	68.58
	< 60ha	69.92	346.43	21.84	54.96	58.64	37.12	168.51	340.02
	< 120ha	37.37	63.07	20.73	38.32	45.72	36.59	52.33	34.23
	> 120ha	20.32	31.17	11.93	14.82	23.14	23.39	24.98	14.32
Proportion of Properties Having Sold Property	< 15ha	0.1	0.42	0.08	0.27	0	0	0.12	0.33
	< 30ha	0.09	0.46	0.06	0.24	0.19	0.39	0	0
	< 60ha	0.13	0.66	0.27	0.44	0.04	0.2	0.29	0.45
	< 120ha	0.17	0.66	0.17	0.37	0.12	0.33	0.25	0.43
	> 120ha	0.09	0.44	0.11	0.31	0	0	0.11	0.31
Proportion of Properties Having Bought Property	< 15ha	0.21	0.56	0.15	0.36	0	0	0.25	0.43
	< 30ha	0.23	0.66	0.24	0.42	0	0	0.5	0.5
	< 60ha	0.33	0.8	0.33	0.47	0.24	0.43	0.64	0.48

	< 120ha	0.43	0.84	0.56	0.5	0.38	0.48	0.33	0.47
	> 120ha	0.71	0.76	0.88	0.33	0.5	0.5	0.67	0.47
Proportion of Properties Not Having Thought of Selling Property	< 15ha	0.77	0.75	0.85	0.36	0.5	0.5	0.75	0.43
	< 30ha	0.81	0.67	0.76	0.42	0.81	0.39	0.87	0.34
	< 60ha	0.67	0.77	0.8	0.4	0.62	0.49	0.71	0.45
	< 120ha	0.8	0.69	0.89	0.31	0.75	0.43	0.75	0.43
	> 120ha	0.64	0.73	0.56	0.5	0.25	0.43	0.89	0.31
Proportion of Properties Having Thought of Selling Part of Property	< 15ha	0	0	0	0	0	0	0	0
	< 30ha	0.02	0.24	0.06	0.24	0	0	0	0
	< 60ha	0.05	0.4	0	0	0.04	0.2	0.14	0.35
	< 120ha	0.02	0.24	0	0	0.06	0.24	0	0
	> 120ha	0.09	0.42	0.22	0.42	0	0	0	0
Proportion of Properties Having Thought of Selling Entire Property	< 15ha	0.23	0.75	0.15	0.36	0.5	0.5	0.25	0.43
	< 30ha	0.17	0.64	0.18	0.38	0.19	0.39	0.13	0.34
	< 60ha	0.28	0.71	0.2	0.4	0.34	0.47	0.14	0.35
	< 120ha	0.17	0.66	0.11	0.31	0.19	0.39	0.25	0.43
	> 120ha	0.27	0.68	0.22	0.42	0.75	0.43	0.11	0.31
Proportion of Properties Feeling Limited by Time in Achieving Goals on Property	< 15ha	0.15	0.54	0.31	0.46	0	0	0.08	0.28
	< 30ha	0.1	0.52	0.12	0.32	0.12	0.33	0.07	0.25
	< 60ha	0.08	0.49	0.07	0.25	0.06	0.24	0.14	0.35
	< 120ha	0.07	0.44	0.06	0.23	0	0	0.17	0.37
	> 120ha	0.05	0.31	0.11	0.31	0	0	0	0
Proportion of Properties Feeling Limited by Labor in Achieving Goals on Property	< 15ha	0.15	0.68	0.08	0.27	0.5	0.5	0.17	0.37
	< 30ha	0.15	0.61	0.18	0.38	0.12	0.33	0.13	0.34
	< 60ha	0.13	0.54	0	0	0.14	0.35	0.21	0.41
	< 120ha	0.11	0.54	0.11	0.31	0.06	0.24	0.17	0.37
	> 120ha	0.27	0.67	0.33	0.47	0	0	0.33	0.47
Proportion of Properties Feeling Limited by Money in Achieving Goals on	< 15ha	0.74	0.62	0.54	0.5	1	0	0.83	0.37
	< 30ha	0.85	0.6	0.88	0.32	0.94	0.24	0.73	0.44
	< 60ha	0.86	0.61	0.93	0.25	0.88	0.32	0.71	0.45
	< 120ha	0.85	0.62	0.83	0.37	0.88	0.33	0.83	0.37

Property	> 120ha	0.59	0.83	0.56	0.5	0.75	0.43	0.56	0.5
Proportion of Properties Feeling Limited by Regulation in Achieving Goals on Property	< 15ha	0.28	0.8	0.23	0.42	0.5	0.5	0.29	0.45
	< 30ha	0.15	0.61	0.18	0.38	0.12	0.33	0.13	0.34
	< 60ha	0.18	0.64	0.27	0.44	0.18	0.38	0.07	0.26
	< 120ha	0.22	0.67	0.33	0.47	0.19	0.39	0.08	0.28
	> 120ha	0.14	0.59	0.11	0.31	0.5	0.5	0	0
Proportion of Properties Not Using Tractors	< 15ha	0.74	0.63	0.62	0.49	1	0	0.79	0.41
	< 30ha	0.25	0.73	0.24	0.42	0.12	0.33	0.4	0.49
	< 60ha	0.41	0.84	0.33	0.47	0.4	0.49	0.5	0.5
	< 120ha	0.33	0.8	0.22	0.42	0.31	0.46	0.5	0.5
	> 120ha	0.41	0.81	0.33	0.47	0.25	0.43	0.56	0.5
Proportion of Properties Owning Tractors	< 15ha	0	0	0	0	0	0	0	0
	< 30ha	0.12	0.55	0.18	0.38	0	0	0.2	0.4
	< 60ha	0.06	0.42	0	0	0.06	0.24	0.14	0.35
	< 120ha	0.15	0.61	0.22	0.42	0.06	0.24	0.17	0.37
	> 120ha	0.36	0.81	0.33	0.47	0.25	0.43	0.44	0.5
Proportion of Properties Renting or Borrowing Tractors	< 15ha	0.26	0.63	0.38	0.49	0	0	0.21	0.41
	< 30ha	0.62	0.77	0.59	0.49	0.88	0.33	0.4	0.49
	< 60ha	0.53	0.84	0.67	0.47	0.54	0.5	0.36	0.48
	< 120ha	0.52	0.84	0.56	0.5	0.62	0.48	0.33	0.47
	> 120ha	0.23	0.69	0.33	0.47	0.5	0.5	0	0
Proportion of Properties Not Using Trucks	< 15ha	0.97	0.27	0.92	0.27	1	0	1	0
	< 30ha	0.75	0.64	1	0	0.44	0.5	0.8	0.4
	< 60ha	0.73	0.67	0.93	0.25	0.66	0.47	0.79	0.41
	< 120ha	0.7	0.69	0.89	0.31	0.38	0.48	0.83	0.37
	> 120ha	0.59	0.63	0.78	0.42	0	0	0.67	0.47
Proportion of Properties Owning Trucks	< 15ha	0	0	0	0	0	0	0	0
	< 30ha	0.02	0.25	0	0	0	0	0.07	0.25
	< 60ha	0.03	0.29	0	0	0.02	0.14	0.07	0.26
	< 120ha	0	0	0	0	0	0	0	0
	> 120ha	0.27	0.68	0.22	0.42	0.75	0.43	0.11	0.31

Proportion of Properties Renting or Borrowing Trucks	< 15ha	0.03	0.27	0.08	0.27	0	0	0	0
	< 30ha	0.23	0.6	0	0	0.56	0.5	0.13	0.34
	< 60ha	0.24	0.63	0.07	0.25	0.32	0.47	0.14	0.35
	< 120ha	0.3	0.69	0.11	0.31	0.62	0.48	0.17	0.37
	> 120ha	0.14	0.6	0	0	0.25	0.43	0.22	0.42
Proportion of Properties Without Future Plans	< 15ha	0.08	0.41	0.15	0.36	0	0	0.04	0.2
	< 30ha	0	0	0	0	0	0	0	0
	< 60ha	0.08	0.4	0	0	0.1	0.3	0.07	0.26
	< 120ha	0.07	0.42	0.11	0.31	0	0	0.08	0.28
	> 120ha	0	0	0	0	0	0	0	0
Proportion of Properties Planning to Expand in Future	< 15ha	0.23	0.73	0.08	0.27	0.5	0.5	0.29	0.45
	< 30ha	0.06	0.41	0.06	0.24	0	0	0.13	0.34
	< 60ha	0.09	0.54	0.13	0.34	0.06	0.24	0.14	0.35
	< 120ha	0.09	0.49	0.11	0.31	0	0	0.17	0.37
	> 120ha	0.23	0.59	0.11	0.31	0	0	0.44	0.5
Proportion of Properties Planning to Sell in Future	< 15ha	0.03	0.2	0	0	0	0	0.04	0.2
	< 30ha	0.02	0.24	0.06	0.24	0	0	0	0
	< 60ha	0.04	0.32	0.07	0.25	0.04	0.2	0	0
	< 120ha	0.02	0.23	0.06	0.23	0	0	0	0
	> 120ha	0.05	0.31	0.11	0.31	0	0	0	0
Proportion of Properties Planning to Intensify/Improve in Future	< 15ha	0.33	0.83	0.31	0.46	0.5	0.5	0.33	0.47
	< 30ha	0.4	0.75	0.35	0.48	0.69	0.46	0.13	0.34
	< 60ha	0.48	0.81	0.2	0.4	0.58	0.49	0.43	0.49
	< 120ha	0.59	0.81	0.44	0.5	0.81	0.39	0.5	0.5
	> 120ha	0.32	0.78	0.22	0.42	0.25	0.43	0.44	0.5
Proportion of Properties Not Planning to Change in Future	< 15ha	0	0	0	0	0	0	0	0
	< 30ha	0.15	0.58	0.18	0.38	0	0	0.27	0.44
	< 60ha	0.05	0.27	0	0	0.08	0.27	0	0
	< 120ha	0.02	0.23	0.06	0.23	0	0	0	0
	> 120ha	0.05	0.31	0.11	0.31	0	0	0	0
Proportion of	< 15ha	0.1	0.45	0.15	0.36	0	0	0.08	0.28

Properties Planning to Reforest in Future	< 30ha	0.12	0.57	0.18	0.38	0.06	0.24	0.13	0.34
	< 60ha	0.05	0.48	0.2	0.4	0	0	0.07	0.26
	< 120ha	0.11	0.55	0.06	0.23	0.06	0.24	0.25	0.43
	> 120ha	0.41	0.59	0.78	0.42	0	0	0.22	0.42
Proportion of Properties Planning to Expand Crops in Future	< 15ha	0.38	0.62	0.15	0.36	0	0	0.54	0.5
	< 30ha	0.35	0.8	0.18	0.38	0.5	0.5	0.4	0.49
	< 60ha	0.32	0.82	0.4	0.49	0.26	0.44	0.43	0.49
	< 120ha	0.13	0.57	0.11	0.31	0.19	0.39	0.08	0.28
	> 120ha	0.09	0.5	0	0	0.5	0.5	0	0
Proportion of Properties Planning to Expand Cattle in Future	< 15ha	0.15	0.42	0.08	0.27	1	0	0.12	0.33
	< 30ha	0.27	0.76	0.24	0.42	0.38	0.48	0.2	0.4
	< 60ha	0.27	0.73	0.13	0.34	0.3	0.46	0.29	0.45
	< 120ha	0.2	0.69	0.11	0.31	0.25	0.43	0.25	0.43
	> 120ha	0.27	0.76	0.11	0.31	0.5	0.5	0.33	0.47
Proportion of Properties Planning to Expand Aquaculture in Future	< 15ha	0.08	0.27	0.08	0.27	1	0	0	0
	< 30ha	0.15	0.6	0.24	0.42	0.06	0.24	0.13	0.34
	< 60ha	0.16	0.61	0.2	0.4	0.18	0.38	0.07	0.26
	< 120ha	0.28	0.76	0.28	0.45	0.38	0.48	0.17	0.37
	> 120ha	0.23	0.62	0.11	0.31	0.75	0.43	0.11	0.31
Proportion of Properties Planning Other Things in Future	< 15ha	0.08	0.41	0.15	0.36	0	0	0.04	0.2
	< 30ha	0.04	0.32	0.12	0.32	0	0	0	0
	< 60ha	0.03	0.34	0.13	0.34	0	0	0	0
	< 120ha	0.04	0.36	0.06	0.23	0	0	0.08	0.28
	> 120ha	0	0	0	0	0	0	0	0
Proportion of Properties Using Irrigation	< 15ha	0.28	0.8	0.23	0.42	0.5	0.5	0.29	0.45
	< 30ha	0.29	0.75	0.29	0.46	0.12	0.33	0.47	0.5
	< 60ha	0.08	0.53	0.07	0.25	0.02	0.14	0.29	0.45
	< 120ha	0.17	0.65	0.17	0.37	0.06	0.24	0.33	0.47
	> 120ha	0.14	0.54	0.11	0.31	0	0	0.25	0.43
Proportion of Properties that have	< 15ha	0.41	0.86	0.46	0.5	0.5	0.5	0.38	0.48
	< 30ha	0.48	0.86	0.47	0.5	0.44	0.5	0.53	0.5

Received Credit	< 60ha	0.57	0.85	0.4	0.49	0.64	0.48	0.5	0.5
	< 120ha	0.59	0.77	0.67	0.47	0.75	0.43	0.25	0.43
	> 120ha	0.5	0.86	0.44	0.5	0.5	0.5	0.56	0.5
Number of Times per Year Worked in Mutirão	< 15ha	1.6	1.41	1	1.41	2	0	2	0
	< 30ha	3.88	6.9	5.83	5.78	3.5	3.27	2	1.87
	< 60ha	8.59	22.02	13.5	18.08	9.83	12.46	2.83	1.6
	< 120ha	4.17	6.2	2.4	1.67	7	4.24	4.8	4.21
	> 120ha	6.33	NaN	5	4.36	0	NaN	7.67	10.79
Number of Times per Year Received Help in Mutirão	< 15ha	0.4	1.41	0	0	0	0	1	1.41
	< 30ha	7.19	44.51	1	2.24	1.17	2.04	20.6	44.4
	< 60ha	4.05	14.88	2.75	3.2	6.18	14.43	1	1.67
	< 120ha	1.33	7.56	1.2	2.68	5	7.07	0	0
	> 120ha	1.83	NaN	3.67	5.51	0	NaN	0	0
Proportion of Properties That Would Plant More if Drought Expected	< 15ha	0.08	0.41	0.15	0.36	0	0	0.04	0.2
	< 30ha	0.07	0.43	0.06	0.24	0.14	0.35	0	0
	< 60ha	0.05	0.36	0.08	0.27	0.06	0.24	0	0
	< 120ha	0.05	0.36	0.06	0.24	0	0	0.08	0.28
	> 120ha	0.06	0.35	0	0	0	0	0.14	0.35
Proportion of Properties That Would Plant Less if Drought Expected	< 15ha	0.51	0.86	0.62	0.49	0.5	0.5	0.46	0.5
	< 30ha	0.53	0.86	0.5	0.5	0.5	0.5	0.6	0.49
	< 60ha	0.68	0.82	0.54	0.5	0.73	0.44	0.64	0.48
	< 120ha	0.7	0.78	0.82	0.38	0.67	0.47	0.58	0.49
	> 120ha	0.65	0.67	0.5	0.5	1	0	0.71	0.45
Proportion of Properties That Would Plant the Same if Drought Expected	< 15ha	0.41	0.82	0.23	0.42	0.5	0.5	0.5	0.5
	< 30ha	0.4	0.85	0.44	0.5	0.36	0.48	0.4	0.49
	< 60ha	0.27	0.79	0.38	0.49	0.21	0.41	0.36	0.48
	< 120ha	0.25	0.74	0.12	0.32	0.33	0.47	0.33	0.47
	> 120ha	0.29	0.61	0.5	0.5	0	0	0.14	0.35
Proportion of Properties That Would Plant Earlier if	< 15ha	0.33	0.64	0.46	0.5	1	0	0.21	0.41
	< 30ha	0.29	0.77	0.25	0.43	0.43	0.49	0.2	0.4
	< 60ha	0.19	0.65	0.08	0.27	0.19	0.39	0.29	0.45

Drought Expected	< 120ha	0.18	0.64	0.22	0.42	0.2	0.4	0.09	0.29
	> 120ha	0.24	0.63	0.25	0.43	0	0	0.29	0.45
Proportion of Properties That Would Plant Later if Drought Expected	< 15ha	0.23	0.58	0.15	0.36	0	0	0.29	0.45
	< 30ha	0.24	0.73	0.31	0.46	0.14	0.35	0.27	0.44
	< 60ha	0.23	0.59	0.15	0.36	0.31	0.46	0	0
	< 120ha	0.27	0.77	0.22	0.42	0.33	0.47	0.27	0.45
	> 120ha	0.12	0.61	0	0	0.5	0.5	0.14	0.35
Proportion of Properties That Would Plant Following Rainfall if Drought Expected	< 15ha	0.28	0.65	0.31	0.46	0	0	0.29	0.45
	< 30ha	0.27	0.74	0.38	0.48	0.14	0.35	0.27	0.44
	< 60ha	0.39	0.83	0.62	0.49	0.31	0.46	0.43	0.49
	< 120ha	0.43	0.86	0.44	0.5	0.4	0.49	0.45	0.5
	> 120ha	0.29	0.78	0.38	0.48	0.5	0.5	0.14	0.35
Proportion of Properties That Would Plant at the Same Time if Drought Expected	< 15ha	0.15	0.49	0.08	0.27	0	0	0.21	0.41
	< 30ha	0.2	0.68	0.06	0.24	0.29	0.45	0.27	0.44
	< 60ha	0.2	0.7	0.15	0.36	0.19	0.39	0.29	0.45
	< 120ha	0.11	0.56	0.11	0.31	0.07	0.25	0.18	0.39
	> 120ha	0.35	0.69	0.38	0.48	0	0	0.43	0.49
Proportion of Cattle Ranchers that use Market Prices as a Stocking Decision Factor	< 15ha	0.11	0.37	0	0	0	0	0.17	0.37
	< 30ha	0.32	0.78	0.25	0.43	0.22	0.42	0.46	0.5
	< 60ha	0.18	0.68	0.2	0.4	0.17	0.37	0.21	0.41
	< 120ha	0.19	0.68	0.12	0.32	0.21	0.41	0.25	0.43
	> 120ha	0.33	0.7	0	0	0.5	0.5	0.56	0.5
Proportion of Cattle Ranchers that use Pasture Conditions as a Stocking Decision Factor	< 15ha	0.89	0.37	1	0	1	0	0.83	0.37
	< 30ha	0.76	0.72	0.83	0.37	0.78	0.42	0.69	0.46
	< 60ha	0.82	0.65	0.67	0.47	0.83	0.37	0.93	0.26
	< 120ha	0.74	0.74	0.76	0.42	0.64	0.48	0.83	0.37
	> 120ha	0.8	0.59	0.62	0.48	1	0	0.88	0.33
Proportion of Cattle Ranchers that use Counsel of Neighbors and Friends as a	< 15ha	0.11	0.46	0.17	0.37	0	0	0.08	0.28
	< 30ha	0.03	0.31	0	0	0.11	0.31	0	0
	< 60ha	0.02	0.25	0.07	0.25	0	0	0	0
	< 120ha	0.12	0.52	0.12	0.32	0.21	0.41	0	0

Stocking Decision Factor	> 120ha	0.1	0.54	0.12	0.33	0.25	0.43	0	0
Level of Knowledge Regarding Forest Code	< 15ha	2.05	0.99	2.08	0.49	2	0	2.04	0.86
	< 30ha	1.83	1.12	2	0.82	2.06	0.57	1.4	0.51
	< 60ha	2	1.09	2.2	0.68	1.96	0.45	1.93	0.73
	< 120ha	2	1.16	2	0.34	2.06	0.77	1.92	0.79
	> 120ha	2.09	1.3	1.89	0.33	2.75	1.26	2	0
Level of Knowledge Regarding Socio-ecological Economic Zoning	< 15ha	1.46	0.82	1.62	0.65	1	0	1.42	0.5
	< 30ha	1.34	0.96	1.44	0.63	1.44	0.63	1.13	0.35
	< 60ha	1.59	1.03	1.67	0.72	1.62	0.53	1.43	0.51
	< 120ha	1.85	1.12	1.83	0.62	2.06	0.77	1.58	0.51
	> 120ha	2	1.83	1.78	1.09	2.5	1.29	2	0.71
Level of Knowledge Regarding Sanctions for Environmental Crimes	< 15ha	1.77	0.99	1.92	0.86	2	0	1.67	0.48
	< 30ha	1.72	1.16	1.88	0.72	1.81	0.66	1.47	0.64
	< 60ha	1.94	1.14	2.2	0.77	1.8	0.64	2.14	0.53
	< 120ha	2.04	1.33	2.06	0.73	2.25	0.93	1.75	0.62
	> 120ha	2.18	1.37	2.11	0.33	2.5	1.29	2.11	0.33
Level of Knowledge Regarding Agrarian Reform and Productive Land Use	< 15ha	2.21	0.99	2.38	0.65	2	0	2.12	0.74
	< 30ha	2.51	4.88	3.25	4.78	2.12	0.62	2.13	0.74
	< 60ha	2.2	1.11	2.47	0.83	2.12	0.59	2.21	0.43
	< 120ha	2.54	1.4	2.56	0.78	2.5	0.73	2.58	0.9
	> 120ha	2.36	1.36	2.33	0.87	2.75	0.96	2.22	0.44
Level of Knowledge Regarding the Accelerated Growth Program	< 15ha	1.87	1.29	2	0.71	1.5	0.71	1.83	0.82
	< 30ha	1.85	1.4	1.69	0.6	1.75	0.68	2.13	1.06
	< 60ha	1.85	1.38	1.93	0.96	1.82	0.63	1.86	0.77
	< 120ha	1.91	1.13	1.78	0.65	1.81	0.54	2.25	0.75
	> 120ha	2.09	1.64	2.11	0.78	2.25	1.26	2	0.71
Level of Knowledge Regarding Environmental Licensing for Rural Properties (LAPRO)	< 15ha	2.23	1.16	2.31	0.75	2	0	2.21	0.88
	< 30ha	2.19	1.47	2.25	0.68	2.19	0.75	2.13	1.06
	< 60ha	2.3	1.3	2.47	0.83	2.24	0.66	2.36	0.74
	< 120ha	2.46	1.32	2.44	0.86	2.56	0.63	2.33	0.78
	> 120ha	2.55	1.18	2.78	0.83	2.75	0.5	2.22	0.67

Proportion of Properties Registered for LAPRO	< 15ha	0.05	0.33	0.08	0.27	0	0	0.04	0.2
	< 30ha	0.26	0.75	0.25	0.43	0.31	0.46	0.2	0.4
	< 60ha	0.29	0.66	0	0	0.38	0.49	0.29	0.45
	< 120ha	0.27	0.75	0.29	0.46	0.31	0.46	0.17	0.37
	> 120ha	0.27	0.76	0.22	0.42	0.25	0.43	0.33	0.47
Proportion of Properties not Registered for LAPRO Due to Perceived Lack of Necessity	< 15ha	0.21	0.75	0.23	0.42	0.5	0.5	0.17	0.37
	< 30ha	0.21	0.69	0.29	0.46	0.12	0.33	0.2	0.4
	< 60ha	0.19	0.69	0.33	0.47	0.16	0.37	0.14	0.35
	< 120ha	0.13	0.53	0.22	0.42	0.12	0.33	0	0
	> 120ha	0.09	0.44	0.11	0.31	0	0	0.11	0.31
Proportion of Properties not Registered for LAPRO Due to Lack of Time	< 15ha	0.18	0.51	0.08	0.27	0	0	0.25	0.43
	< 30ha	0.06	0.41	0.12	0.32	0	0	0.07	0.25
	< 60ha	0.09	0.48	0.2	0.4	0.08	0.27	0	0
	< 120ha	0.07	0.4	0.06	0.23	0.12	0.33	0	0
	> 120ha	0.09	0.44	0.11	0.31	0	0	0.11	0.31
Proportion of Properties not Registered for LAPRO Due to Disagreement with Program	< 15ha	0	0	0	0	0	0	0	0
	< 30ha	0	0	0	0	0	0	0	0
	< 60ha	0.01	0.25	0.07	0.25	0	0	0	0
	< 120ha	0	0	0	0	0	0	0	0
	> 120ha	0	0	0	0	0	0	0	0
Proportion of Properties not Registered for LAPRO Because Still Waiting	< 15ha	0.05	0.33	0.08	0.27	0	0	0.04	0.2
	< 30ha	0	0	0	0	0	0	0	0
	< 60ha	0.01	0.14	0	0	0.02	0.14	0	0
	< 120ha	0.09	0.48	0.11	0.31	0.06	0.24	0.08	0.28
	> 120ha	0.14	0.47	0.33	0.47	0	0	0	0
Proportion of Properties not Registered for LAPRO Because Program Would Impede Production	< 15ha	0	0	0	0	0	0	0	0
	< 30ha	0.04	0.34	0.06	0.24	0	0	0.07	0.25
	< 60ha	0.03	0.36	0.07	0.25	0	0	0.07	0.26
	< 120ha	0.09	0.49	0.11	0.31	0	0	0.17	0.37
	> 120ha	0.05	0.31	0	0	0	0	0.11	0.31
Proportion of	< 15ha	0.23	0.77	0.23	0.42	0.5	0.5	0.21	0.41

Properties not Registered for LAPRO Due to Lack of Information	< 30ha	0.12	0.57	0.06	0.24	0.12	0.33	0.2	0.4
	< 60ha	0.15	0.64	0.13	0.34	0.14	0.35	0.21	0.41
	< 120ha	0.07	0.43	0	0	0.12	0.33	0.08	0.28
	> 120ha	0.23	0.72	0.11	0.31	0.5	0.5	0.22	0.42
Proportion of Properties not Registered for LAPRO Due to Lack of Documentation	< 15ha	0.23	0.6	0.23	0.42	0	0	0.25	0.43
	< 30ha	0.29	0.77	0.18	0.38	0.44	0.5	0.27	0.44
	< 60ha	0.16	0.61	0.07	0.25	0.18	0.38	0.21	0.41
	< 120ha	0.2	0.67	0.06	0.23	0.19	0.39	0.42	0.49
	> 120ha	0.05	0.43	0	0	0.25	0.43	0	0
Proportion of Properties not Registered for LAPRO Due to Lack of Money	< 15ha	0.03	0.2	0	0	0	0	0.04	0.2
	< 30ha	0	0	0	0	0	0	0	0
	< 60ha	0	0	0	0	0	0	0	0
	< 120ha	0	0	0	0	0	0	0	0
	> 120ha	0.05	0.31	0	0	0	0	0.11	0.31
Proportion of Properties not Registered for LAPRO Without Explanation	< 15ha	0.03	0.27	0.08	0.27	0	0	0	0
	< 30ha	0.02	0.24	0.06	0.24	0	0	0	0
	< 60ha	0.06	0.47	0.13	0.34	0.04	0.2	0.07	0.26
	< 120ha	0.11	0.52	0.17	0.37	0.06	0.24	0.08	0.28
	> 120ha	0.05	0.31	0.11	0.31	0	0	0	0

Appendix F

Significance Statistics

This appendix presents Pearson Correlation Coefficients (R) and p-values (p) for raw correlations between survey responses and property size for all data presented in this study

Correlations significant at 90% confidence are marked in **boldface**

	Average across All Sites		**Ji-Paraná**		**Machadinho**		**Cacoal**	
Description	**R**	**p**	**R**	**p**	**R**	**p**	**R**	**p**
Proportion of Property in Pasture	0.05	0.4	-0.03	0.79	-0.01	0.96	0.11	0.34
Proportion of Property in Crops	**-0.16**	**0.01**	-0.13	0.27	**-0.2**	**0.07**	**-0.28**	**0.01**
Proportion of Property in Regrowth	-0.06	0.34	-0.03	0.8	-0.09	0.39	-0.09	0.43
Proportion of Property in Forest	**0.16**	**0.01**	**0.27**	**0.02**	**0.26**	**0.01**	**0.36**	**0**
Raw VOP	**0.48**	**0**	**0.51**	**0**	0.14	0.18	**0.31**	**0.01**
Raw VOP Per Hectare	-0.07	0.25	-0.08	0.51	-0.09	0.42	-0.14	0.24
Income Entropy	**-0.2**	**0**	**-0.22**	**0.06**	-0.14	0.21	**-0.27**	**0.02**
Cattle Density	-0.07	0.31	-0.07	0.57	0.13	0.3	-0.18	0.14
Average Cost of Fungicide per Hectare	-0.02	0.76	-0.03	0.83	**0.3**	**0**	-0.05	0.68
Average Cost of Herbicide per Hectare	-0.08	0.25	-0.12	0.33	0.16	0.13	-0.14	0.23
Average Cost of Chemical Fertilizer per Hectare	-0.02	0.73	-0.03	0.8	**0.29**	**0.01**	-0.07	0.57

Maintenance Costs per Hectare	-0.07	0.37	-0.08	0.59	**-0.27**	**0.04**	-0.11	0.38
Proportion of Pasture Recuperated per Year	0.01	0.92	0.01	0.91	**0.26**	**0.02**	-0.07	0.58
Average Importance of Local Extension Services as a source of Information Regarding Prices	**-0.13**	**0.04**	**-0.22**	**0.06**	0.06	0.59	-0.16	0.18
Average Importance of Local Extension Services as a source of Information Regarding Agricultural Techniques	**-0.15**	**0.02**	**-0.27**	**0.02**	0.14	0.2	-0.1	0.39
Average Importance of Local Extension Services as a source of Information Regarding Climate	**-0.13**	**0.04**	-0.14	0.24	0.01	0.94	**-0.26**	**0.02**
Average Importance of Local Extension Services as a source of Information Regarding Credit	**-0.17**	**0.01**	**-0.26**	**0.02**	-0.06	0.57	-0.18	0.11
Average Importance of Neighbors as a source of Information Regarding Prices	**-0.14**	**0.03**	-0.19	0.11	**-0.23**	**0.03**	-0.04	0.72
Average Importance of Neighbors as a source of Information Regarding Agricultural Techniques	-0.08	0.23	-0.13	0.25	**-0.2**	**0.06**	0.1	0.41
Average Importance of Neighbors as a source of Information Regarding Climate	-0.08	0.23	-0.1	0.37	**-0.19**	**0.08**	0.01	0.94
Average Importance of Neighbors as a source of Information Regarding Credit	-0.07	0.3	-0.12	0.3	-0.14	0.2	0.07	0.57
Average Importance of Associations as a source of Information Regarding Prices	**-0.13**	**0.04**	**-0.22**	**0.06**	0.02	0.84	**-0.21**	**0.07**
Average Importance of Associations as a source of Information Regarding Agricultural Techniques	**-0.13**	**0.05**	-0.19	0.1	-0.1	0.33	-0.19	0.11
Average Importance of Associations as a source of Information Regarding Climate	-0.1	0.12	-0.12	0.32	-0.05	0.62	-0.18	0.11

Average Importance of Associations as a source of Information Regarding Credit	**-0.13**	**0.05**	-0.18	0.13	-0.11	0.31	**-0.21**	**0.06**
Average Importance of Passersby as a source of Information Regarding Prices	**-0.12**	**0.07**	-0.12	0.3	-0.02	0.86	-0.11	0.34
Average Importance of Passersby as a source of Information Regarding Agricultural Techniques	-0.07	0.3	-0.06	0.6	-0.09	0.39	-0.03	0.78
Average Importance of Passersby as a source of Information Regarding Climate	-0.06	0.36	-0.05	0.68	-0.11	0.29	-0.03	0.78
Average Importance of Passersby as a source of Information Regarding Credit	-0.06	0.32	-0.08	0.49	-0.12	0.28	-0.02	0.88
Average Importance of Radio, Television, and Newspapers as sources of Information Regarding Prices	-0.04	0.56	-0.08	0.51	0.03	0.8	-0.04	0.76
Average Importance of Radio, Television, and Newspapers as sources of Information Regarding Agricultural Techniques	0.06	0.39	0.03	0.82	0.04	0.74	0.15	0.21
Average Importance of Radio, Television, and Newspapers as sources of Information Regarding Climate	0	0.95	-0.04	0.75	0.1	0.34	0.06	0.61
Average Importance of Radio, Television, and Newspapers as sources of Information Regarding Credit	-0.08	0.22	-0.12	0.31	0.02	0.88	-0.08	0.51
Average Importance of the Internet as a source of Information Regarding Prices	**0.45**	**0**	**0.45**	**0**	0.09	0.39	**0.58**	**0**
Average Importance of the Internet as a source of Information Regarding Agricultural Techniques	**0.4**	**0**	**0.43**	**0**	0.03	0.81	**0.52**	**0**
Average Importance of the Internet as a source of Information Regarding Climate	**0.36**	**0**	**0.27**	**0.02**	0.06	0.59	**0.68**	**0**

Average Importance of Neighbors as a source of Information Regarding Credit	**0.15**	**0.02**	-0.06	0.61	0.05	0.66	**0.58**	**0**
Person-days of Contracted Labor per Year	**0.16**	**0.02**	**0.24**	**0.08**	**0.42**	**0**	**0.23**	**0.07**
Person-days of Family Labor per Year	-0.04	0.62	-0.13	0.36	-0.17	0.13	0.04	0.75
Person-days of Contracted Labor per Hectare per Year	-0.06	0.41	-0.06	0.64	-0.11	0.33	-0.08	0.55
Person-days of Family Labor per Hectare per Year	-0.11	0.13	-0.12	0.4	**-0.26**	**0.02**	-0.15	0.25
Proportion of Property Intercropped	-0.05	0.44	-0.03	0.79	-0.05	0.67	-0.14	0.23
Proportion of Properties Producing Milk	-0.06	0.34	-0.12	0.32	-0.11	0.32	-0.03	0.77
Proportion of Properties Raising Cattle	0.08	0.19	0.09	0.43	-0.06	0.55	0.14	0.21
Milk Production per Hectare Pasture per Day	-0.07	0.31	-0.07	0.58	**-0.23**	**0.04**	-0.11	0.38
Proportion of Properties Having Sold Property	-0.05	0.44	-0.06	0.58	-0.06	0.55	-0.08	0.5
Proportion of Properties Having Bought Property	**0.2**	**0**	**0.22**	**0.06**	0.08	0.44	**0.24**	**0.04**
Proportion of Properties Not Having Thought of Selling Property	-0.04	0.49	-0.17	0.13	-0.03	0.75	0.1	0.37
Proportion of Properties Having Thought of Selling Part of Property	**0.24**	**0**	**0.43**	**0**	-0.03	0.8	-0.03	0.78
Proportion of Properties Having Thought of Selling Entire Property	-0.06	0.32	-0.07	0.57	0.05	0.67	-0.1	0.41
Proportion of Properties Feeling Limited by Time in Achieving Goals on Property	-0.05	0.43	-0.07	0.55	-0.07	0.53	-0.07	0.55
Proportion of Properties Feeling Limited by Labor in Achieving Goals on Property	0.03	0.68	0.11	0.35	-0.08	0.45	-0.08	0.47
Proportion of Properties Feeling Limited by Money in Achieving Goals on Property	**-0.22**	**0**	**-0.28**	**0.01**	-0.04	0.74	**-0.2**	**0.08**
Proportion of Properties Feeling Limited by Regulation in Achieving Goals on Property	**0.15**	**0.02**	**0.26**	**0.02**	0.06	0.55	0	0.98

Proportion of Properties Not Using Tractors	**-0.11**	**0.08**	-0.12	0.3	0.1	0.35	**-0.24**	**0.04**
Proportion of Properties Owning Tractors	**0.33**	**0**	**0.37**	**0**	0.12	0.27	**0.37**	**0**
Proportion of Properties Renting or Borrowing Tractors	**-0.11**	**0.08**	-0.17	0.14	-0.15	0.15	-0.05	0.68
Proportion of Properties Not Using Trucks	-0.07	0.26	-0.14	0.22	-0.05	0.64	**-0.27**	**0.02**
Proportion of Properties Owning Trucks	**0.27**	**0**	**0.26**	**0.03**	**0.36**	**0**	**0.47**	**0**
Proportion of Properties Renting or Borrowing Trucks	-0.07	0.3	-0.04	0.74	-0.1	0.36	-0.05	0.68
Proportion of Properties Without Future Plans	-0.03	0.6	-0.04	0.72	-0.04	0.74	-0.04	0.73
Proportion of Properties Planning to Expand in Future	-0.04	0.5	-0.05	0.67	-0.07	0.52	-0.08	0.47
Proportion of Properties Planning to Sell in Future	0	0.98	-0.01	0.94	-0.02	0.85	-0.03	0.79
Proportion of Properties Planning to Intensify/Improve in Future	0.07	0.29	0.11	0.36	0.01	0.96	0.19	0.1
Proportion of Properties Not Planning to Change in Future	0.08	0.22	0.16	0.18	-0.05	0.64	-0.06	0.6
Proportion of Properties Planning to Reforest in Future	-0.04	0.55	-0.07	0.54	-0.04	0.72	-0.07	0.54
Proportion of Properties Planning to Expand Crops in Future	-0.08	0.24	-0.08	0.48	-0.05	0.63	-0.1	0.38
Proportion of Properties Planning to Expand Cattle in Future	**0.14**	**0.03**	**0.22**	**0.06**	-0.07	0.51	**0.27**	**0.02**
Proportion of Properties Planning to Expand Aquaculture in Future	0.02	0.74	0.06	0.64	0.12	0.26	-0.04	0.72
Proportion of Properties Planning Other Things in Future	-0.03	0.6	-0.06	0.59	NaN	NaN	-0.04	0.76
Proportion of Properties Using Irrigation	0.05	0.4	0.05	0.64	-0.07	0.54	0.04	0.74
Proportion of Properties that have Received Credit	0	0.98	0.06	0.63	0.05	0.65	-0.08	0.48
Times per Year Worked in Mutirão	0.03	0.83	-0.15	0.53	0.21	0.36	**0.49**	**0.02**
Times per Year Received Help in Mutirão	-0.09	0.49	0.18	0.47	0.16	0.49	-0.23	0.33

Proportion of Properties That Would Plant More if Drought Expected	-0.04	0.58	-0.05	0.67	-0.07	0.52	-0.03	0.79
Proportion of Properties That Would Plant Less if Drought Expected	-0.08	0.21	-0.07	0.53	-0.13	0.22	-0.12	0.29
Proportion of Properties That Would Plant the Same if Drought Expected	-0.04	0.54	-0.1	0.38	0.11	0.3	0	0.99
Proportion of Properties That Would Plant Earlier if Drought Expected	-0.08	0.2	-0.1	0.41	-0.16	0.14	-0.11	0.35
Proportion of Properties That Would Plant Later if Drought Expected	-0.07	0.3	-0.08	0.48	0.16	0.13	-0.11	0.34
Proportion of Properties That Would Plant Following Rainfall if Drought Expected	-0.03	0.64	-0.02	0.85	0.01	0.91	-0.13	0.28
Proportion of Properties That Would Plant at the Same Time if Drought Expected	0	1	-0.05	0.69	-0.12	0.28	0.1	0.41
Proportion of Cattle Ranchers that use Market Prices as a Stocking Decision Factor	**0.14**	**0.03**	0.09	0.43	0.05	0.67	**0.33**	**0**
Proportion of Cattle Ranchers that use Pasture Conditions as a Stocking Decision Factor	-0.05	0.44	-0.08	0.48	-0.01	0.91	-0.06	0.61
Proportion of Cattle Ranchers that use Counsel of Neighbors and Friends as a Stocking Decision Factor	-0.03	0.69	-0.05	0.69	0.06	0.55	-0.03	0.79
Level of Knowledge Regarding Forest Code	**0.13**	**0.04**	0.15	0.2	0.1	0.35	**0.2**	**0.07**
Level of Knowledge Regarding Socio-ecological Economic Zoning	**0.21**	**0**	**0.22**	**0.06**	0.08	0.44	**0.4**	**0**
Level of Knowledge Regarding Sanctions for Environmental Crimes	**0.18**	**0**	**0.2**	**0.08**	0.12	0.28	**0.29**	**0.01**
Level of Knowledge Regarding Agrarian Reform and Productive Land Use	0.02	0.7	0.02	0.86	0.1	0.37	-0.05	0.64

Level of Knowledge Regarding the Accelerated Growth Program	0.04	0.54	0.03	0.79	0.08	0.45	0.06	0.62
Level of Knowledge Regarding Environmental Licensing for Rural Properties (LAPRO)	0.1	0.12	0.06	0.63	0.06	0.57	**0.22**	**0.05**
Proportion of Properties Registered for LAPRO	**0.16**	**0.01**	**0.2**	**0.08**	-0.1	0.35	**0.38**	**0**
Proportion of Properties not Registered for LAPRO Due to Perceived Lack of Necessity	-0.07	0.29	-0.1	0.4	-0.08	0.46	-0.09	0.45
Proportion of Properties not Registered for LAPRO Due to Lack of Time	-0.05	0.46	-0.06	0.61	-0.02	0.84	-0.08	0.5
Proportion of Properties not Registered for LAPRO Due to Disagreement with Program	-0.01	0.89	-0.02	0.86	NaN	NaN	NaN	NaN
Proportion of Properties not Registered for LAPRO Because Still Waiting	-0.01	0.82	-0.03	0.8	0	0.99	-0.03	0.77
Proportion of Properties not Registered for LAPRO Because Program Would Impede Production	-0.01	0.83	-0.04	0.74	NaN	NaN	-0.01	0.91
Proportion of Properties not Registered for LAPRO Due to Lack of Information	0.04	0.56	0.12	0.3	0.31	**0**	-0.09	0.42
Proportion of Properties not Registered for LAPRO Due to Lack of Documentation	-0.08	0.24	-0.07	0.56	-0.07	0.51	-0.12	0.28
Proportion of Properties not Registered for LAPRO Due to Lack of Money	0	0.98	NaN	NaN	NaN	NaN	0	1
Proportion of Properties not Registered for LAPRO Without Explanation	-0.03	0.68	-0.05	0.66	-0.03	0.81	-0.03	0.82
(NaN: No Qualifying Data Points)								

Appendix G

Complete Survey Results and Discussion

FARM CHARACTERISTICS

Property size and land use

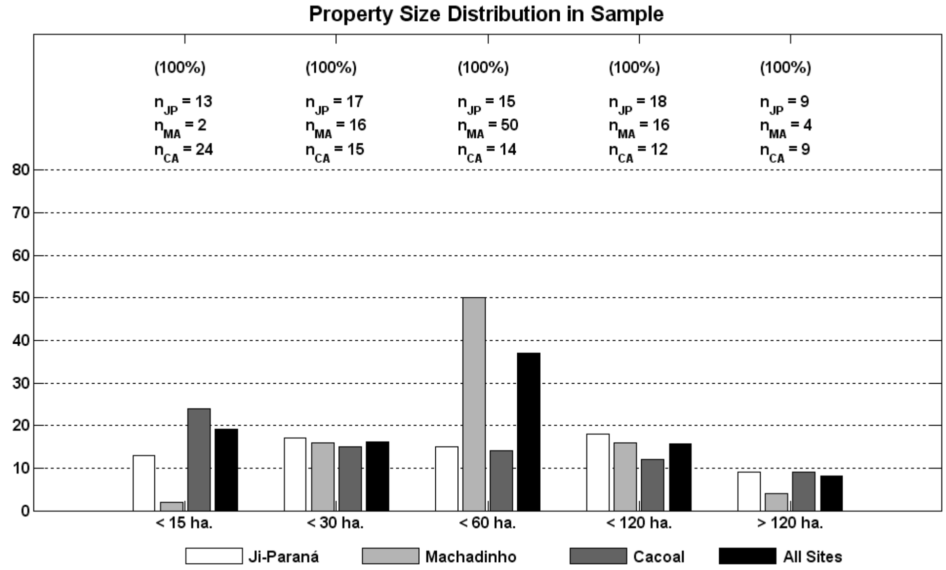

Figure G.1: Property size distribution in sample. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

The samples from the older settlements of Ji-Paraná and Cacoal are fairly evenly distributed across size classes – Cacoal shows a smooth decline as properties increase in size while Ji-Paraná shows a slight peak across the middle size classes. Machadinho, a newer settlement where less time has passed for subdivision or aggregation of properties, has a sampled distribution clustered much more tightly around the original lot allocation size of 50ha (Figure G.1). Land use follows a similar pattern across scale in all three sites, with cropland in smaller properties giving way to pasture land as property size increases (Figure G.2); the amount of land committed to pasture across all size classes is greatest in Ji-Paraná, followed by Cacoal and then Machadinho (Appendix E). Land committed to forest increases with property size for all but the largest size class in the sample, and is higher in Machadinho than in the two older sites (Appendix E). Muchagata and Brown (2003) observed higher proportions of land in pasture and specialization in cattle on older and larger family farms in Marabá, Pará, owing in part to their low labor demands and low risks in comparison to crops; the patterns in Cacoal and Ji-Paraná and the newer settlement in Machadinho fit this model of Rondônian farm evolution as well. Land-use intensity appears to fall off as property size increases – the proportion of land in pasture recuperated each year is generally lower, averaged across all three sites, for larger properties (Figure G.3), as is the per-hectare use of agro-toxins such as herbicides (whose use is most intense in Cacoal, where coffee production is intense) (Figure G.4). Farmers in the surveys were generally unable to reliably itemize the annual costs for maintaining their properties, but could estimate their overall annual maintenance costs, and these too reflect the same pattern in land-use intensity (Figure G.5). Several of the smallest properties in the sample were specialized chicken producers and horticulturalists with high infrastructure costs, giving the steep rise in maintenance costs per hectare seen for small properties; focusing only on properties that raise cattle as a more internally comparable subset still shows the same pattern in declining cost intensity with property size.

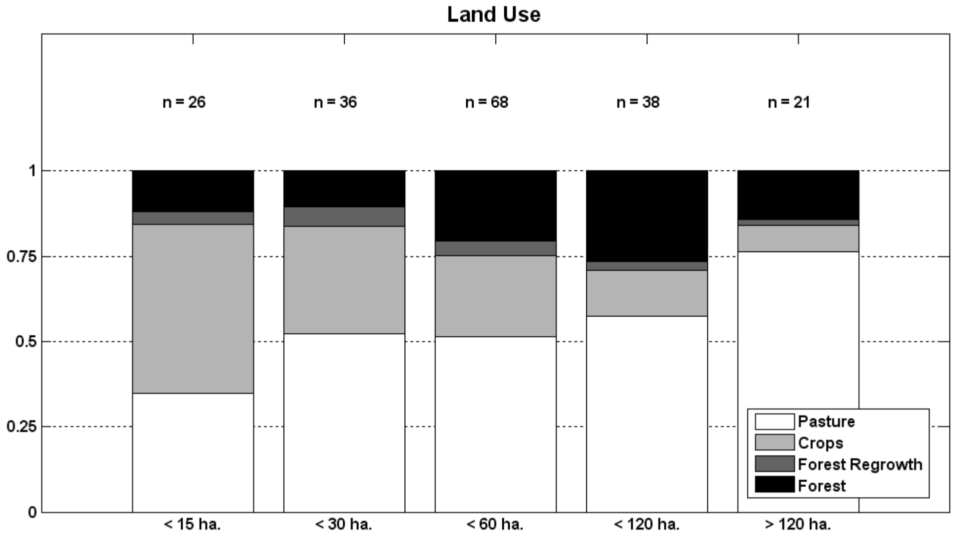

Figure G.2: Trends in land use across property size, aggregated across all 3 sites. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

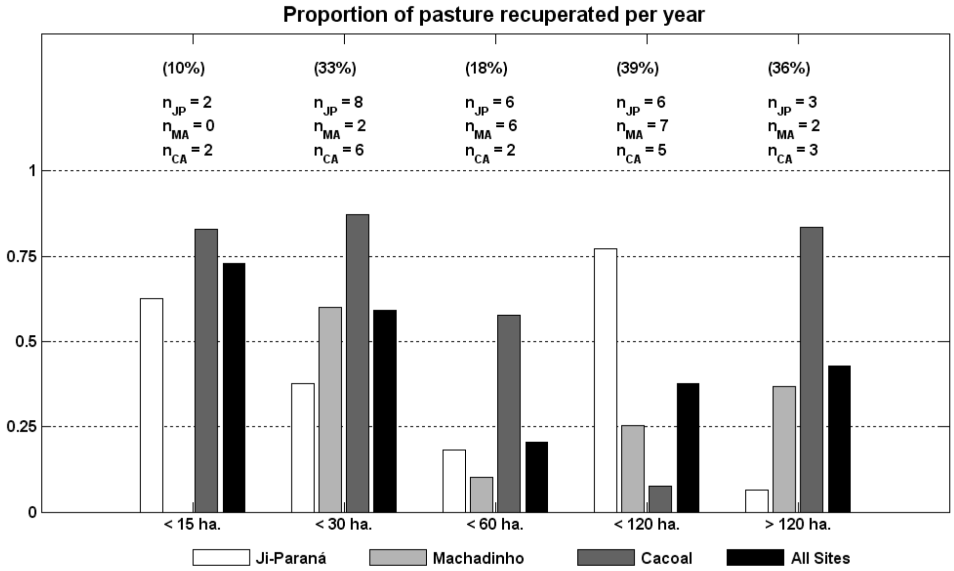

Figure G.3: Proportion of pasture recuperated annually. Percent refers to the percent of surveys in each size class who reported pasture recuperation; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

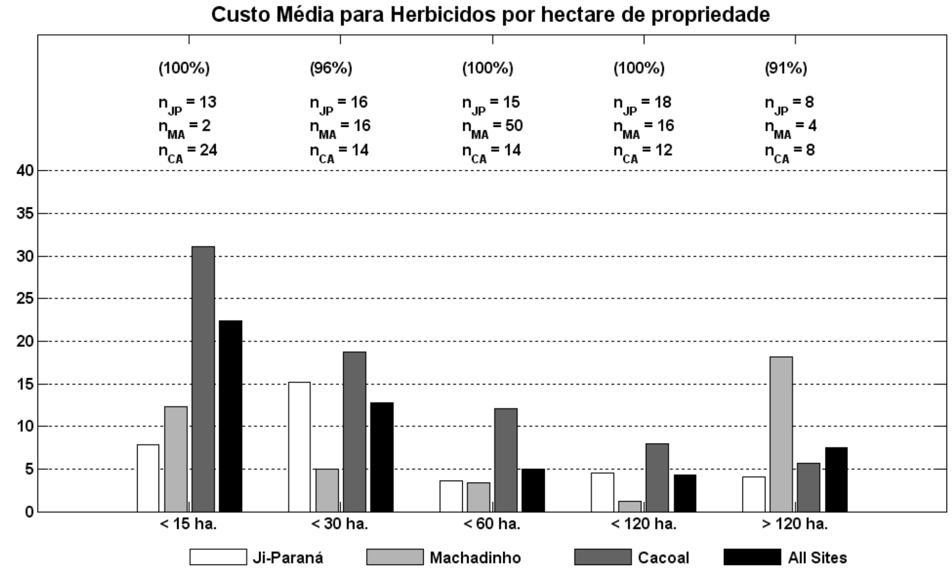

Figure G.4: Average investment in herbicides per hectare, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

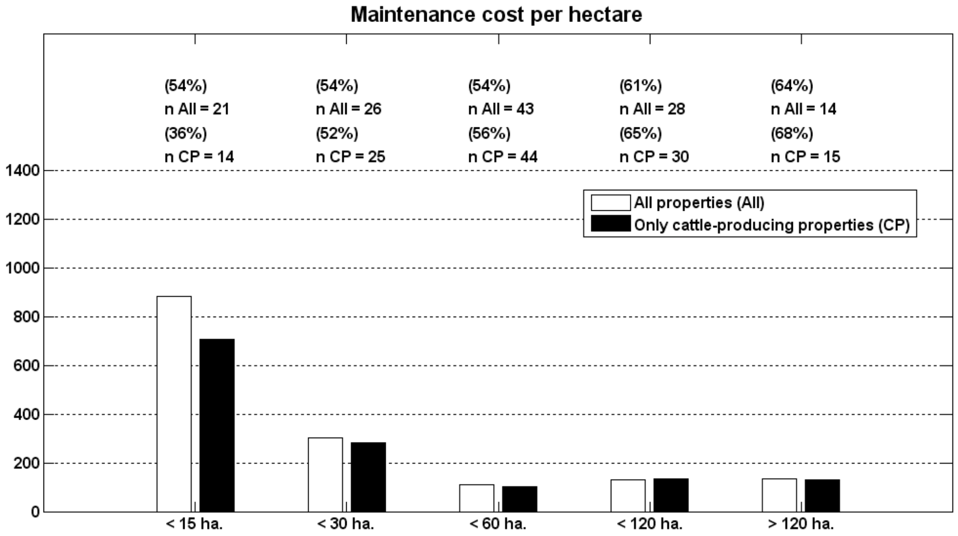

Figure G.5: Maintenance cost per hectare, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{All}, n_{CP}, are the number of surveys used from the set of all surveys, and the set of surveys of cattle-producing properties, respectively.

Labor use

Labor use, measured in person-days, increases with property size as the land area to be managed increases (Figures G.6, G.7). Labor-use intensity decreases with increasing property size (Figures G.8, G.9) which, together with the land-use intensity results in

Figures G.3 – G.5, signals an underutilization of land and a shift away from it being a scarce resource for larger properties. The ratio of family labor to contracted labor decreases with increasing property size, reflecting the shift from peasant production toward a more market-integrated capitalist family enterprise.

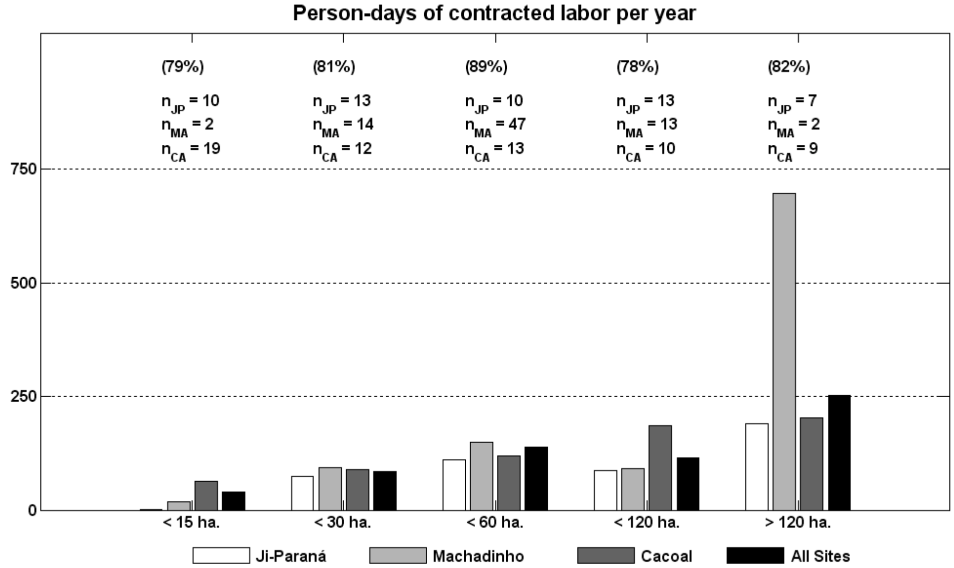

Figure G.6: Person-days of contracted labor, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

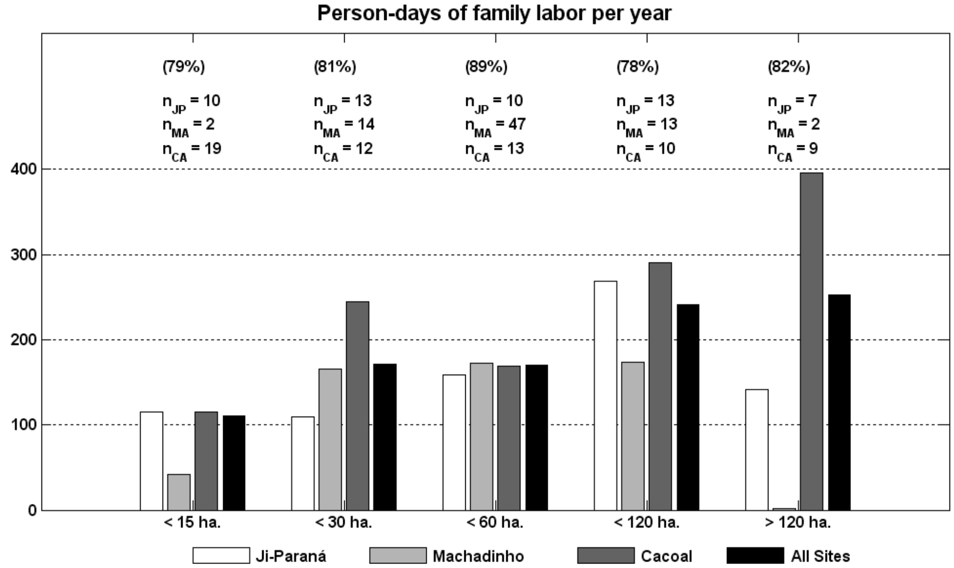

Figure G.7: Person-days of family labor, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

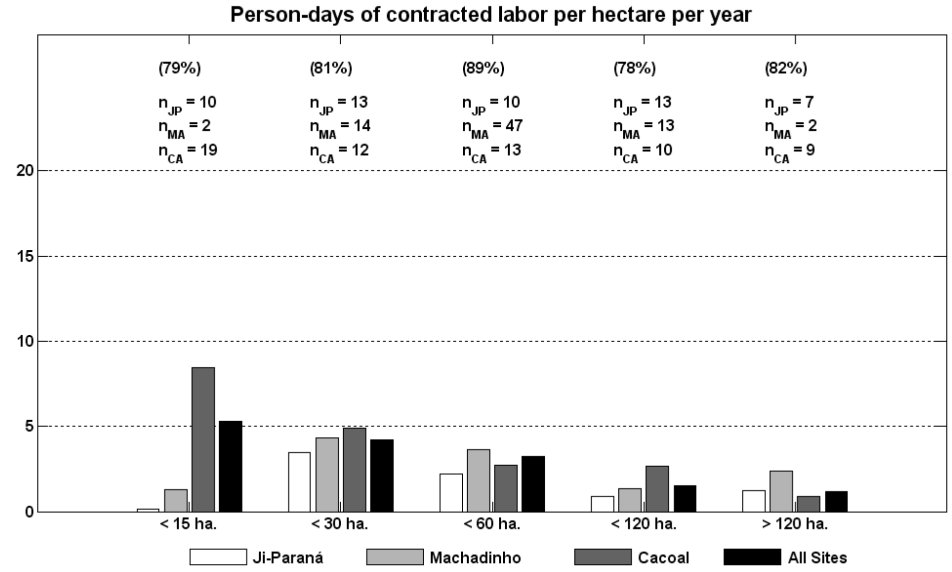

Figure G.8: Person-days of contracted labor per hectare, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

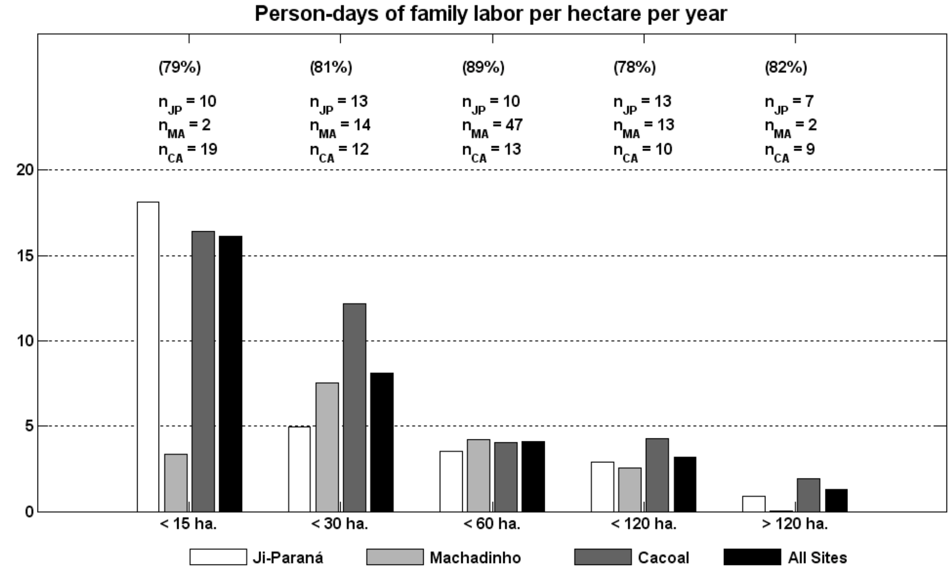

Figure G.9: Person-days of family labor per hectare, annually. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Farm production

The underutilization of land resources emerges again when looking at production as a function of farm size. The proportion of farms engaging in cattle ranching increases smoothly to encompass all properties above 120ha in size (Figure G.10), but the density of cattle (in head per hectare) is generally lower for larger properties (Figure G.11). Looking at averages across all three sites, the decision of how many cattle to stock is made exclusively on the basis of pasture conditions for smaller properties in the sample, though as property increases in size other factors – such as market prices for beef or the counsel of friends or neighbors – begin to contribute to decision-making (Figure G.12).

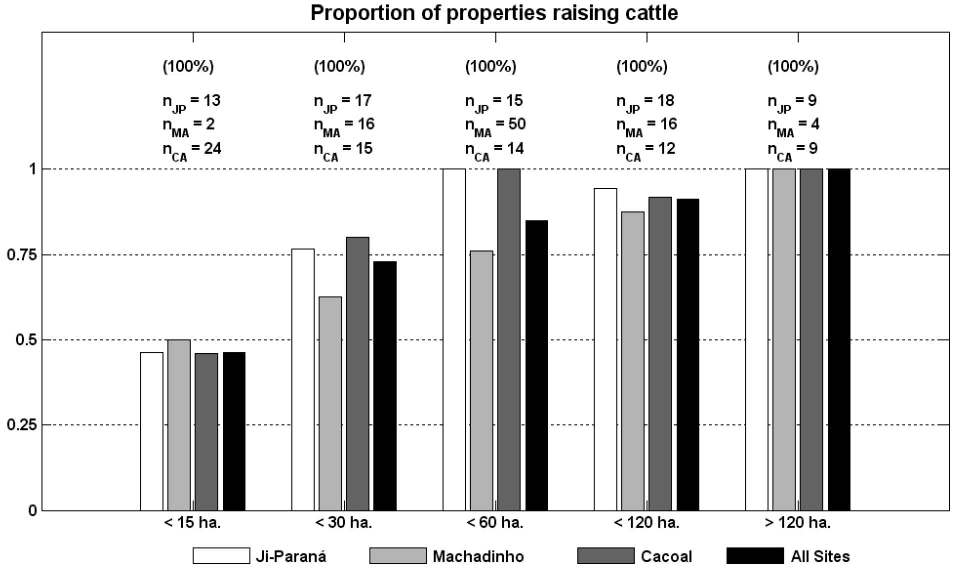

Figure G.10: Proportion of all properties raising cattle. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

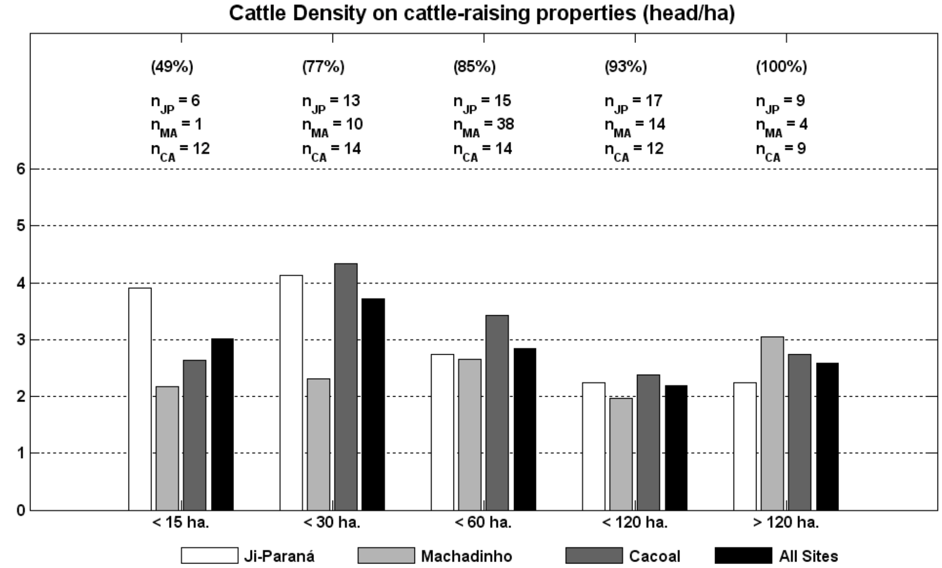

Figure G.11: Cattle stocking density on cattle raising properties. Percent refers to the percent of surveys in each size class reporting cattle stocking rate; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

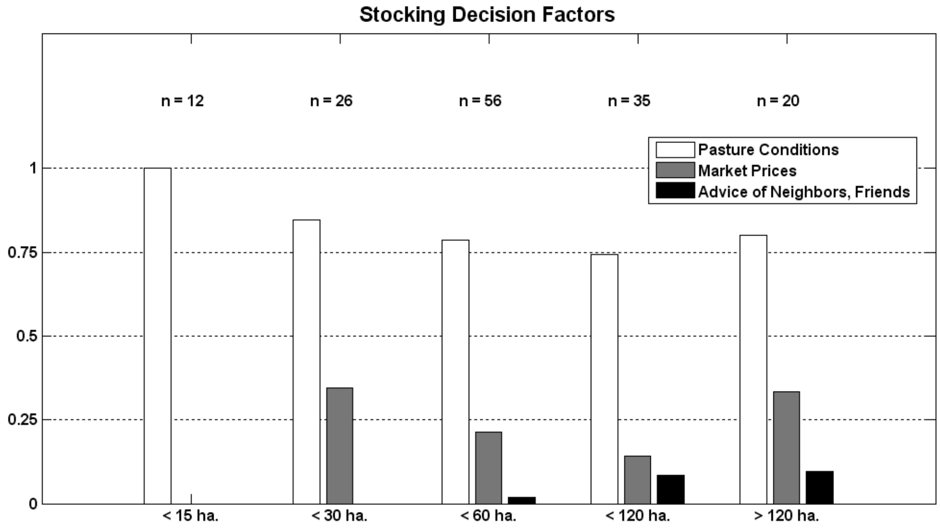

Figure G.12: Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

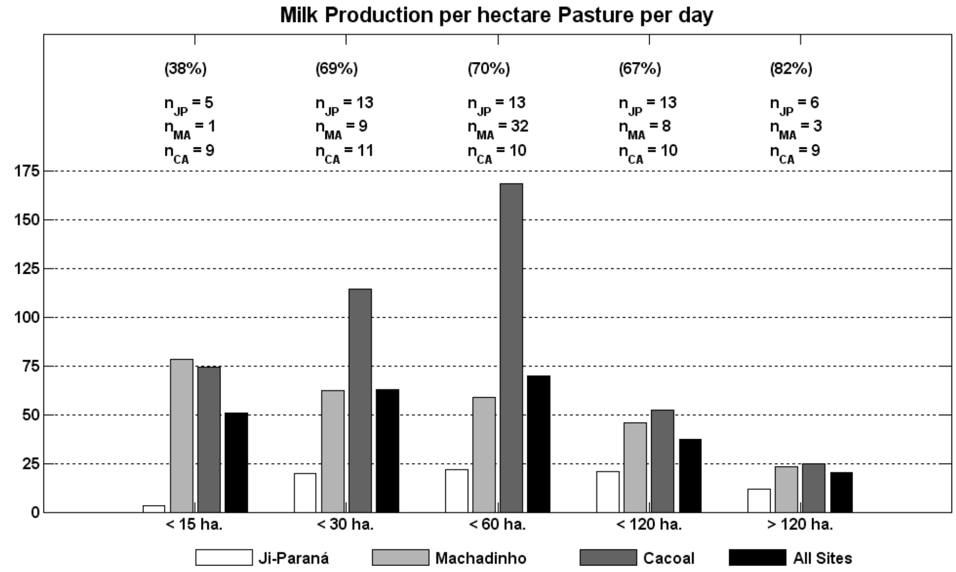

Figure G.13: Milk production intensity in liters. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Milk production among cattle producers in the sample shows a single peak, with production most intense on properties between 30 and 60ha in size, and important differences between the three sites (Figure G.13). Milk production intensity rises sharply in Cacoal, perhaps reflecting increased capital investment in milk production technology, before dropping off significantly as larger properties then move on to specialize in extensive beef production. Milk production intensity drops smoothly with size in Machadinho, possibly following the drop in land-use intensity that accompanies increasing farm size, without significant investment into milk production technology. Milk production intensity is generally low in Ji-Paraná, reflecting a local production focus on cattle for beef.

In general, production intensity decreases as farms increase in size. The raw value of production (VOP) is calculated here as the sum of farm production multiplied through by each product's per-unit economic value:

$$VOP = \sum_i M_i \cdot P_i$$

where M_i and P_i are the mass produced and per-unit price for product *i*. The per-unit price is estimated here as the average of the stated per-unit price reported by farmers across the sample. VOP and VOP per hectare in the sample are both highest for Ji-Paraná, followed by Cacoal, with Machadinho a distant third (Figures G.14, G.15).

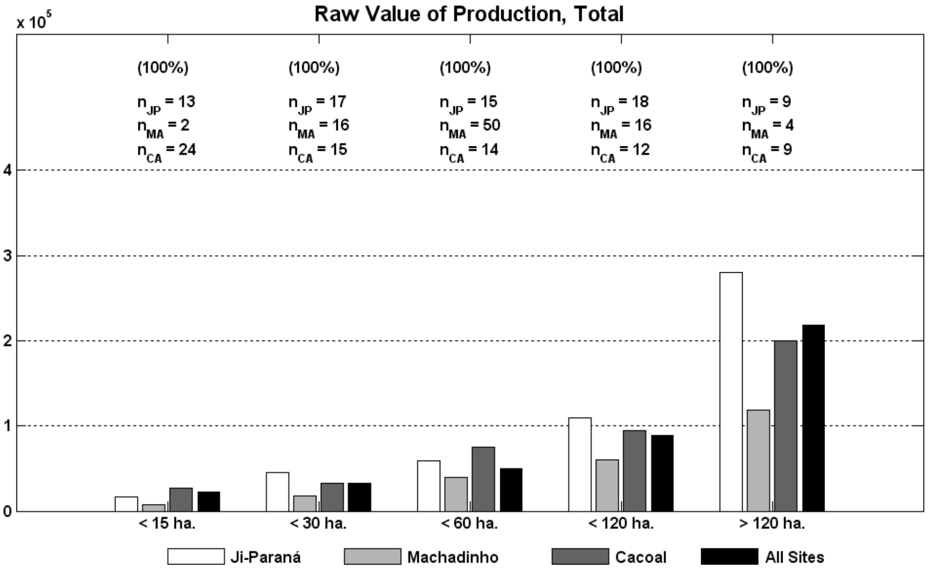

Figure G.14: Raw value of production in $R. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

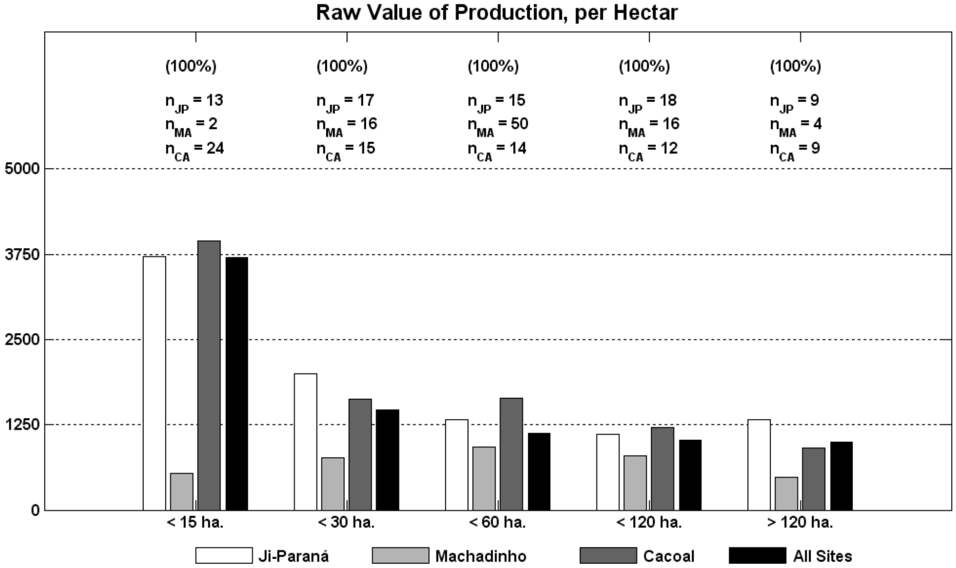

Figure G.15: Raw value of production in \$R/ha. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Income diversification

Beyond understanding the magnitude of a farm's income, it is important as well to understand how diversified it is. Diversity in farm income is measured here as the income entropy *E*:

$$E = -\sum_i f_i \cdot \ln(f_i)$$

where f_i is the fraction of farm income derived from source *i*. Income entropy is equal to 0 when all income is derived from a single source, and is maximized when income is derived equally from a large number of sources. For example, when income is derived in equal parts from two different sources, $E = 0.69$, and when derived in equal parts from ten different sources, $E = 2.3$. Income entropy in Machadinho shows a smooth decline with increasing farm size, while Ji-Paraná and Cacoal both show single-peaked distributions for income entropy across farm size (Figure G.16), and a drop in income diversity for the smallest size class. Some of the very small properties in these classes are urban horticulturalists, operating small, specialized operations that irrigate from river water and grow in greenhouses to supply labor- and water-intensive products like salad greens; others are capital intensive chick-hatching and chicken-raising operations. These examples of specialization at small scales highlight the departure that agriculture can take, once an area is sufficiently urban, from models like that of Muchagata and Brown (2003), where specialization follows an accumulation of property.

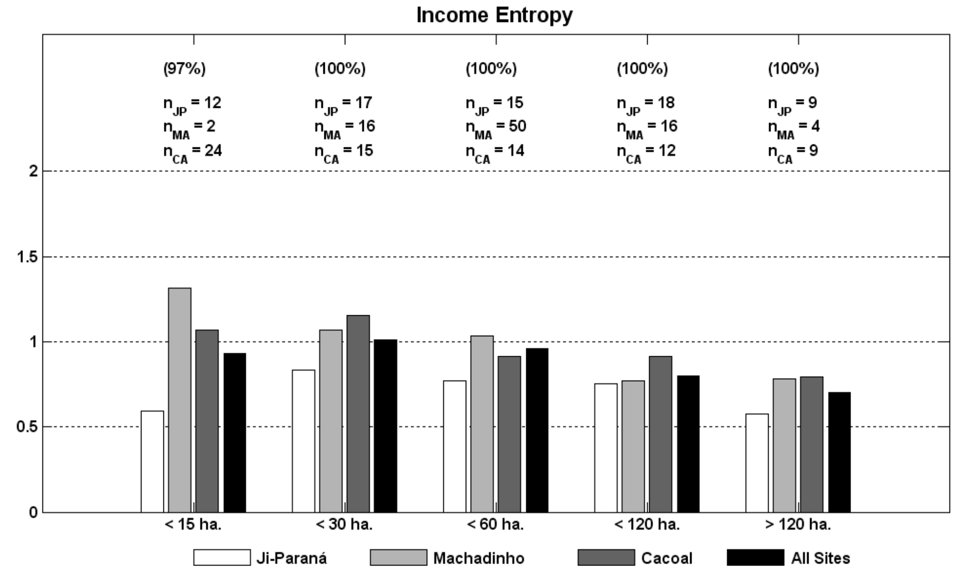

Figure G.16: Income entropy. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Technology

I look at the use and ownership of tractors and trucks as indicators of the use of technology and capitalization on farms. In both cases, looking at the average use of these technologies across all three sites, while ownership of trucks and tractors is largely restricted to larger landholders, use of these technologies is relatively constant across farm size for farms greater than 30ha in size (Figure G.17, G.18). Personal relationships between farmers as well as membership in local rural associations and syndicates provide access to farmers to rent or borrow farm equipment, and help smaller farms to behave like larger properties with respect to their use of technologies such as tractors and trucks. Put differently, network ties and the ability to share equipment reduces the diseconomy associated with bringing expensive big machines to small farms (Ellis 1993a).

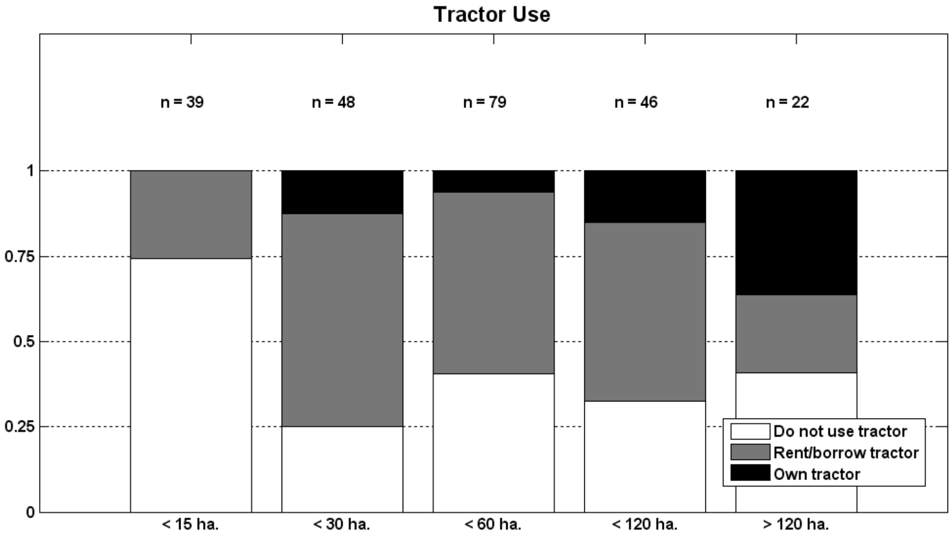

Figure G.17: Tractor use. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

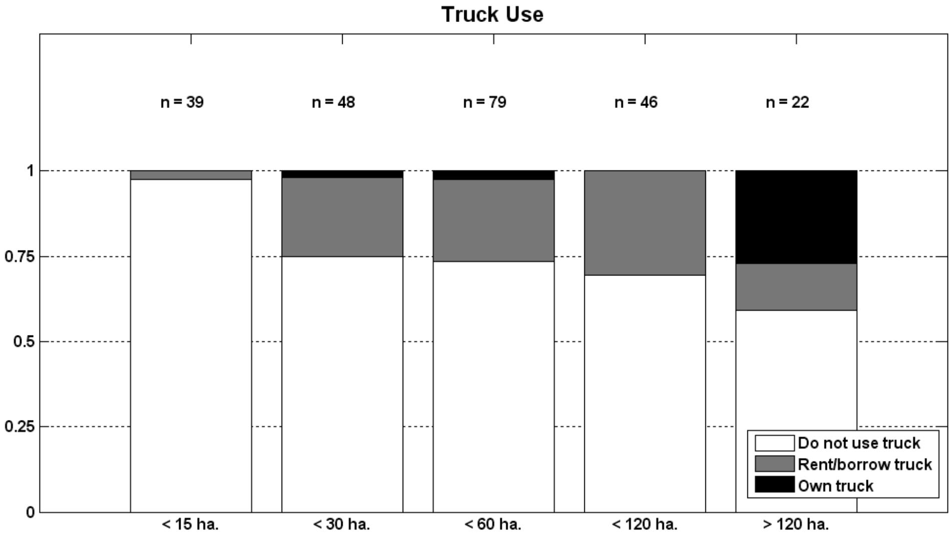

Figure G.18: Truck use. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

The way in which tractors affect production is a contentious topic in the rural economics literature, with two prevailing views dominating the discussion (Ellis 1993c). The substitution view argues that tractors simply substitute for animal and human labor without increasing yields or lowering costs; the net contribution view holds that tractors lead to a net increase in yields by making more land usable and allowing for more timely preparation of land, among other factors (Ellis 1993c). Ellis (1993) reviews the literature to find that tractors contribute little to net productivity in most developing countries, suggesting that the substitution view explains better the role of tractors in these areas, but this result is not borne out in this data. The minority of farmers on properties up to 60ha in size in the sample report higher labor use as well as higher value of production relative to other farmers in the same size classes who rent, borrow, or do not report using a tractor (Figures C.19, C.20). This paints a picture, within a size class of farm where production is already intense relative to larger farms, of a minority of well-capitalized farms where production is even more intensive.

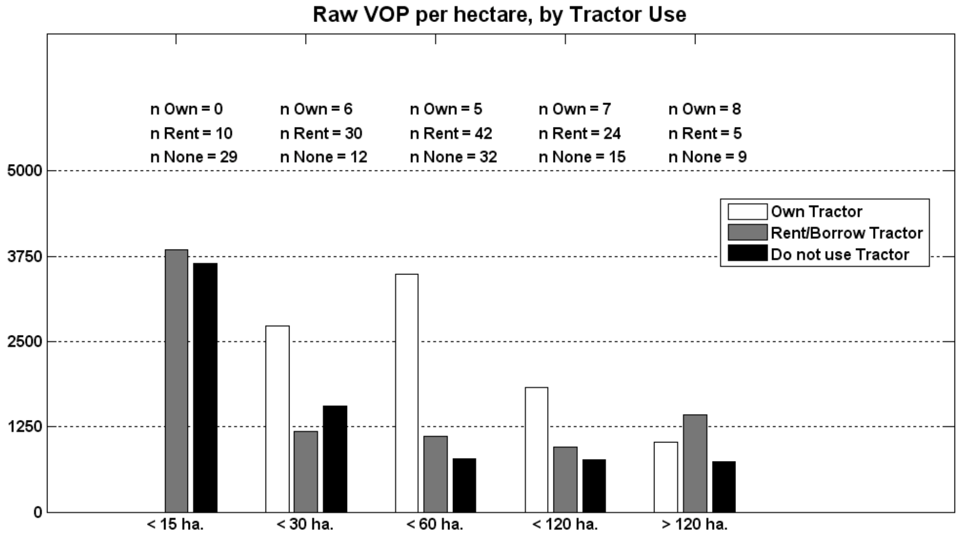

Figure G.19: Raw VOP per hectare. Percent refers to the percent of surveys in each size class used to generate bars; n_{Own}, n_{Rent}, and n_{None} are the number of farmer surveys in each size class reporting ownership of tractors, renting or borrowing of tractors, or no use of tractors, respectively.

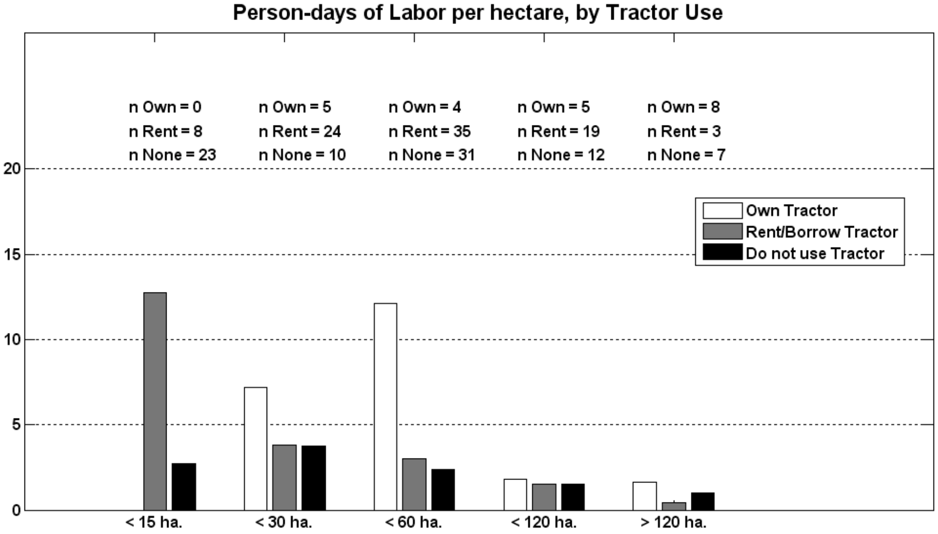

Figure G.20: Person-days of labor per hectare. Percent refers to the percent of surveys in each size class used to generate bars; n_{Own}, n_{Rent}, and n_{None} are the number of farmer surveys in each size class reporting ownership of tractors, renting or borrowing of tractors, or no use of tractors, respectively.

Networks and Information

Respondents were asked to rate, on a scale of 0 to 5, the importance of a variety of different sources in obtaining information regarding market prices, agricultural techniques, climate, and credit programs, and the results reveal several important features of the way farms in the region operate. Firstly, rural associations as well as rural extension services play similar roles as information brokers to farmers across the scales of family production, with extension services being regarded as a slightly more important source of information regarding agricultural techniques and credit programs (Figures G.21, G.22).

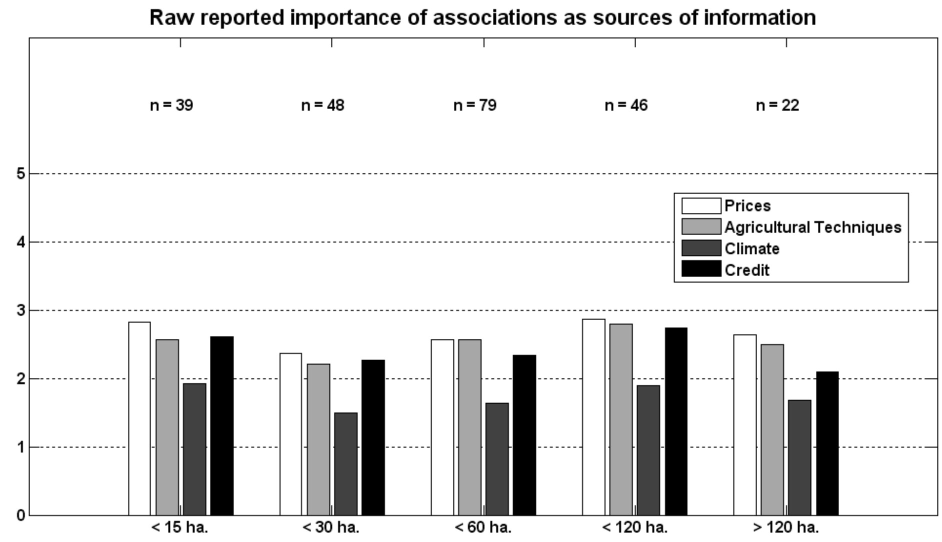

Figure G.21: Reported importance of associations as sources of information aggregated across all 3 sites. Farmers were asked to rate the importance on a scale of 0 to 5 for information regarding market prices, agricultural techniques, climate and credit; n refers to the number of surveys used in each class.

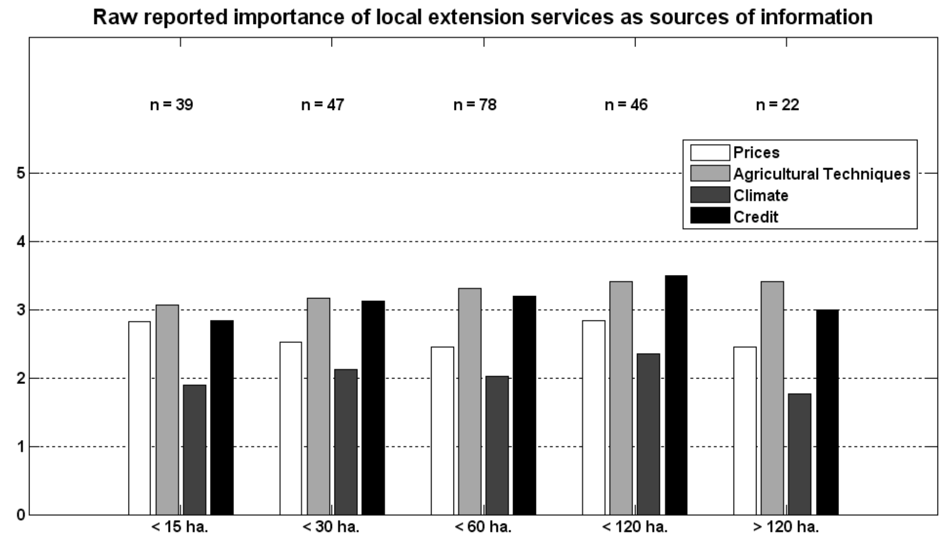

Figure G.22: Reported importance of local extension services as sources of information aggregated across all 3 sites. Farmers were asked to rate the importance on a scale of 0 to 5 for information regarding market prices, agricultural techniques, climate and credit; n refers to the number of surveys used in each class.

Neighbors (a component of more general personal social networks) also play significant roles in keeping farmers informed; as to a lesser extent do other passersby (Figures G.23, G.24), particularly as sources of information regarding current market prices.

Interestingly, the importance of both of these local sources of information peaks in farmers between 30ha and 60ha in size. In properties larger than this, the declining importance of neighbors may reflect a change in the relationships between farmers of larger properties and their neighbors, an increased reliance on mass communication for more current information, or simply a decrease in the number of neighbors for larger properties. For smaller properties, the declining importance of neighbors as sources of information may reflect simply a decreased consumption of current information on smaller, less capitalized and less market integrated farms, or decreased access among equivalently small farms to information that can be shared.

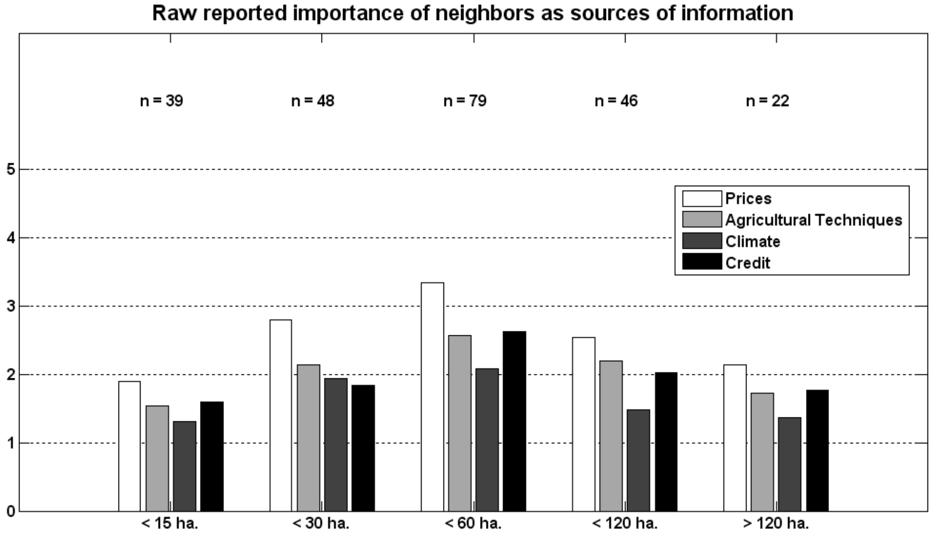

Figure G.23: Reported importance of neighbors as sources of information aggregated across all 3 sites. Farmers were asked to rate the importance on a scale of 0 to 5 for information regarding market prices, agricultural techniques, climate and credit; n refers to the number of surveys used in each class.

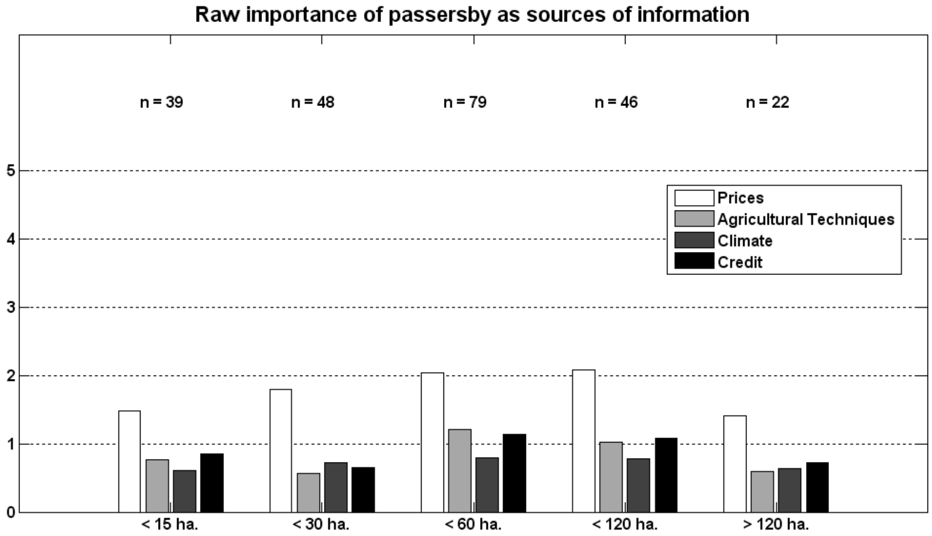

Figure G.24: Reported importance of passersby as sources of information aggregated across all 3 sites. Farmers were asked to rate the importance on a scale of 0 to 5 for information regarding market prices, agricultural techniques, climate and credit; n refers to the number of surveys used in each class.

Radio, television, and newspapers are important sources of information across all size classes, with slightly higher value discernible for larger properties (Figure G.25). The Internet yet remains a largely unused resource for most farms in the sample (Figure G.26).

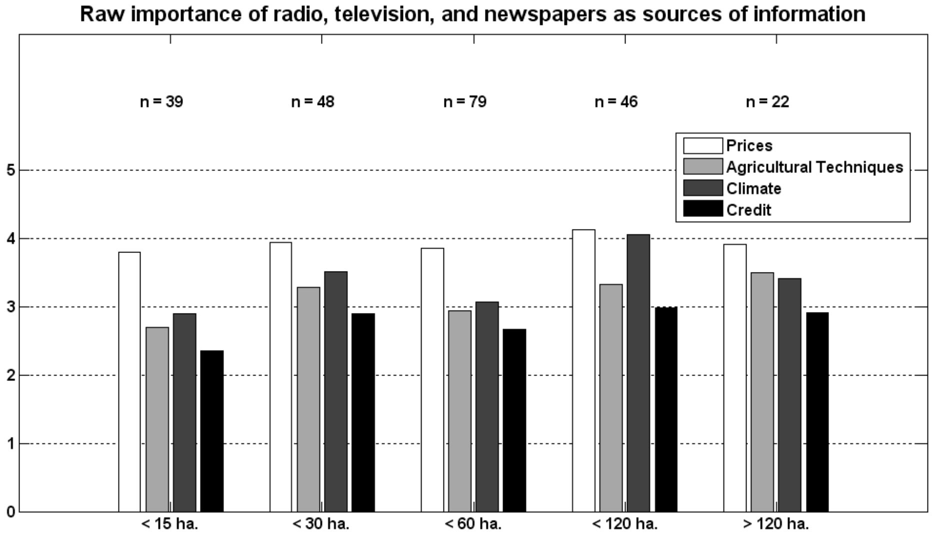

Figure G.25: Reported importance of radio, television, and newspapers as sources of information aggregated across all 3 sites. Farmers were asked to rate the importance on a scale of 0 to 5 for information regarding market prices, agricultural techniques, climate and credit; n refers to the number of surveys used in each class.

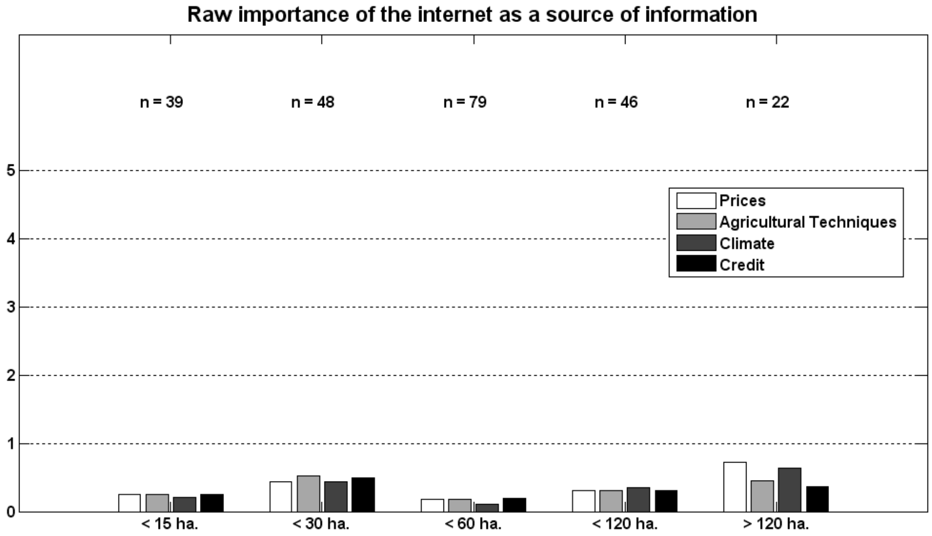

Figure G.26: Reported importance of the internet as a source of information aggregated across all 3 sites. Farmers were asked to rate the importance on a scale of 0 to 5 for information regarding market prices, agricultural techniques, climate and credit; n refers to the number of surveys used in each class.

Patterns of information consumption are similar across the three sites in the sample, with the notable exception that associations and rural extension services have lower importance in Machadinho, while neighbors and passersby are reported to be more important sources of information than in the other two sites (Appendix E). This may reflect a reduced capacity of rural extension offices and associations in Machadinho, relative to their more urban counterparts in Ji-Paraná and Cacoal, and a correspondingly higher dependence of farmers on more local, personal networks.

Another interesting signal of the strength of community ties in ranching landscapes is the effort given volunteer *mutirão* work groups, which engage in pasture weeding and recuperation activities, as well as other farm- and nonfarm-tasks such as hospital work. About a quarter of farmers in the sample had given mutirão service in the previous year, with most of the service being given by mid to large farms (Figure G.27). About a quarter of farms in the sample had received assistance from mutirão groups, with much of it being received by smaller properties (Figure G.28), suggesting a norm of larger properties (where labor use is less intensive) lending a hand to smaller properties and helping to bridge the gap between richer and poorer farms.

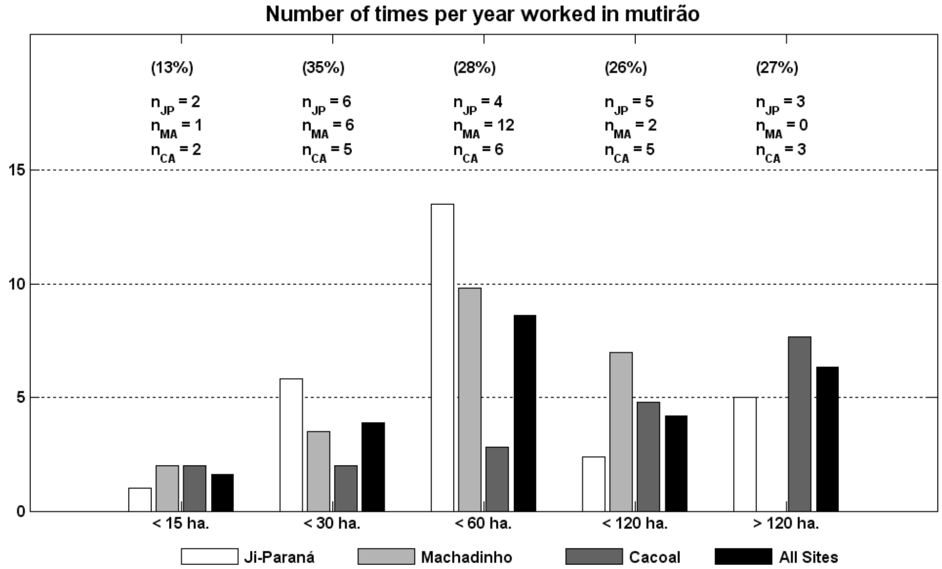

Figure G.27: Annual effort in Mutirão. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

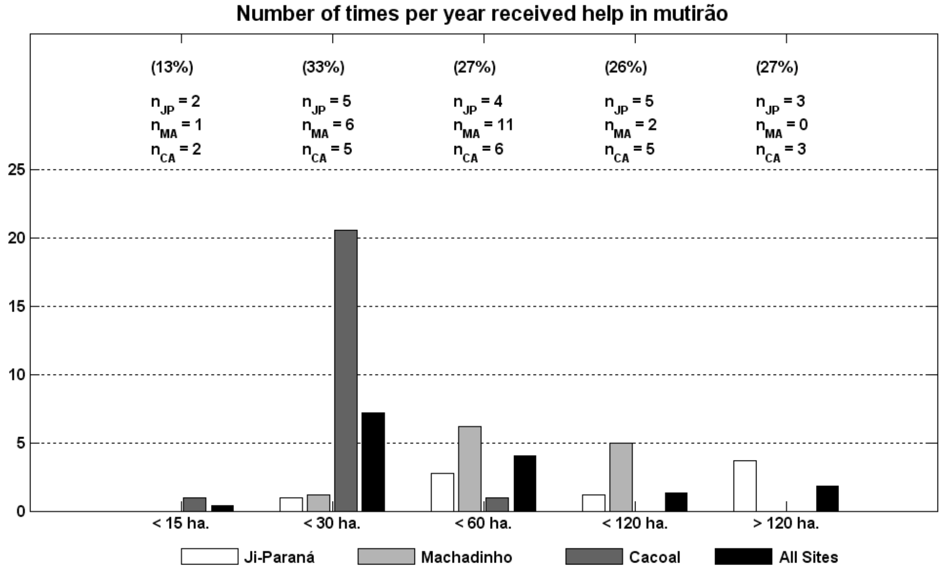

Figure G.28: Annual reception of Mutirão work effort. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

Risk behavior

We have already seen a signal of risk averse behavior in the smaller to midsize properties in the sample with diversification of income (Figure G.16), but the survey yielded several other signals of risk aversion that are worth mentioning. First, the proportion of the property committed to intercropping, where several different crops are grown in the same area, is higher in smaller properties (Figure G.29). Second, the use of irrigation is more prevalent on smaller properties, though its use remains relatively higher across all size classes in Cacoal where coffee production is more intensive (Figure G.30). Both intercropping and irrigation are techniques that can lessen the risks associated with crop failure and lower yield uncertainty (Ellis 1993b). Intercropping, beyond having a number of ecological advantages such as the improved use of light, nutrients and soil (Norman 1974), acts as a means of diversifying income and thus also helps hedge against shifts in market prices, lowering price uncertainty. Together, these are indicators of more risk-averse behavior in properties in the sample below 60ha in size.

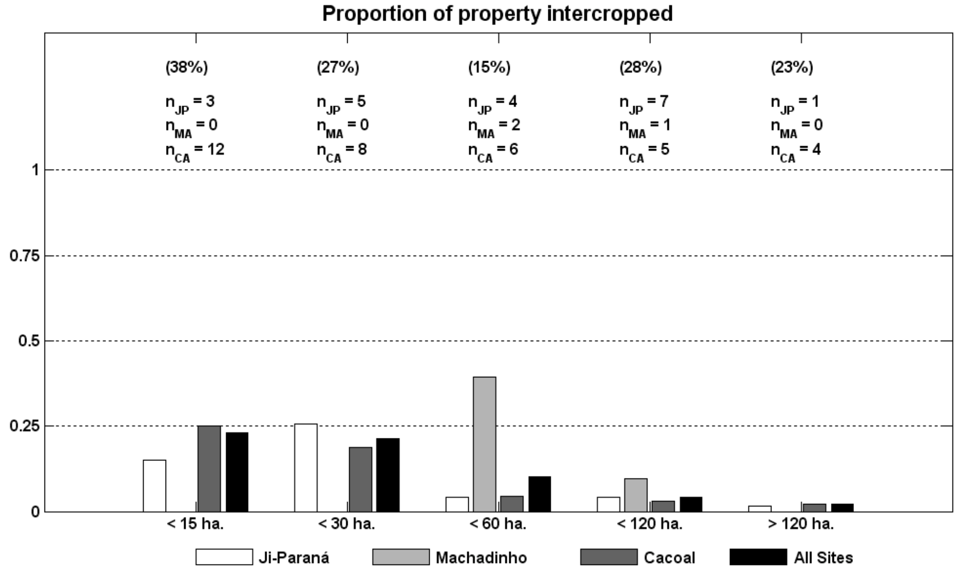

Figure G.29: Proportion of property intercropped. Percent refers to the percent of surveys in each size class reporting intercropping; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

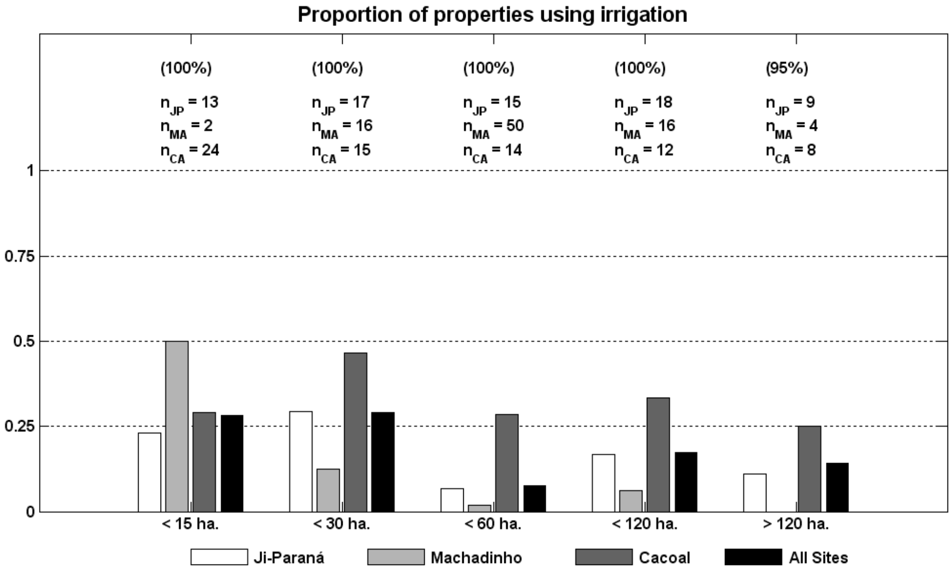

Figure G.30: Proportion of properties utilizing irrigation. Percent refers to the percent of surveys in each size class used to generate bars; n_{JP}, n_{MA}, and n_{CA} are the number of surveys used from each of Ji-Paraná, Machadinho, and Cacoal, respectively.

The survey asked respondents as well about the ways in which they would respond to the expectation of a drought. A greater proportion of farmers on properties less than 30ha in size indicated that they would plant earlier, while a greater proportion of mid- to large-size properties indicated that they would wait and plant when the rains came (Figure G.31), suggesting a greater flexibility on the part of larger properties to deal with drought. A greater proportion of these same mid- to large-size properties indicated that they would plant less in the expectation of drought, while on smaller properties, a relatively greater proportion of farmers indicated they would either plant the same amount or more (Figure G.32). These two sets of responses reflect perhaps a lower margin for error and more risk-averse behavior for properties below 30ha in size in the sample. It is valuable to characterize how shifts in risk aversion occur across scale, because the economic literature on risk-averse behavior is not unambiguous. In some studies, smallholders have been found more willing to gamble than farmers on larger holdings (Parikh and Bernard 1988); the signals obtained in Figures G.29-G.32 suggest that if any of the size classes in the sample are more risk averse, it is strictly the smaller size classes.

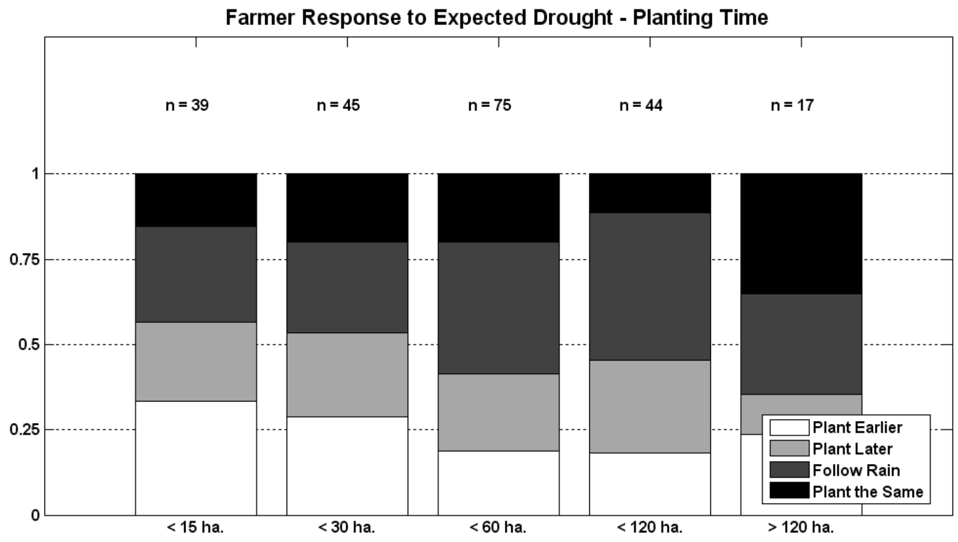

Figure G.31: Reported changes in planting time to the expectation of drought. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

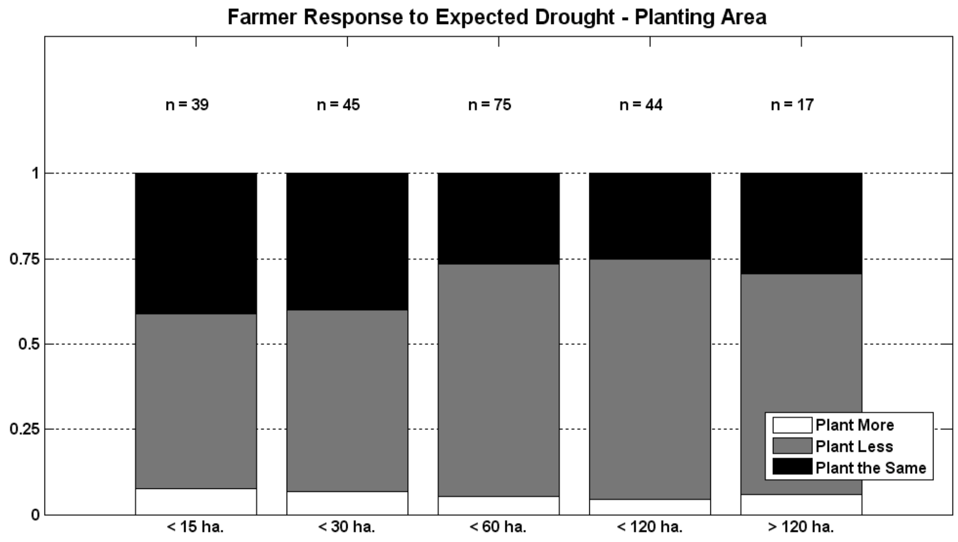

Figure G.32: Reported changes in planting area to the expectation of drought. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

Property division and aggregation

The purchase or sale of land holdings is an important indicator of socio-economic stratification in rural households (Browder et al. 2008). In the sample, the pattern of land consolidation suggests a 'success to the successful' archetypal behavior – the bigger the property, the more likely that it had augmented its holdings through land purchase

(Figure G.33). The proportion of properties reporting having sold some of their holdings held relatively constant across size classes in the sample, but this is misleading. The sample shows less willingness to subdivide holdings in properties in smaller size classes (Figure G.34). Because subdivision of an already small holding is unlikely to help a farmer in the long term, we would expect land sale to increasingly be a last resort and result in the sale of the entire property, for properties in smaller size classes. Since such farmers would be leaving the sample frame, these transactions would not appear in the survey.

Figure G.33: Proportion of properties in the sample having bought or sold land. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

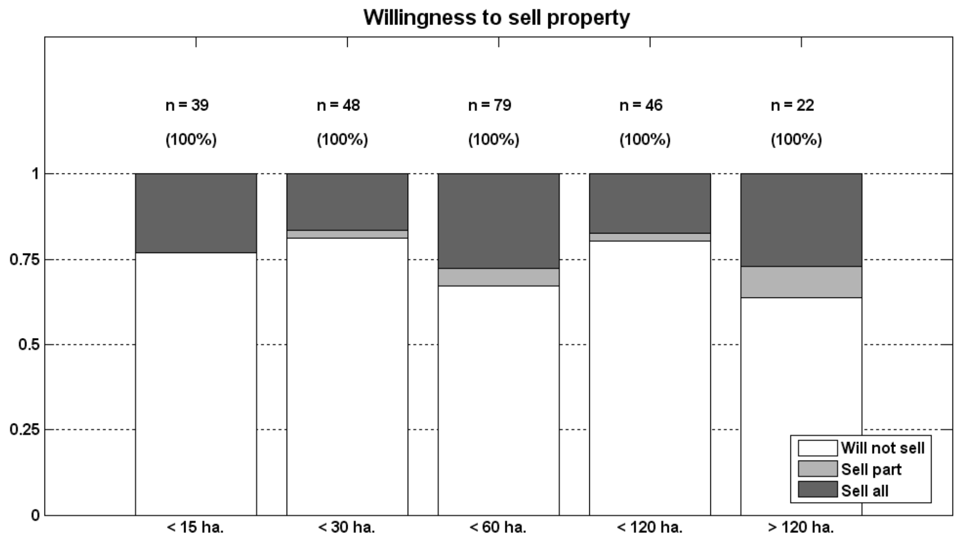

Figure G.34: Willingness in sample to sell land. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

The number of sale transactions is low (30 total) and trends across property size are not readily discernible (Figure G.35). The reasons given for selling portions of land vary and include the need to cover a debt or pay for care during an illness (27%), the desire to invest in capital (27%) or other land holdings (10%), or the subdivision of properties within family due to inheritance or divorce (23%). In a longitudinal study from 1992 to 2002 in three other municipalities local to the BR-364 within the sate, Browder et al. (2008) found family 'life-cycle' reasons to be the dominant explanation for property subdivision, indicating the passage between a first generation of frontier settlers and their children or unrelated second generation farmers. That life-cycle reasons are not the most significant factor in the transactions in this study may be an indicator that this generational transition is now passing.

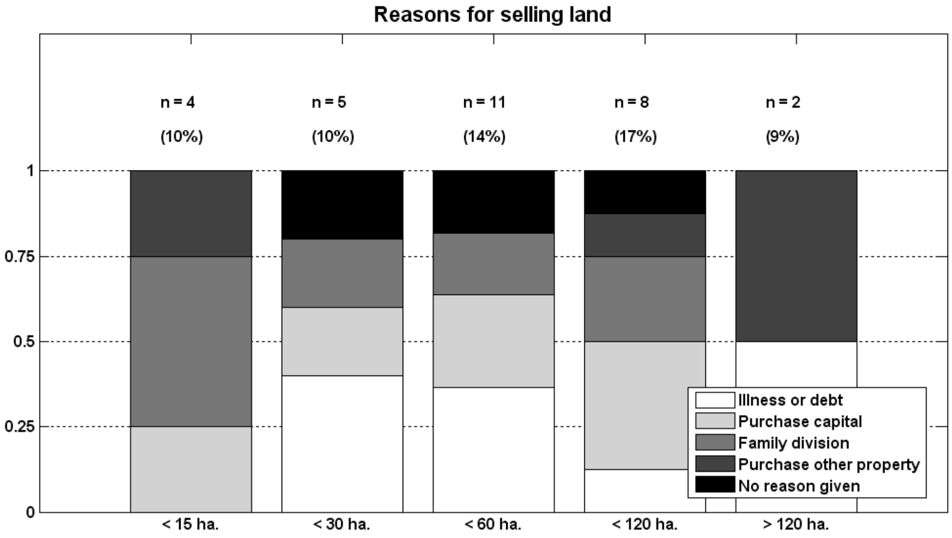

Figure G.35: Reasons given for past sales of land. Percent refers to the percent of surveys in each size class reporting having sold land; n is the number of surveys used.

Future farm goals

Very broadly, future plans for landholdings can first be classed into plans to expand, and plans to make better or different use of currently held land (Figure G.36). In this sample, the proportion of properties with plans to improve or intensify use of their current holdings increases smoothly with property size up to 120ha, following the same smooth decline in current land- and labor-use intensity observed earlier. Plans to intensify are markedly lower in larger properties. Plans to expand holdings are higher in very small (< 15ha) properties, suggesting a desire to move beyond a threshold endowment of land resources, and in very large (> 120ha) properties.

Taken together, these results for land-use and expansion goals suggest the existence of a 'basin of attraction' for the size of a family farm, between about 30 and 120ha in size, that reflects the scale most appropriate for a family-managed farming unit in the post-frontier region where access to new land is restricted. Smaller properties have endowments insufficient to meet household needs and attempt to grow; properties at the upper boundary in size focus more on improving existing holdings without looking to expand. The results observed for properties larger than 120ha in size suggest other basins of attraction at greater scales that reflect better scales for the operation of larger capitalist enterprises and agribusinesses. Thus, sufficiently large and prosperous family farms may find themselves in positions to choose between staying within a family production model, or leaving that attractor to transition into a larger business venture.

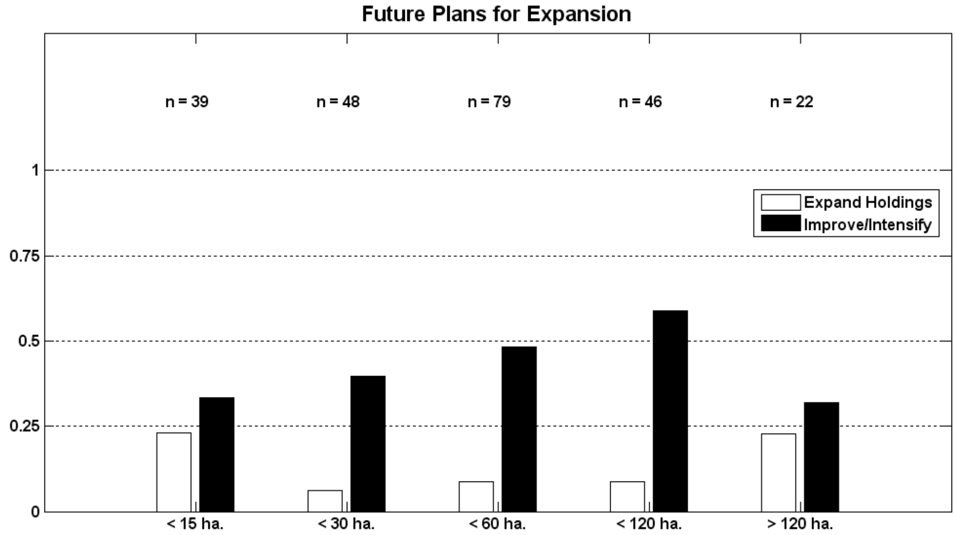

Figure G.36: Future plans for farm expansion and improvement. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

Within plans for intensification and improvement, some clear differences across farm size can be observed (Figure G.37). While it is a common goal among all but the smallest properties to invest more in cattle ranching, the desire to invest more into crop production drops off sharply for properties larger than 60ha in size. Only large family properties, perhaps conscious of their greater visibility in the face of the new licensing program, and belying the smaller fractions of their land that are actively held in production, express a significant desire to reforest on their properties. While few producers in the sample actively produce fish, the building of dams and reservoirs and investment in aquaculture appears to be a common goal among larger properties in the sample. Fish production may thus grow in the region as a capital-intensive, non-labor intensive, lower risk activity alongside the raising of other livestock.

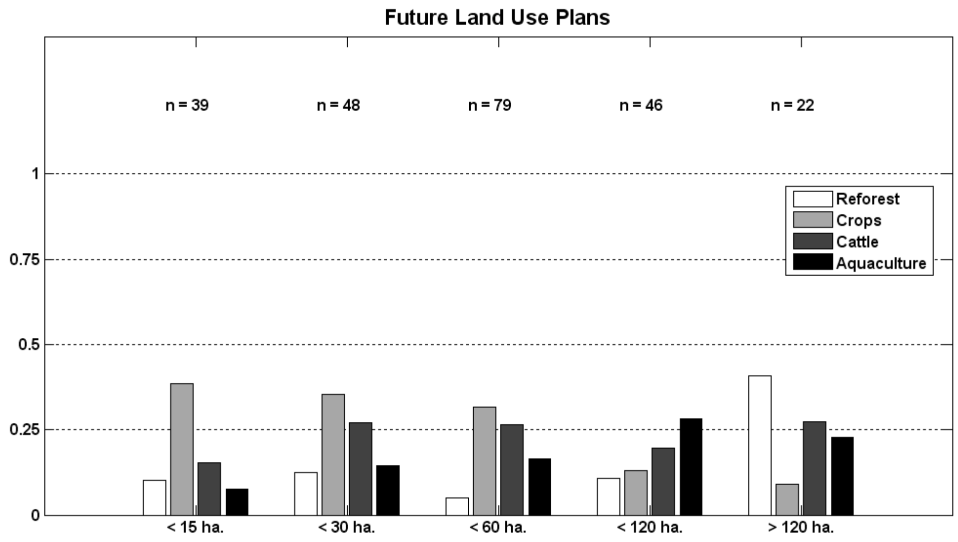

Figure G.37: Plans for land improvement on land. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

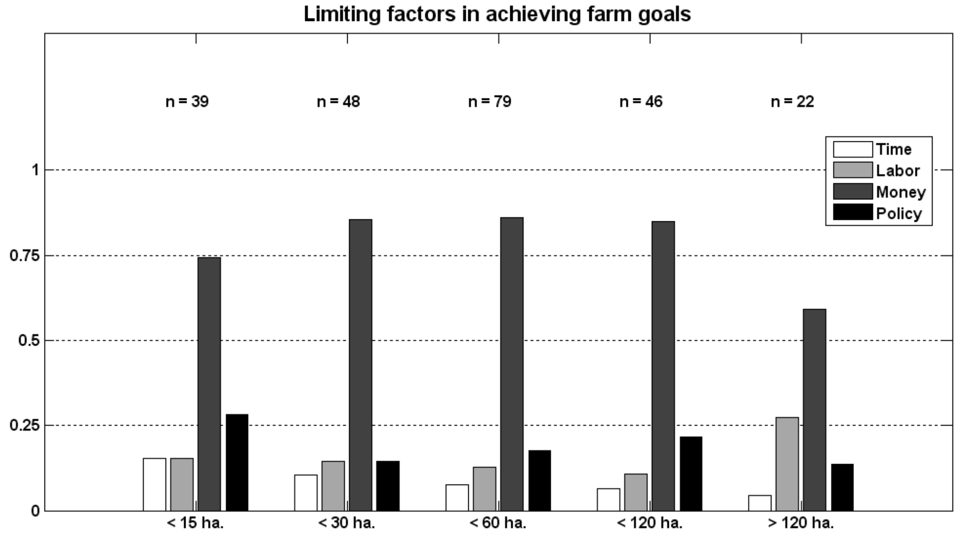

Figure G.38: Limiting factors in achieving farm goals. Percent refers to the percent of surveys in each size class used to generate bars; n is the number of surveys used.

When asked what limited them in realizing these goals for their properties, money was the overwhelming response, although it appears to be more strongly a crisis for the middle (size) classes (Figure G.38). Time was more commonly a limiting factor in smaller rather than larger properties, illustrating the constraints that intensive production on smaller properties places on farmers' capacity to invest time elsewhere.

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Appendix H

Agent-based Model Description

Climate

In the model, daily precipitation is drawn from an exponential distribution of mean λ_i, where i is the month of the year:

$$Precipitation_i(mm) = X \sim Exp\left[\left(1+\Delta_{Prec}\right)\lambda_i\right] \qquad \text{(H.1)}$$

Integer values for each month have been chosen that preserve rainy-dry season structure and an average rainfall for the region of about 1800-2200 mm per year, consistent with actual field measurements for Rondônia (von Randow et al. 2004). The term $(1+\Delta_{Prec})$ scales the annual precipitation up or down by the factor Δ_{Prec}.

Hydrology

The model includes a full hydrological submodel that partitions incoming rainfall into overland flow, groundwater runoff, and evapotranspiration. This submodel was designed to investigate rates of overland flow and soil erosion, though these outcomes are not of interest to the current study. The full hydrological model is introduced in this appendix however, as the evapotranspiration outcome is used to calculate grass growth.

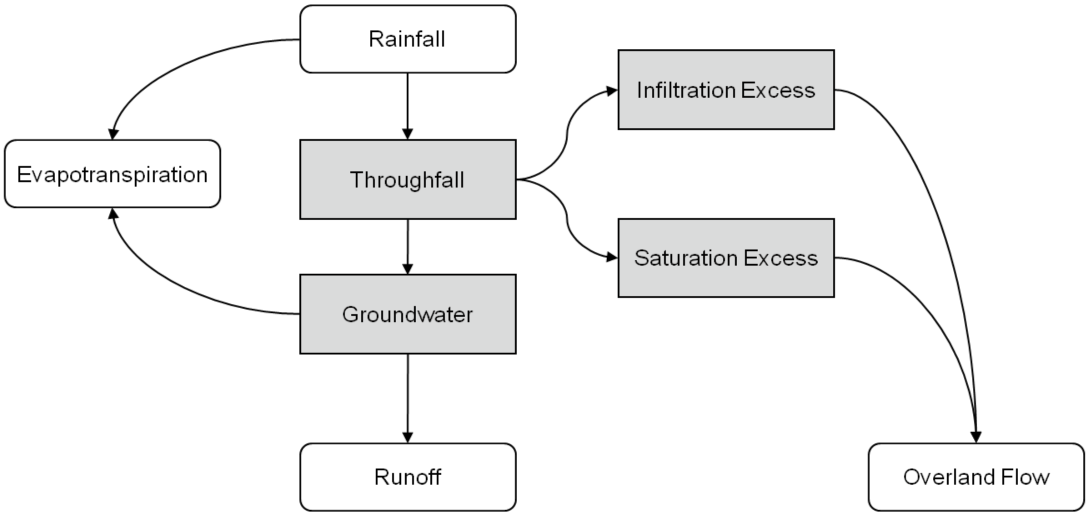

Figure A.1: Hydrological submodel scheme

A component of the precipitation is taken up on the leaf surface and lost as evapotranspiration, while the remaining precipitation reaches the ground as throughfall (Figure A.1). Assuming a mean duration l_{event} hours for rainfall events, there may be some component of rainfall in intense storms that exceeds the infiltration capacity for the soil (though in the present set of experiments there was no such infiltration excess). Some component of the throughfall flows over the surface as saturation excess. Together, infiltration and saturation excess make up the total overland flow in the system. The remaining throughfall enters the ground, and some component is taken up by plant roots; the remainder exits the system as stream runoff. This system is represented mathematically by:

$$Throughfall = \left(1 - f_{EV,Leaf}\right) Precipitation - InfiltExcess - SatExcess \tag{H.2}$$

$$\begin{aligned} Groundwater = {} & Throughfall \\ & - \max\left(Groundwater, EV_{pot} - f_{EV,Leaf} \cdot Precipitation\right) \\ & - Runoff \end{aligned} \tag{H.3}$$

$$Runoff = \frac{Head}{L} \cdot K_{Sat} \tag{H.4}$$

$$\mathit{Head} = \frac{R}{\sqrt{R^2 + L^2}} \cdot \frac{\frac{SD \cdot L}{2R} - SD + \sqrt{SD^2 + 2L\left(\frac{L}{R} + \frac{R}{L}\right) \cdot \mathit{Groundwater}}}{\left(\frac{L}{R} + \frac{R}{L}\right)} \tag{H.5}$$

$$\mathit{InfiltExcess} = \max\left(0, \mathit{Throughfall} - K_{\mathit{Infilt}} \cdot l_{\mathit{event}}\right) \tag{H.6}$$

$$\mathit{SatExcess} = \max\left(0, \mathit{Throughfall} - \mathit{InfiltExcess} - \left(SC \cdot SD - \mathit{Groundwater}\right)\right) \tag{H.7}$$

Where L and R are the length and rise of the grid cell, fixed by the slope parameter and the total area per grid cell, and SC and SD are the soil water capacity and soil depth, respectively. This hydrological model is similar to that implemented by the Soil and Water Assessment Tool (SWAT) (Neitsch et al. 2005), minus a baseflow component (which is not relevant for the calculation of evapotranspiration). Potential evapotranspiration is assumed to be constant for forested land, and to vary linearly with the amount of grass in pasture land, so that:

$$EV_{pot} = \left(f_{past}\left(\frac{G}{G_{\max}}\right) + f_{for}\right) EV_{0,pot} \tag{H.8}$$

where f_{past} and f_{for} are the fractions of land in the grid cell committed to pasture and forest, respectively, G is the grass biomass, G_{max} is the grass capacity for the grid cell, and $EV_{0,pot}$ is the nominal evapotranspiration. In this model, a grid cell fully committed to forest or filled to capacity with grass will have potential evapotranspiration of $EV_{0,pot}$, while any consumption of grass or degradation of pasture will lead to lower potential evapotranspiration. This simple model reproduces the observed large drops in pasture potential evapotranspiration during the dry season, and the relatively stable potential evapotranspiration of forested land.

Cattle

Cattle are modeled with a logistic growth rate:

$$\frac{dM}{dt} = k_{cattle} M \left(1 - \frac{M}{M_{\max}}\right) \tag{H.9}$$

where M is the mass of the animal, M_{max} is the maximum mass, and k_{cattle} is the intrinsic relative growth rate.

Grass

Grass in each grid cell is modeled by simple carrying-capacity-limited growth, in a similar manner as cattle but with water for evapotranspiration as an additional constraint:

$$\frac{dG}{dt} = k_{grass} G \left(1 - \frac{G}{G_{\max}}\right)\left(\frac{EV_{act}}{EV_{pot}}\right) \tag{H.10}$$

where G is the grass stock for the grid cell, G_{max} is the grass capacity, k_{grass} the maximum growth rate for the cell, and EV_{act} the actual water available for evapotranspiration.

The purpose of the logistic model, as applied to both cattle and grass, is to reproduce the basics of growth – low growth rates when the cow is small (or when grass is scarce), low growth rates when the cattle is nearing maturity (or when grass is nearing capacity), and faster growth rates in between.

Numerical Method

All hydrological balances and growth rates are solved using a Runge-Kutta 4-step (RK4) algorithm.

Ranchers

Ranching agents in this model are defined by a list of grid cells they possess, a list of cattle objects they are raising, a purse of their net gains from ranching, a rate at which they stock their pastures with cattle, and a base of information about how often other ranches in the watershed are being fined. Ranchers must decide in each time step what changes to make to their land use, how many new cattle to stock their pastures with, and whether to buy or sell their land.

Land-use change

Ranchers base their land-use decisions on the present value of expected returns, at discount rate d and over the average lifetime of a pasture, of three different options: restoring degraded pasture, clearing new forest, or restoring forest. When ranchers possess an environmental license, the expected values for each of these options are:

$$PV_{r,dp}(\$/ha) = -C_{r,dp} - PV\left(C_{e,n}\right) + PV\left(I_{e,p}\right) \tag{H.11}$$

$$PV_{c,f}(\$/ha) = -C_{c,f} - PV\left(C_{e,n}\right) + PV\left(I_{e,p}\right)\left(1 - \Delta_{EI}\left[A_p + 1\right]p_{mon}\Delta p_{lose}\right) \tag{H.12}$$

$$PV_{r,f}(\$/ha) = -C_{r,f} + PV\left(C_{e,n}\right) - PV\left(I_{e,p}\right)\left(1 - \Delta_{EI}\left[A_p - 1\right]p_{mon}\Delta p_{lose}\right) \tag{H.13}$$

When they do not possess licenses, the expected values are:

$$PV_{r,dp}(\$/ha) = -C_{r,dp} - PV\left(C_{e,n}\right) + PV\left(I_{e,p}\right)\left(1 - \Delta_{EI}\right) \tag{H.14}$$

$$PV_{c,f}(\$/ha) = -C_{c,f} - PV\left(C_{e,n}\right) + PV\left(I_{e,p}\right)\left(\left[1 - \Delta_{EI}\right] - \Delta_{EI}\left[A_p + 1\right]\Delta p_{gain}\right) \tag{H.15}$$

$$PV_{r,f}(\$/ha) = -C_{r,f} + PV\left(C_{e,n}\right) - PV\left(I_{e,p}\right)\left(\left[1 - \Delta_{EI}\right] - \Delta_{EI}\left[A_p - 1\right]\Delta p_{gain}\right) \tag{H.16}$$

where C indicates a cost, I income, and PV a present value. The subscript e denotes expected, and the subscripts r, c, dp, p, f, n and wc denote restore, clear, degraded pasture, pasture, forest, nutrient, and water charge, respectively. The bracketed expressions modifying the $PV(I_{e,p})$ terms reflect the changes in income that result from losing or gaining the environmental license. All of the individual cost terms ($C_{r,dp}$, $C_{c,f}$, $C_{r,f}$, $C_{e,n}$) above are explained in the following sections on cost structure and environmental licensing.

Ranchers are able to modify up to A_{change} hectares of land during each time step. If, for example, clearing new forest had the highest present value, the rancher would begin by clearing an amount of forest equal to the lesser of the amount of forest available to clear, the amount of forest the rancher could afford to clear, or the amount of land he was able to change in the time step (A_{change}). If this amount was less than A_{change} (i.e., the rancher was constrained by the amount of forest left, rather than by money or labor/time constraints), the rancher would then proceed to option with the second highest present value, and so on. The spatial patterns of land use change are different for each option. New pastures are cleared in the order of proximity to roads. Degraded pastures are restored in the order of the severity of erosion from each grid cell. Forests are restored (ie, riparian buffers are planted) in strips of width w_{buffer} in cells in the order of the severity of erosion emanating from the cell.

The only other mechanism by which land use changes is through pasture degradation, which occurs each time step according to the relationship:

$$dA_{dp} = dt_{decision}\left(\frac{A_p}{L_0\left(\frac{N}{N_0}\right)}\right) \tag{H.17}$$

where A_{dp} and A_p are the areas of degraded pasture and pasture respectively, L_0 is the nominal lifetime of pasture, $dt_{decision}$ is the time interval at which the rancher makes decisions (1 year in this study) and N and N_0 are the actual and nominal numbers of cattle on the land. This bottom term allows the lifetime of pasture to be reduced under conditions of over stocking.

Cattle stocking

Ranching agents stock their pastures with cattle at a rate based on the average grass growth rate on their land:

$$\frac{dC}{dt_{decision}} = f \cdot \left(\frac{dG}{dt}\right)_{ave} \cdot \frac{A_{pasture}}{U_{daily,kg} M_{cattle,avg} t_{slaughter}} \tag{H.18}$$

where C is the stocking rate in head of cattle per hectare, f is a scalar multiplier (calibrated in these experiments to 2.4 – see Appendix C), $(dG/dt)_{avg}$ is the observed average growth rate of grass per hectare over the year, $A_{pasture}$ is the total pasture area on the property, $U_{daily,kg}$ is the nutrient requirement of cattle per kg of body mass per day, M_{max} is the maximum weight of cattle, $M_{cattle,avg}$ is the average weight of a head of cattle over its lifetime, and $t_{slaughter}$ is the age at which cattle are slaughtered, expressed as the number of decision intervals.

Land sale

We follow the approach of other agent-based rural land market models (Berger 2001, Happe et al. 2006) and allow ranchers who fall into deficit the option of putting a parcel of their land up for sale in order to fill their income gap. Ranchers begin by selling off cattle, until the cattle density on their property falls below the capacity of (n-1) land cells, where n is the current size of their property in grid cells. They then put up a parcel of land to potentially be sold in an auction, and continue the cycle until the revenue from cattle sold plus the potential revenue from land put up for sale offsets the current deficit. The potential revenue from land sale per hectare is estimated by the seller as the average of observed values per hectare (based on the values for land calculated by ranchers in equations A.11-A.16) communicated through the network at each timestep. The ranchers' estimates for land value stabilize during the 10-year spin-up period as they have the opportunity to sell cattle and stock land appropriately.

For each parcel in the auction, neighboring ranches that have profit to invest place a bid on the parcel equal to the shadow price of the land, given their stocking rate and cost structure, and the highest bidder wins the auction. As noted by Happe, the actual price paid for the parcel should lie somewhere between the maximum the buyer is willing to pay (the auction bid) and the minimum that the seller will accept (Happe et al. 2006). In this model, we do not have a good basis to estimate the minimum acceptable bid, since in all cases the seller is already losing money on their land; as a simplifying assumption we set the actual price paid to equal a fraction of 0.9 times the winning bid.

Rancher cost structure

Ranchers are subject to a number of different costs during each decision interval. Each rancher has a basic household cost C_h that is constant across all ranchers. Additionally, each rancher pays overhead costs that are a linear function of farm size:

$$C_o = C_{o,ha} A_{total} \tag{H.19}$$

where C_o is estimated at about \$100/ha, based on the data shown in Figure A.3. When grass growth rates are insufficient to sustain cattle on the land (interpreted in this model as whenever grass stocks drop below half of their capacity, i.e., fall below their maximum growth rate), ranchers must supplement the balance of cattle dietary needs externally at a cost of $C_{n,kg}$ per kg:

$$C_n \sum_{lots} \sum_{days} C_{n,kg} \left(U_{daily,kg} - \left(G - G_{1/2} \right) \right) \tag{H.20}$$

where G, $U_{daily,kg}$, and $G_{1/2}$ are the grass stock, demanded grass, and grass half-capacity, respectively.

Ranchers incur costs when they change land use to clear forest or restore pasture or degraded pasture. These costs are modeled as sigmoidal functions of farm size, implying that the marginal cost of land use change decreases as farms grow in size and, presumably, become more mechanized:

$$C_i = \frac{c_{min} - c_{max}}{1 + e^{-r(A_{actual} - A_{mech})}} + c_{max} \qquad \text{(H.21)}$$

where i denotes forest clearing, degraded pasture restoration to pasture, or pasture restoration to forest; c_{max} and c_{min} are the maximum and minimum possible costs, A_{actual} is the farm size, A_{mech} is the midpoint of the drop in the sigmoid, interpreted here as a 'mechanization point', and r is a parameter that controls the steepness of the drop. The basis for this mechanization point comes from our survey; we asked ranchers what types of technology they owned or made use of, and used tractors as an indicator of farm mechanization (Figure A.2).

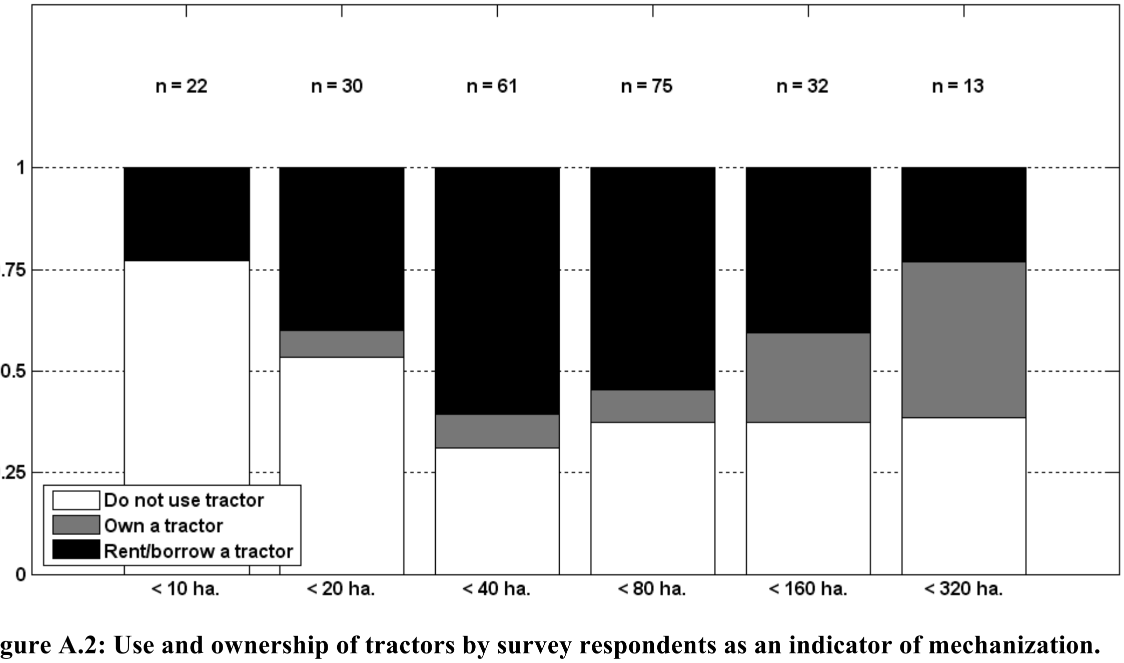

Figure A.2: Use and ownership of tractors by survey respondents as an indicator of mechanization. The n for each bar represents the number of properties of that size in the simulation.

While ownership of tractors is clearly more limited to larger properties, even smaller properties have access to tractors – through neighbors or membership in syndicates and associations – and are able to function more efficiently. This maps into a lower cost for maintenance per hectare of land (Figure A.3). Participants in the survey were not able to give reliable breakdowns of their annual costs to maintain their land; however, they were able to give rough estimates of the overall amount of money they had spent for maintenance in the previous year – this value, normalized by the land they have in pasture, is what is shown in Figure A.3. Because, for smaller properties in particular, some land in the property is committed to more cost-intensive crops, these results should not be taken as a pure signal of how ranching costs vary across scale. They do however suggest that maintenance costs drop off quickly as ranches grow and gain access to technology such as tractors.

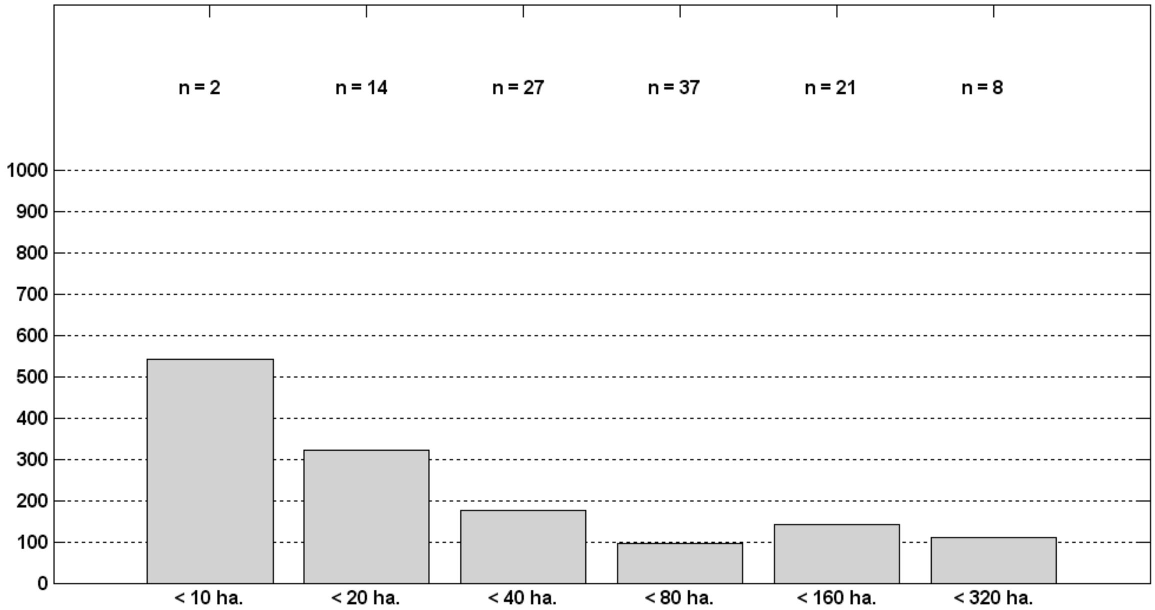

Figure A.3: General maintenance cost per hectare per year ($R) for properties using some fraction of land to raise cattle. Smaller properties tend also to grow crops, so that the rise in cost for smaller properties is at least partially explained by increased use of fertilizers and pesticides. The n for each bar represents the number of properties of that size in the simulation.

Based on visual inspection of the patterns in the use of tractors, the costs to maintain land, and the proportion of the property (Figure A.4) that is maintained in a year, the 'mechanization point' appears to lie somewhere between 40 and 80ha; we use a value of 50ha in the simulations in this study.

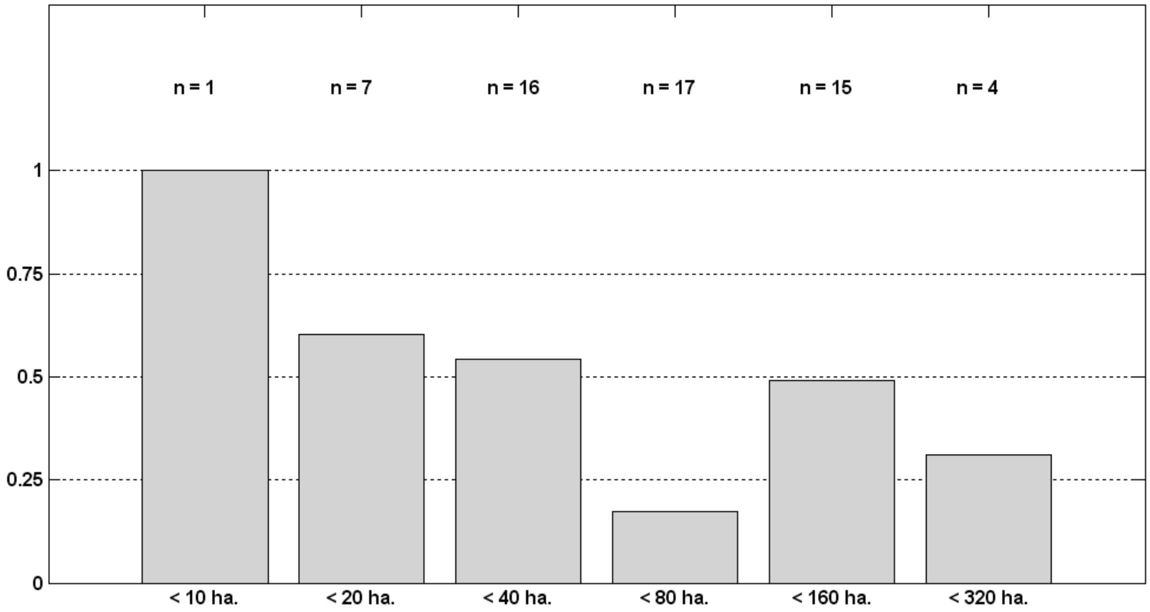

Figure A.4: Proportion of pasture on property recuperated each year. The n for each bar represents the number of properties of that size in the simulation.

This same functional form as that for the land change costs is used to evaluate the ability of a rancher to make land use change within a decision interval, although here A_{change} grows as a function of farm size, to imply greater mechanization and land-use change capacity:

$$A_{change} = \frac{A_{change,max} - A_{change,min}}{1 + e^{-r\left(A_{actual} - A_{mech}\right)}} + A_{change,min} \tag{H.22}$$

where A_{change} is the area of land the rancher can modify in one decision interval, A_{actual} is the size of the ranch, and A_{mech} is the inflection point between non-mechanized and mechanized properties.

Environmental Licensing

The model for environmental licensing is simple. Ranchers are granted a license at the beginning of the simulation period, which stipulates that they must reforest their properties up to the target forest proportion $f_{targ,final}$ by the end of the management period T. This corresponds to a required annual rate of reforestation, and ranchers failing to reforest their properties close to the required rate run the risk of having their licenses revoked.

Rancher income changes depending on whether the rancher possesses an environmental license or not. Ranchers not in possession of a license have more difficulty selling their cattle, such that the overall income they receive is a proportion Δ_{EI} lower than the market price for their product. Thus, for ranchers with a license, the decision to clear a hectare of forest changes their expected income by:

$$PV\left(I_{e,p}\right)\left(\Delta_{EI}\left[A_p+1\right]p_{mon}\Delta p_{lose}\right) \tag{H.23}$$

Where $PV(I_{e,p})$ is the expected income at market price derived from one hectare of pasture, Δ_{EI} is the proportional change in received income with a loss in license, A_p+1 is the new area of pasture following the clearing, P_{mon} is the probability of being monitored during a period and ΔP_{lose} is the change in the probability that the monitor will strip the rancher of their license, given by:

$$p_{lose} = \max\left(0, \frac{f_{targ,i} - f_{act}}{f_{targ,i}}\right) \tag{H.24}$$

$$\Delta p_{lose} = \frac{-\Delta f_{act}}{f_{targ,i}} \tag{H.25}$$

where f_{act} is the actual proportion of forested area on the property and $f_{targ,i}$ is the target forest proportion on the property for year i. If they fail to maintain sufficient forest land and lose their licenses, this only means that the rate of reforestation they will need in order to regain their licenses is higher each year:

$$\Delta f_{targ,i} = \frac{f_{targ,final} - f_{act}}{T - t} \tag{H.26}$$

where $\Delta f_{targ,i}$ is the proportion of new forest expected at the end of each year, T is the total length of the management period, and t is the current year in the management period.

Similarly, for ranchers without licenses, the decision to clear a hectare of forest changes their expected income by:

$$PV\left(I_{e,p}\right)\left(\Delta_{EI}\left[A_p+1\right]\Delta p_{gain}\right) \tag{H.27}$$

where it is assumed that P_{mon} is 1 for ranchers without licenses (i.e., they are continually monitored until the license is restored) and ΔP_{gain} is the change in the probability that the monitor will strip the rancher of their license, given by:

$$p_{gain}=1-\max\left(0,\frac{f_{targ,i}-f_{act}}{f_{targ,i}}\right) \tag{H.28}$$

$$\Delta p_{gain}=\frac{\Delta f_{act}}{f_{targ,i}} \tag{H.29}$$

Ranching Network

The expected sanction for each rancher is informed by what ranchers hear from other ranchers in the watershed. Ranchers observe the frequency that ranches are being fined as a function of their size and use this information to estimate the frequency with which their own ranch will be monitored and fined. The better the information they have about other ranchers in their watershed, the better their estimates of expected sanctions will be.

There are a number of contributing factors to the strength of a network link between two particular ranchers – they may belong to the same rural syndicate or agricultural cooperative, they may share pastures or work together in volunteer work parties or *mutirão*, or they may be family, for example. Because these links are shaped by a number of different events, I have chosen to model their strength with a normal distribution. In the *g x g* matrix *P*, where *g* is the number of ranchers present at the start of the simulation, the strength of the link between two ranchers *i* and *j* is given by:

$$P_{ij} = N\left(p_{base}, \delta p_{base}\right) \qquad 0 \le P_{ij} \le 1 \tag{H.30}$$

where δ is the parameter for variability (δp gives the standard deviation) and N indicates a normal distribution. When rancher *i* is fined in a given time period, P_{ij} is the probability that he communicates to rancher *j* that he was fined.

Network links may provide more than just information. Membership in syndicates and cooperatives and relationships with other ranchers may provide access to labor resources as well as equipment. In this sense, network ties may make smaller farms more resilient by allowing them to behave, from a cost perspective, more like larger farms. In this simulation, this effect is interpreted as an effective size for each farm, given by:

$$A_{eff,i} = A_{act,i} + \frac{\sum_{i \neq j} P_{ij} A_{act,j}}{q} \tag{H.31}$$

where $A_{eff,I}$ is the effective farm size for rancher *i,* and *q* is a scaling factor. When *q* is small, the contribution of other farms to the effective farm size is large; when *q* is very large, network ties have little effect on the effective size of the farm for rancher *i*. The nature of the sigmoid curve used to model costs as a function of size means that large properties will gain little in this way, while small ranchers have more to gain by sharing resources.

Variability

The variability δ is used in the initial model setup to define the land characteristics G_{max}, and k_{grass} for each grid cell, such that:

$$G_{max} = G_{max,base}\left(1 \pm \left(1 + U[-\delta,\delta]\right)\right) \tag{H.32}$$

$$k_{grass} = k_{grass,base}\left(1 \pm \left(1 + U[-\delta,\delta]\right)\right) \tag{H.33}$$

where U is a uniform random distribution.

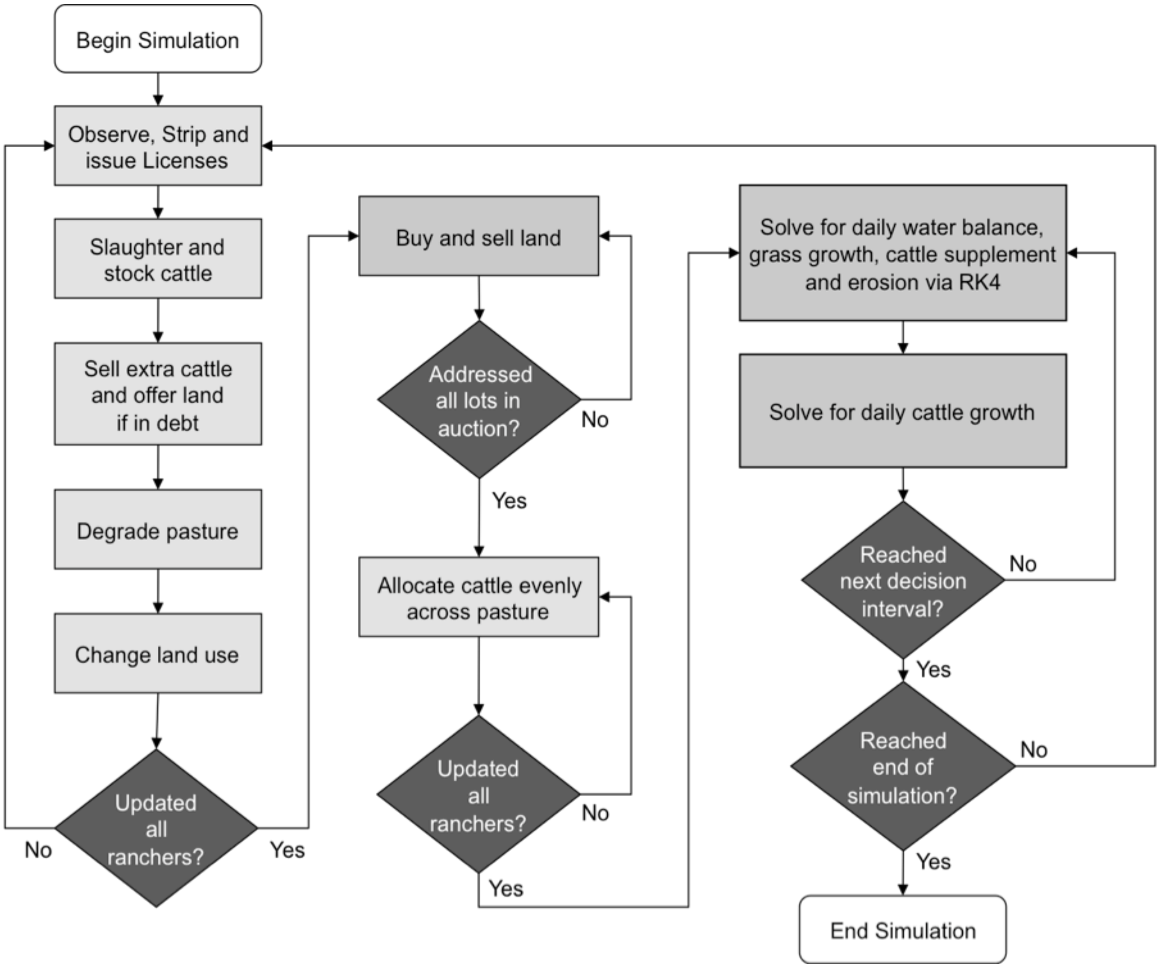

Figure A.5: Simulation Flow Chart

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Appendix I

Agent-based Model Parameter Values for Reference Mode

Name	Parameter description	Value	Literature Values/Justifications
k_{cattle}	Cattle Growth rate	0.5 kg/d	Based on an adult weight of about 410kg and a slaughter age of 4y (Mattos and Uhl 1994)
M_{max}	Max Cattle Weight	400 kg	
p_{cattle}	Price, Beef	\$1.5 /kg	Reported revenue of \$R45-60/@ (\$R3-4/kg) in our sample
$C_{r,p}$	Pasture Restoration Cost per hectare	\$200 - \$400	\$116-234/ha in 1991 (Smith, Serrão et al. 1995) \$260/ha in 1994 (Mattos and Uhl 1994)
$C_{r,f}$	APP Restoration Cost per hectare	\$600 - \$1,500	\$2000/ha in São Paulo State (GEF 2005) \$800/ha in Amazonia (Fearnside 2001)
$C_{c,dp}$	APP Clearing Cost per hectare	\$10 - \$50	Assumed
C_o	Maintenance cost per hectare	\$100	Based on data presented in Appendix 1
C_h	Household Annual Cost	\$4000/y	An average rural monthly expense of \$R867 (~\$5500/y) across Brasil, noting that costs are significantly lower in the North region (\$R1218 per month overall (urban + rural) in the North vs \$R1778 for Brasil) (IBGE 2004)

A_{mech}	Logistic Function Parameter	50 ha	Based on data presented in Appendix 1
r	Logistic Function Parameter	0.05	Assumed
$C_{n,kg}$	Cost per kg Nutrient Supplement	\$0.1	Based on assumed grain prices of \$2-3/bushel; supplement costs then calibrated to ~\$30/head/y under normal climate conditions
$U_{daily,kg}$	Nutritional Needs, Cattle	7 kg/100kg/d	20-25kg/animal/d (NRC 2001)
A_{change}	Maximum Land Use Change Rate	10-80 ha/y	Based on data presented in Appendix 1
SC	Soil Water Capacity	40 cm/m	Assumed. Reasonable values estimated from SIGTERON Soil Profile database (Cochrane and Cochrane 2006)
SD	Soil Depth	0.5m	
(R/L)	Slope Grade	5%	
$K_{infilt,f}$	Soil Infiltration Rate, Forest	1500 mm/h	1533 mm/h (Zimmermann, Elsenbeer et al. 2006)
$K_{infilt,p}$	Soil Infiltration Rate, Pasture	120 mm/h	122 mm/h (Zimmermann, Elsenbeer et al. 2006)
$K_{sat,f}$	Forest saturated flow	200 mm/h	206 mm/h (Zimmermann, Elsenbeer et al. 2006)
$K_{sat,p}$	Pasture saturated flow	20 mm/h	26 mm/h (Zimmermann, Elsenbeer et al. 2006)
l_{event}	Mean Rain Event Length	1 h	An operational variable to generate realistic hourly rainfall intensities from modeled daily rainfall distributions. Estimated from precipitation data for Ji-Paraná (ANA 2009)
L_0	Nominal Pasture Lifetime	10 years	5-10 years (Mattos and Uhl 1994)
$dt_{decision}$	Decision Interval	1 y	Assumed
d	Discount Rate	5%	Assumed

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Appendix J

Sensitivity Analyses Used in Calibration

In our model of ranching productivity, there are several key processes that shape ranch outcomes. The first is the way in which grass grows in pasture, in response to climate and land conditions. The second is the way in which grass is demanded by cattle raised on this pasture, and the third is the ability of ranchers to sell cattle and meet their income needs. In a large model such as this, there are many different parameters to assign, but many of them affect model results in similar ways. For instance, changing the maximum size reached by full grown cattle will have a similar effect on grass demand as will changing the rate at which ranchers choose to stock their lands. To make sensitivity analysis more tractable to the reader, I focus on representative variables for the three important processes given above. The responses of the ranch to climate conditions, as well as to changes in market prices, are treated already in the set of experiments of the main paper through varying Δ_{EI} and Δ_{Prec}. It remains to look at the response of grass to different growing conditions, and the response to changing demand for grass by cattle. I look at these processes by focusing on the the intrinsic grass growth rate k_{grass}, pasture capacity G_{max} as indicators of grass response to growth conditions, and the scalar f from the stocking rate equation (an 'aggressiveness' parameter for rancher pasture use) as an indicator of shifting demand on grass resources by cattle. The following sections present the set of real conditions to which I mean to calibrate the current model, the sensitivity results of the model outcomes to shifts in these three key parameters, and the parameter choices made in calibration.

Calibration conditions

Ranchers in our sample stocked cattle at an average of 2.78 head/ha. Smaller properties stocked more densely, reflecting a maximization of land productivity; larger properties stocked less densely, reflecting a maximization of labor productivity, a phenomenon commonly observed in rural agricultural systems (Ellis 1994, Coomes et al. 2000) (Figure C.1). This differential use of land is shown clearly by looking at the reported rates at which ranchers recuperate their land; small ranchers report recuperating most of all of their pastures on an annual basis, while on larger properties little more than a quarter of the pasture is recuperated each year (Figure A.4). At the reported stocking rates, ranchers reported an average cost of about $US31 to supplement their cattle during the dry season, mostly with extra mineral salts and sugar cane leaves.

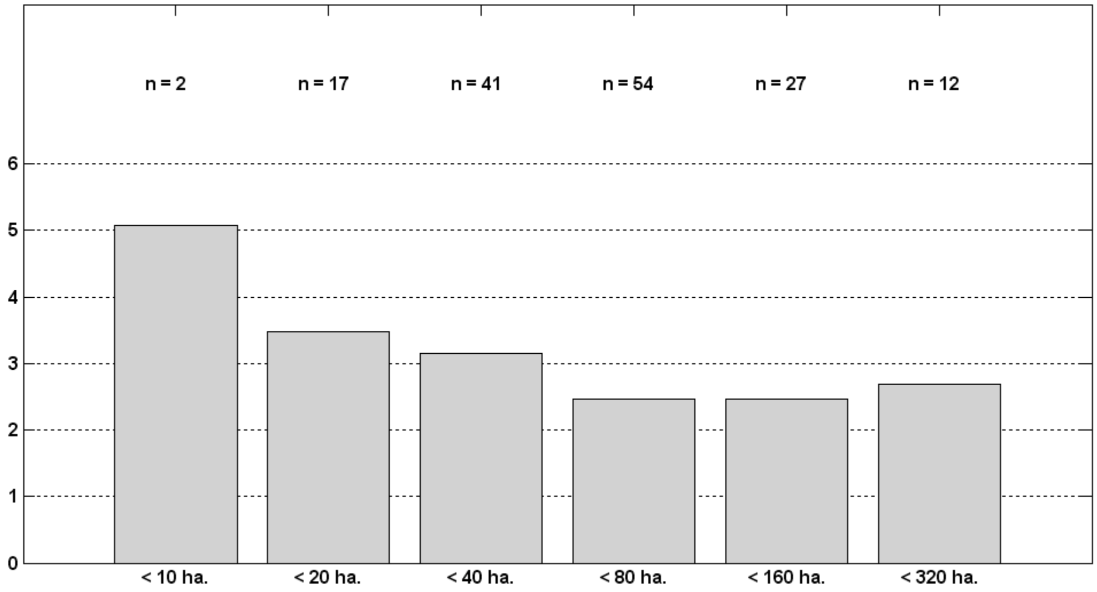

Figure C.1: Cattle stocking density in head/ha as a function of property size. The n for each bar represents the number of admissable survey responses used to derive the result.

To find model parameters that best matched these conditions, we ran a three-level factorial design (Table C.1) with n=5 repetitions along the dimensions of the intrinsic grass growth rate k_{grass}, pasture capacity G_{max}, and scalar f, and took the time-averaged value over the final 10 years of each 40-year simulation of the average stocking rate and nutrient cost across all ranchers.

Table C.1 – Parameter values for factorial design. 4 points along k_{grass}, 5 points along G_{max}, and 6 points along f, for a total of 120 condition sets, and 5 repetitions for a total of 600 model runs in the calibration

Parameter	**Range**
k_{grass}	0.03, 0.06, 0.09, 0.12
G_{max}	4000, 5000, 6000, 7000, 8000
f	1.6, 1.8, 2, 2.2, 2.4, 2.6

All other model parameters were set to available literature values, as described in Appendix B. The full set of model outcomes generated by this analysis is shown below in Figures C.2 to C.9:

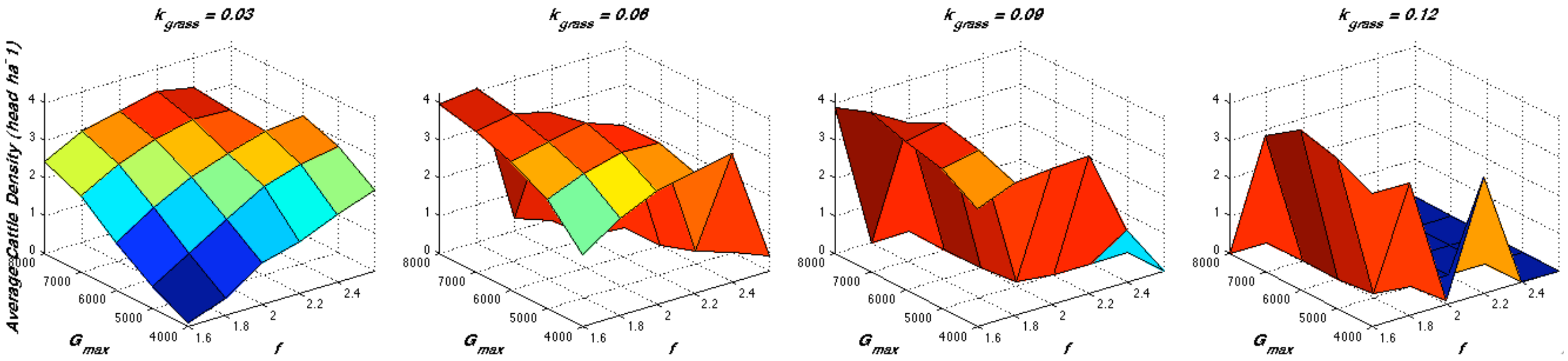

Figure C.3: Average cattle density (head/ha) across dimensions of grass capacity G_{max} (kg/ha), scalar stocking factor f, and maximum intrinsic grass growth rate k_{grass} (/t). Individual surfaces show average cattle density as a function of grass capacity and stocking factor f at a constant intrinsic grass growth rate.

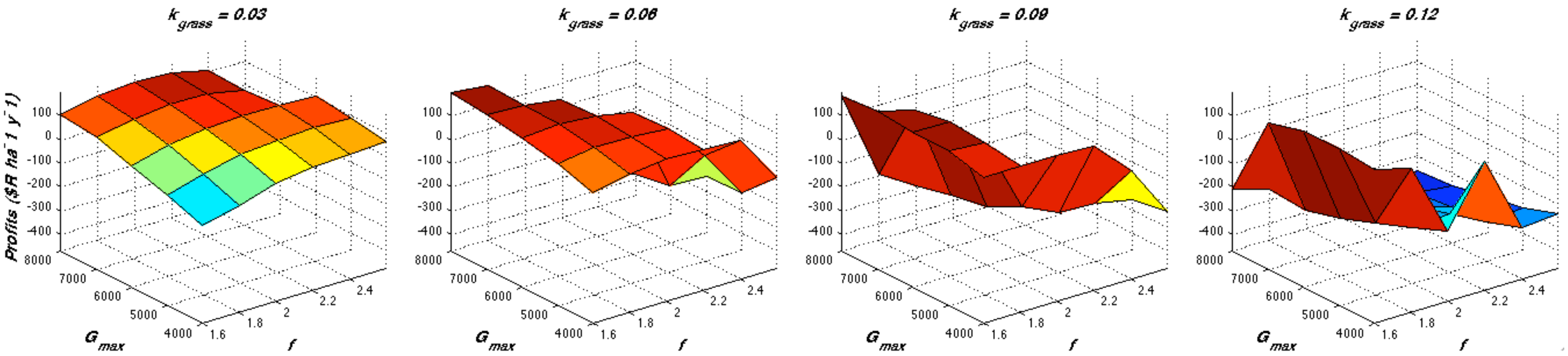

Figure C.4: Average profits ($R/ha/y) across dimensions of grass capacity G_{max} (kg/ha), scalar stocking factor f, and maximum intrinsic grass growth rate k_{grass} (/t). Individual surfaces show profits as a function of grass capacity and stocking factor f at a constant intrinsic grass growth rate.

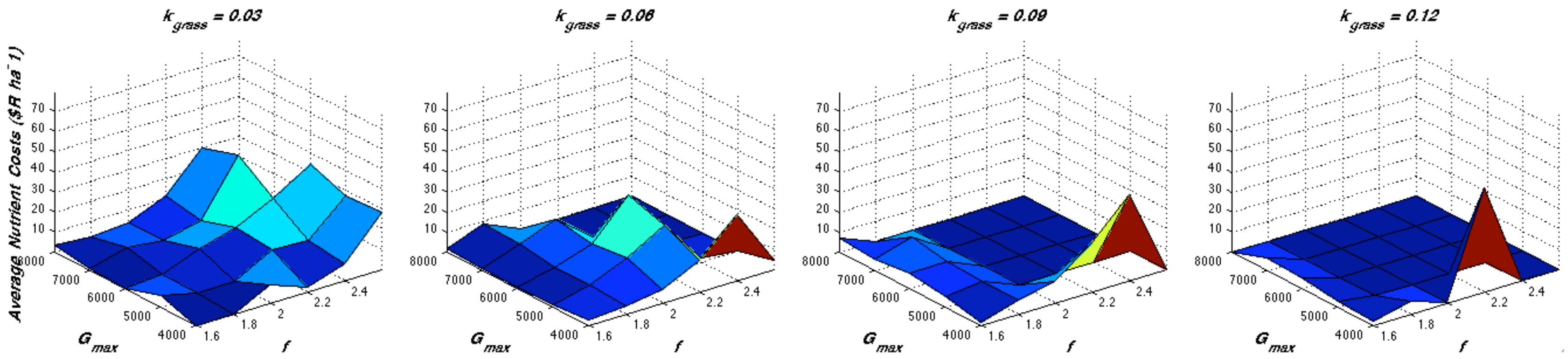

Figure C.5: Average nutrient costs ($R/ha/y) across dimensions of grass capacity G_{max} (kg/ha), scalar stocking factor f, and maximum intrinsic grass growth rate k_{grass} (/t). Individual surfaces show average nutrient costs as a function of grass capacity and stocking factor f at a constant intrinsic grass growth rate.

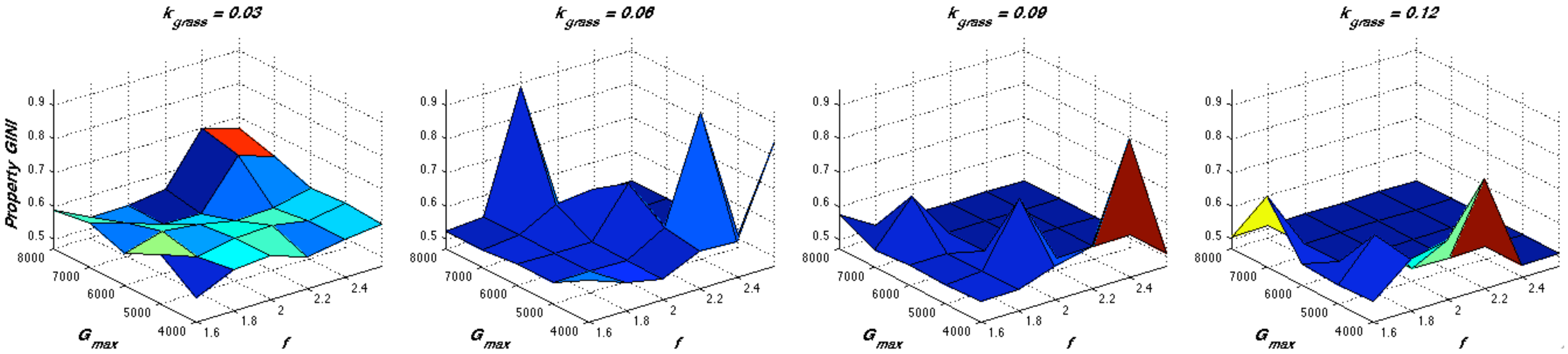

Figure C.6: Property GINI across dimensions of grass capacity G_{max} (kg/ha), scalar stocking factor f, and maximum intrinsic grass growth rate k_{grass} (/t). Individual surfaces show GINI as a function of grass capacity and stocking factor f at a constant intrinsic grass growth rate.

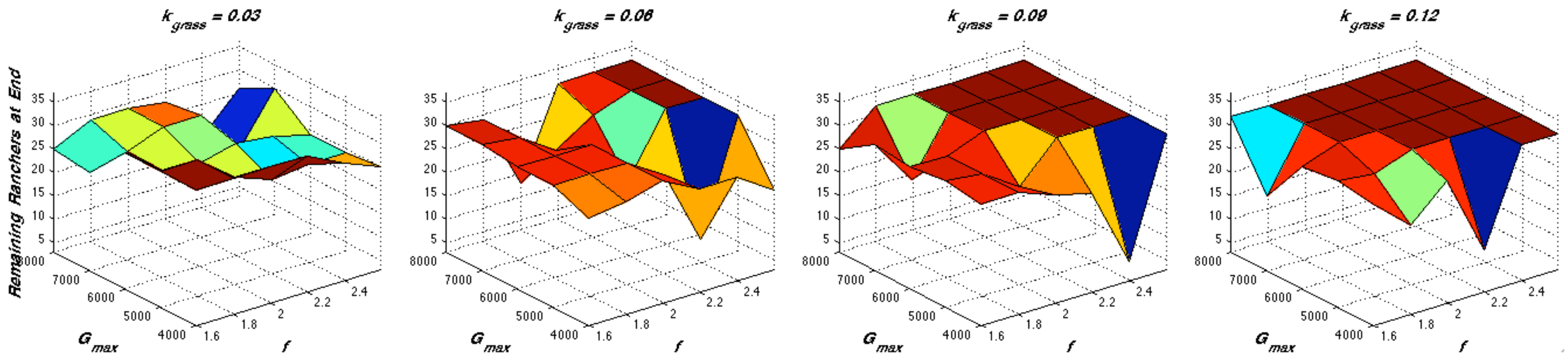

Figure C.7: Number of ranchers remaining at end of simulation across dimensions of grass capacity G_{max} (kg/ha), scalar stocking factor f, and maximum intrinsic grass growth rate k_{grass} (/t). Individual surfaces show number of ranchers as a function of grass capacity and stocking factor f at a constant intrinsic grass growth rate.

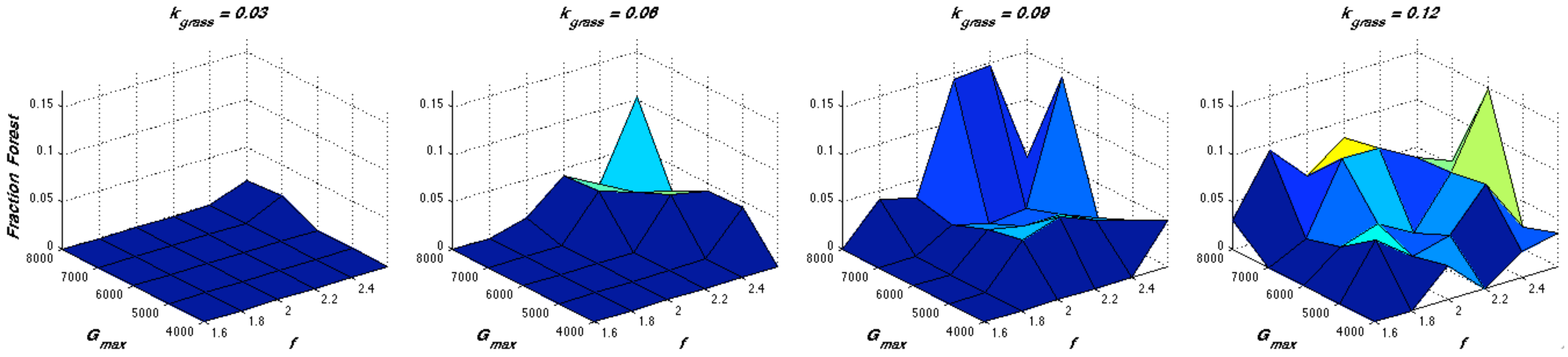

Figure C.8: Fraction of property in forest across dimensions of grass capacity G_{max} (kg/ha), scalar stocking factor f, and maximum intrinsic grass growth rate k_{grass} (/t). Individual surfaces show forest fraction as a function of grass capacity and stocking factor f at a constant intrinsic grass growth rate.

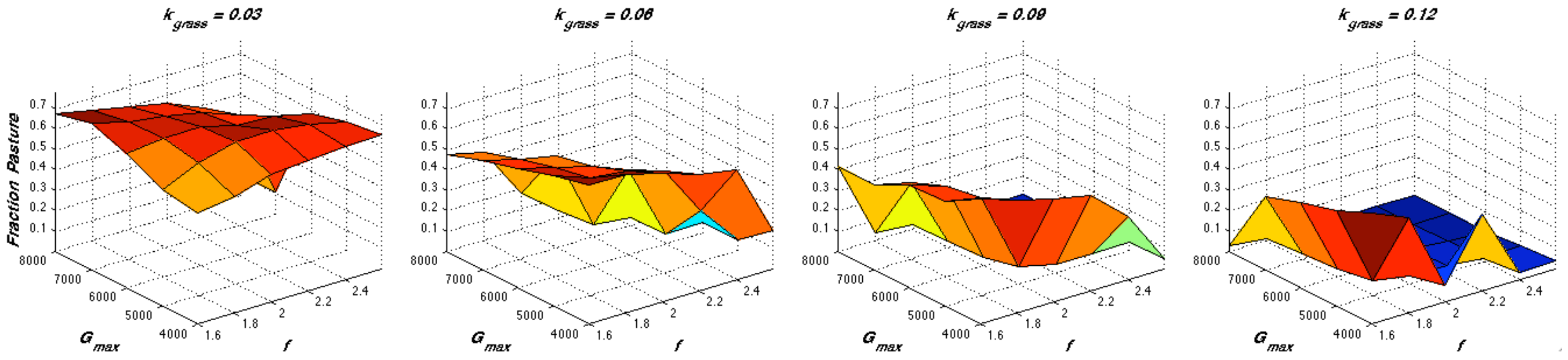

Figure C.9: Fraction of property in pasture across dimensions of grass capacity G_{max} (kg/ha), scalar stocking factor f, and maximum intrinsic grass growth rate k_{grass} (/t). Individual surfaces show pasture fraction as a function of grass capacity and stocking factor f at a constant intrinsic grass growth rate.

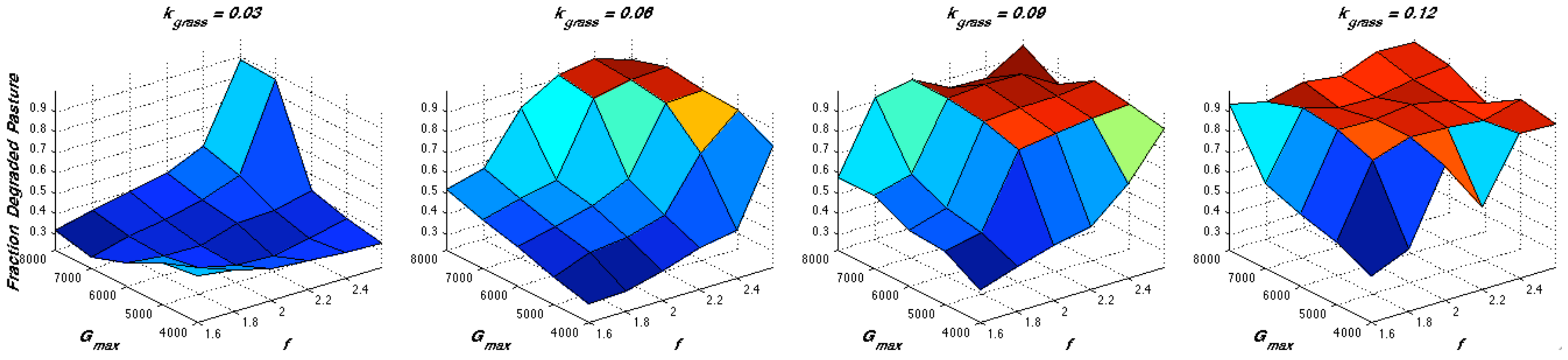

Figure C.10: Fraction of property in degraded pasture across dimensions of grass capacity G_{max} (kg/ha), scalar stocking factor f, and maximum intrinsic grass growth rate k_{grass} (/t). Individual surfaces show degraded pasture fraction as a function of grass capacity and stocking factor f at a constant intrinsic grass growth rate.

In general, all three parameters are initially positively related to ranch profitability. However, as they rise in concert they lead ranchers to overstock and crash the ranch productivity. In the calibration effort of this study, the set of points (k_{grass} = 0.03t^{-1}; G_{max} = 7t/ha; f = 2.4) was chosen as the best fit to our field observed stocking rates, with average annual supplement costs of about $US29.50, and an average stocking rate of 3.1 head/ha. This parameter set corresponds to a point near the ridge before performance begins to drop in the left-most figures for the outcomes below. In other words, the observed data correspond to a locally optimal, less resilient point in the parameter space of our model.

As an independent point of comparison, Andrade et al. (2006) find capacities of 3-8 t/ha and maximum growth rates ranging from 30-120 kg/ha/year across different months for pastures in neighboring Acre State stocked with 2.3-3 head/ha of cattle (Andrade et al. 2006). The equivalent maximum growth rate in our study, using k_{grass} = 0.03 and $G_{1/2}$ = 3.5t/ha, is 53kg/ha/year (see equation A.10).

Face Validity of Modeled Ranching Activity

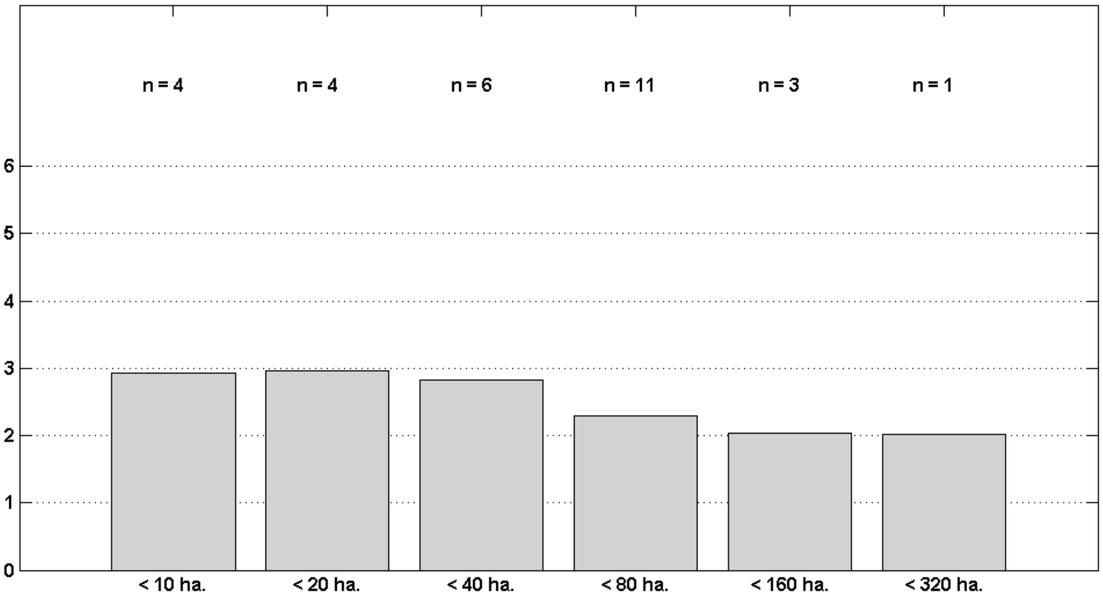

Figure C.2: Modeled cattle stocking density in head/ha as a function of property size. The n for each bar represents the number of properties of that size in the simulation.

A snapshot of a typical model run (year 7; $\Delta_{Prec} = 0$; $\Delta_{EI} = 0$), as calibrated to the above conditions, shows a decrease in stocking rates as property size increases, though without the sharp increase observed for the two very small (<10ha) properties in our sample (Figure C.2).

The model mechanism behind this pattern lies in the limits placed on how much land a rancher can modify (in any manner) each year. This amount is modeled sigmoidally and grows from 10 ha for small properties up to 80 ha for large properties (Eq. A.22), based on the reported areas recuperated in Figure A.4. Pasture in the model degrades at a rate linearly proportional to cattle stocking, with a lifetime of 10 years when stocked at 1 head/ha (for comparison, Mattos and Uhl (1994) discuss a pasture lifetime of 5-10 years with respect to medium and large ranches stocking cattle at 0.51 and 0.66 head/ha in Pará State (Mattos and Uhl 1994). Because ranchers on smaller properties restore a greater proportion of their land each year, the amount of degraded pasture is lower, and the land is able to support a greater number of cattle; thus, stocking rates should increase with decreasing property size, a pattern which emerges in Figure C.2.

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Appendix K

Full Results for Different Rancher Scenarios

Results begin in landscape layout on the following page.

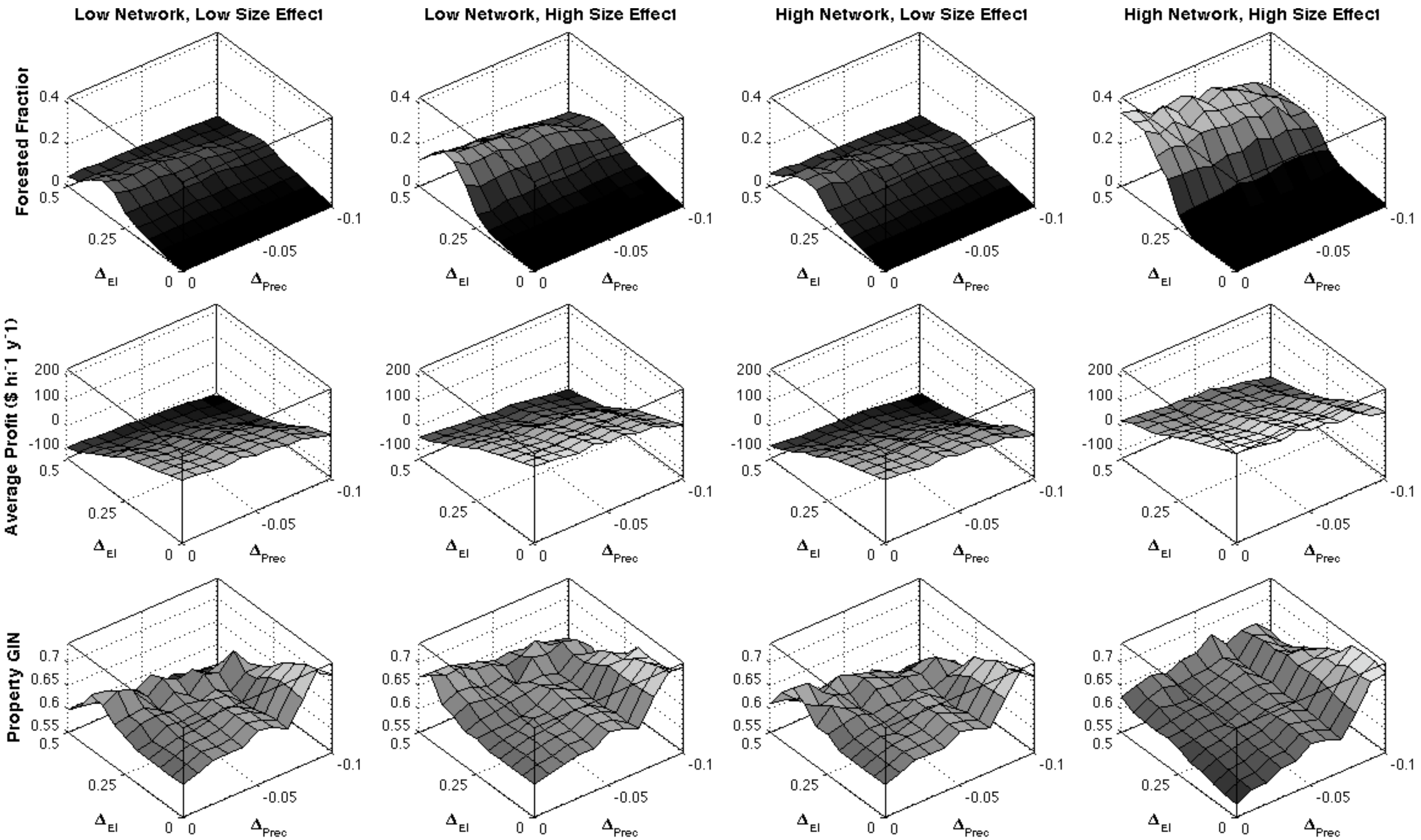

Figure D1: Response surfaces for Policy Scenario 1 – Sensitivity to change in expected income Δ_{EI} and in precipitation Δ_{Prec}, non-tiered environmental licensing. Surfaces in row 1 show average forested fraction across the landscape; row 2 shows average profit per hectare of property per year; row 3 shows the level of land aggregation measured by the property GINI coefficient. Each column represents a different scenario of rancher interaction.

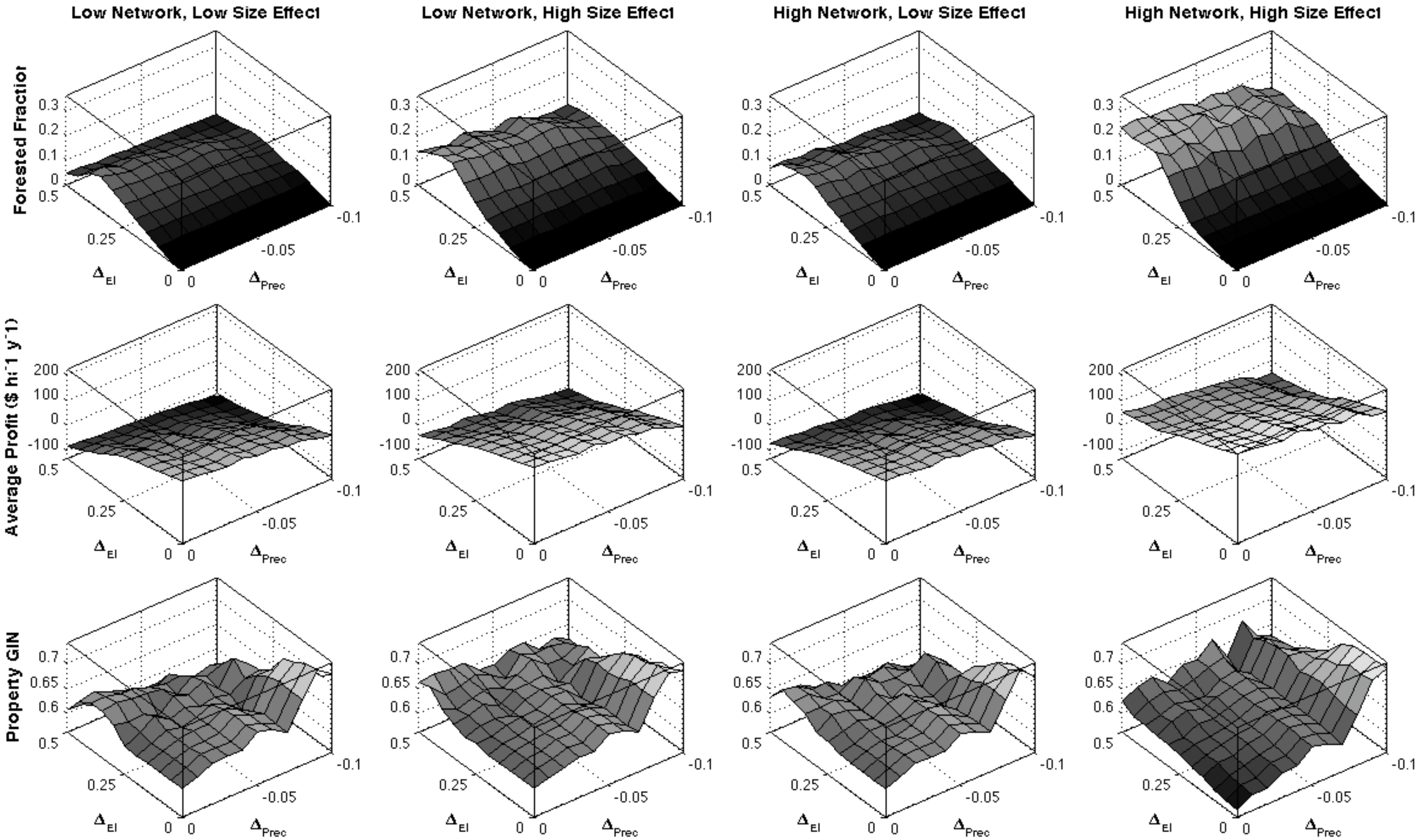

Figure D2: Response surfaces for Policy Scenario 2 – Sensitivity to change in expected income Δ_{EI} and in precipitation Δ_{Prec}, tiered environmental licensing. Surfaces in row 1 show average forested fraction across the landscape; row 2 shows average profit per hectare of property per year; row 3 shows the level of land aggregation measured by the property GINI coefficient. Each column represents a different scenario of rancher interaction.

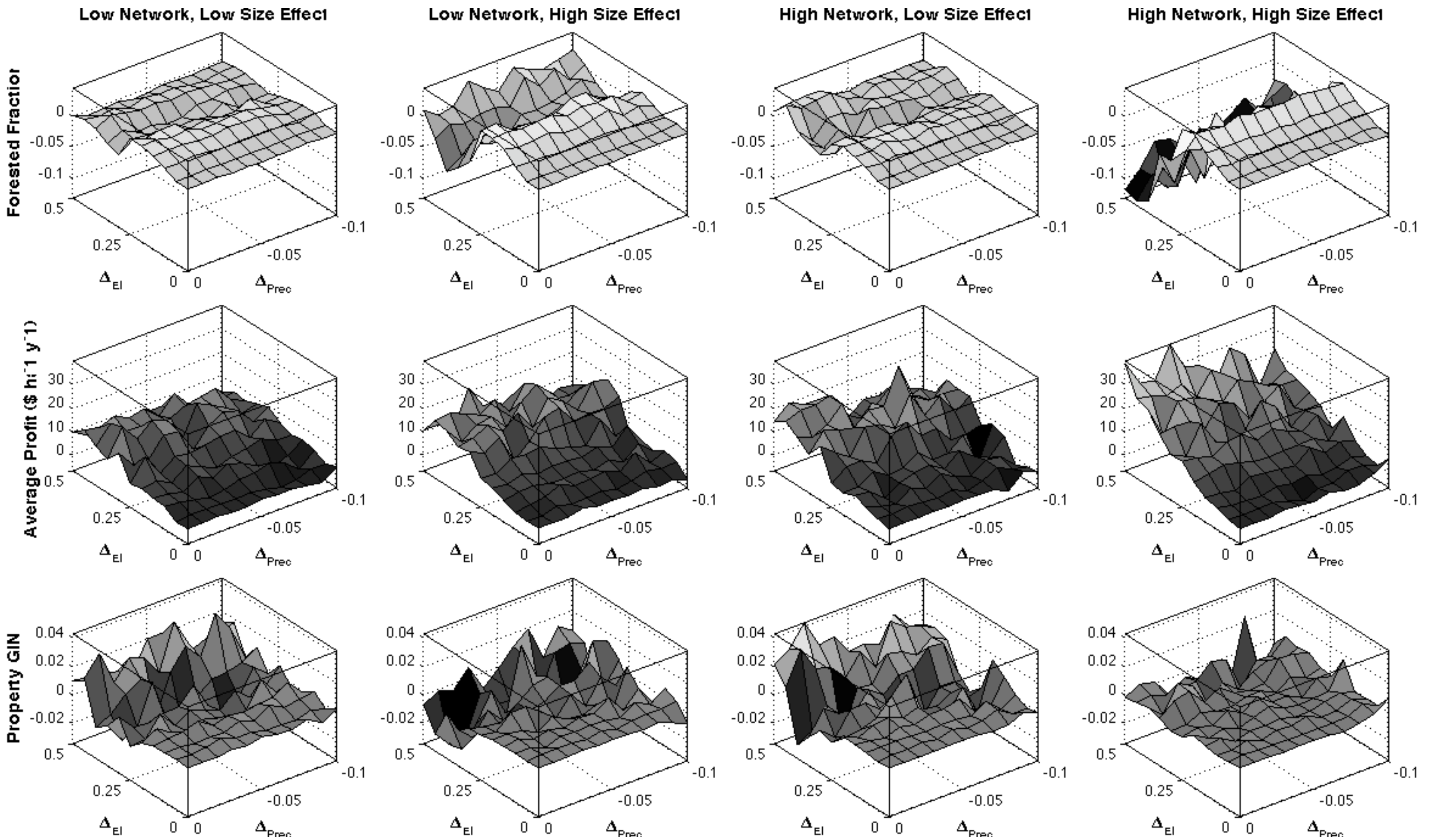

Figure D3: Response surfaces for the differences between Policy Scenarios 1 and 2, given as (Outcome 2 – Outcome 1)/Outcome 2. Surfaces in row 1 show difference in average forested fraction across the landscape; row 2 shows difference in average profit per hectare of property per year; row 3 shows difference in the level of land aggregation measured by the property GINI coefficient. Each column represents a different scenario of rancher interaction.

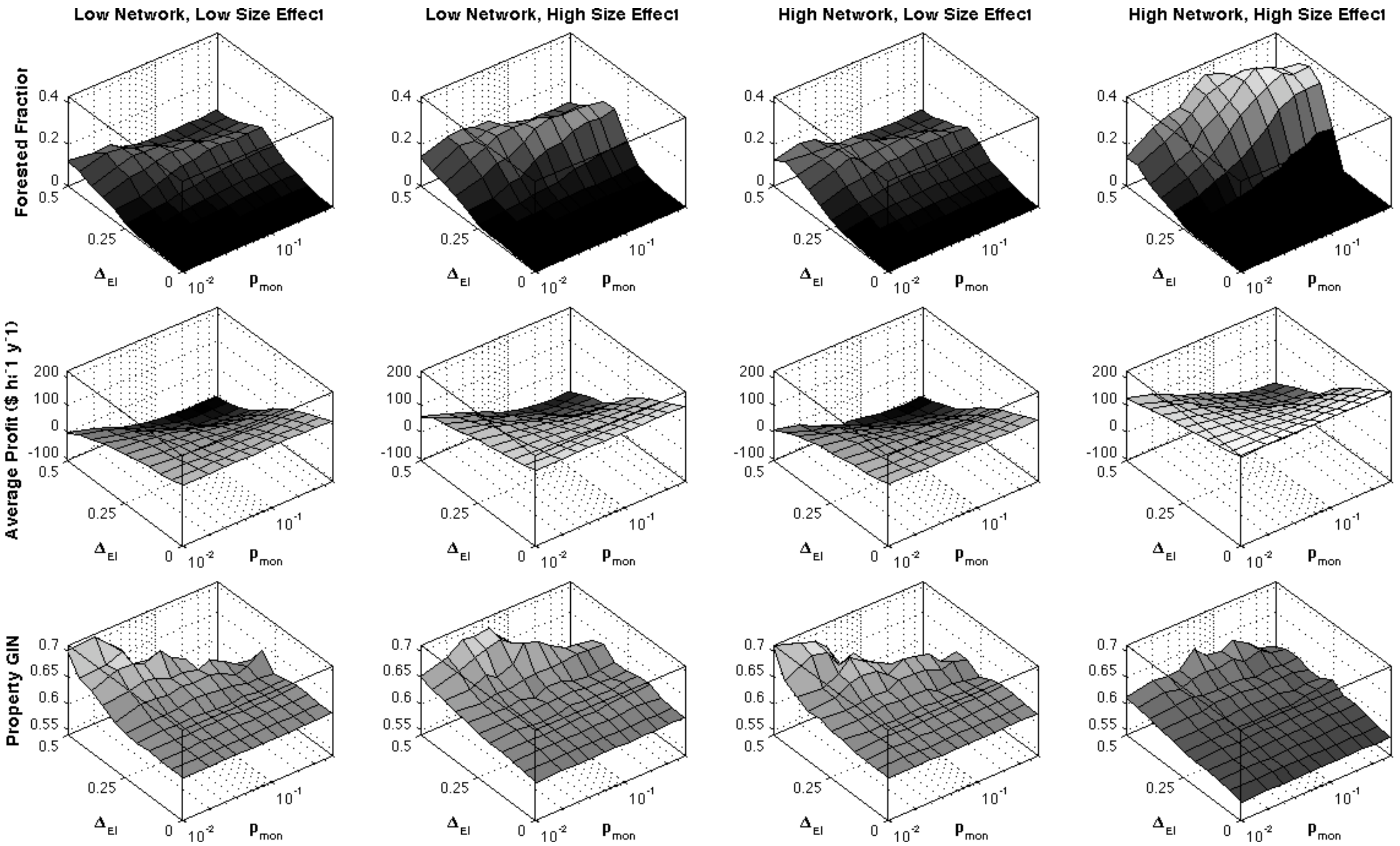

Figure D4: Response surfaces for Policy Scenario 3 – Sensitivity to change in expected income Δ_{EI} and in monitoring probability p_{mon}, non-tiered environmental licensing. Surfaces in row 1 show average forested fraction across the landscape; row 2 shows average profit per hectare of property per year; row 3 shows the level of land aggregation measured by the property GINI coefficient. Each column represents a different scenario of rancher interaction.

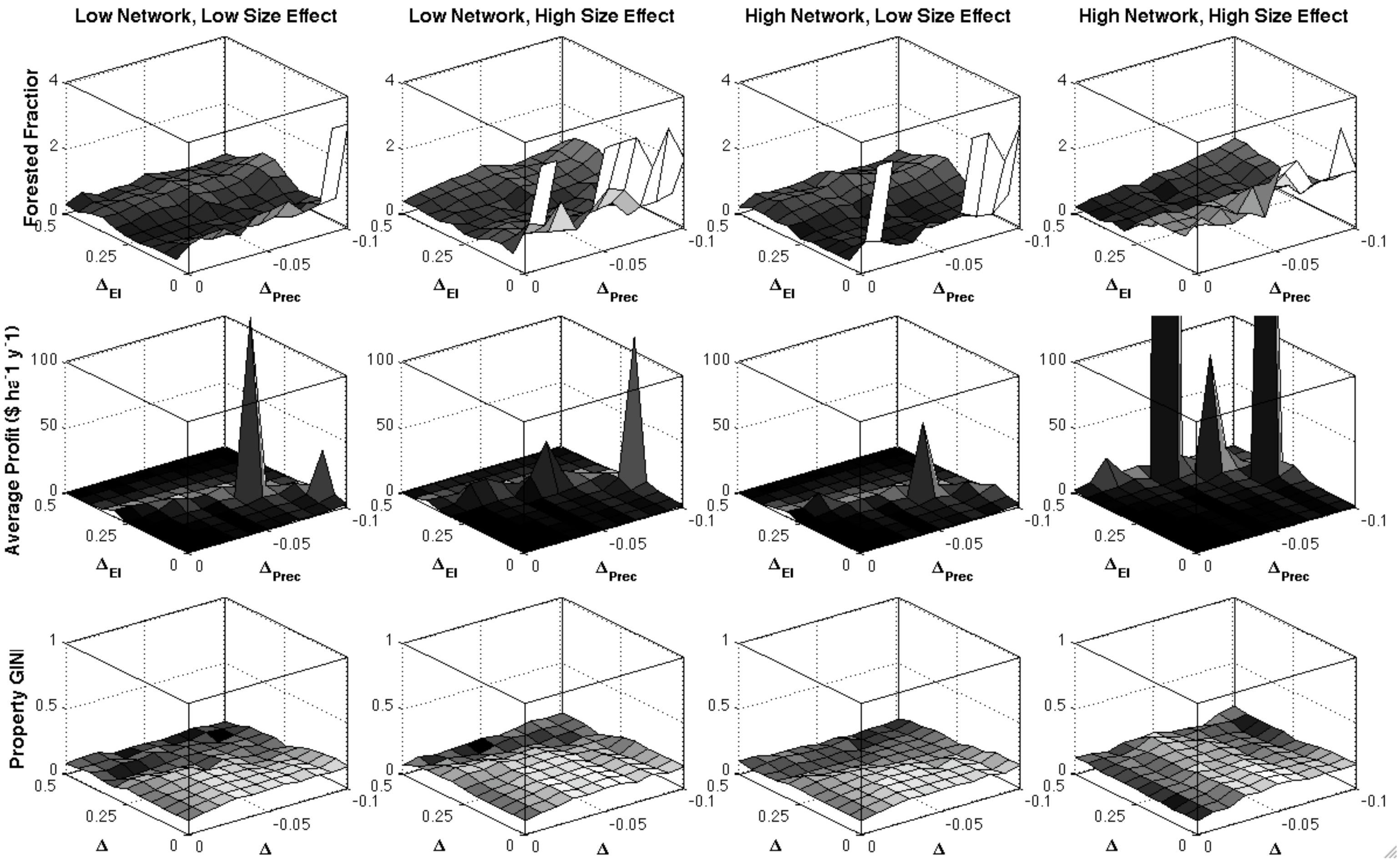

Figure D5: Standard deviations for response surfaces for Policy Scenario 1 – Sensitivity to change in expected income Δ_{EI} and in precipitation Δ_{Prec}, non-tiered environmental licensing. Surfaces in row 1 show standard deviation for forested fraction across the landscape; row 2 shows standard deviation for profit per hectare of property per year; row 3 shows the standard deviation for level of land aggregation measured by the property GINI coefficient. Each column represents a different scenario of rancher interaction. Values reflect the standard deviation across n replicates, divided by the mean across the n replicates.

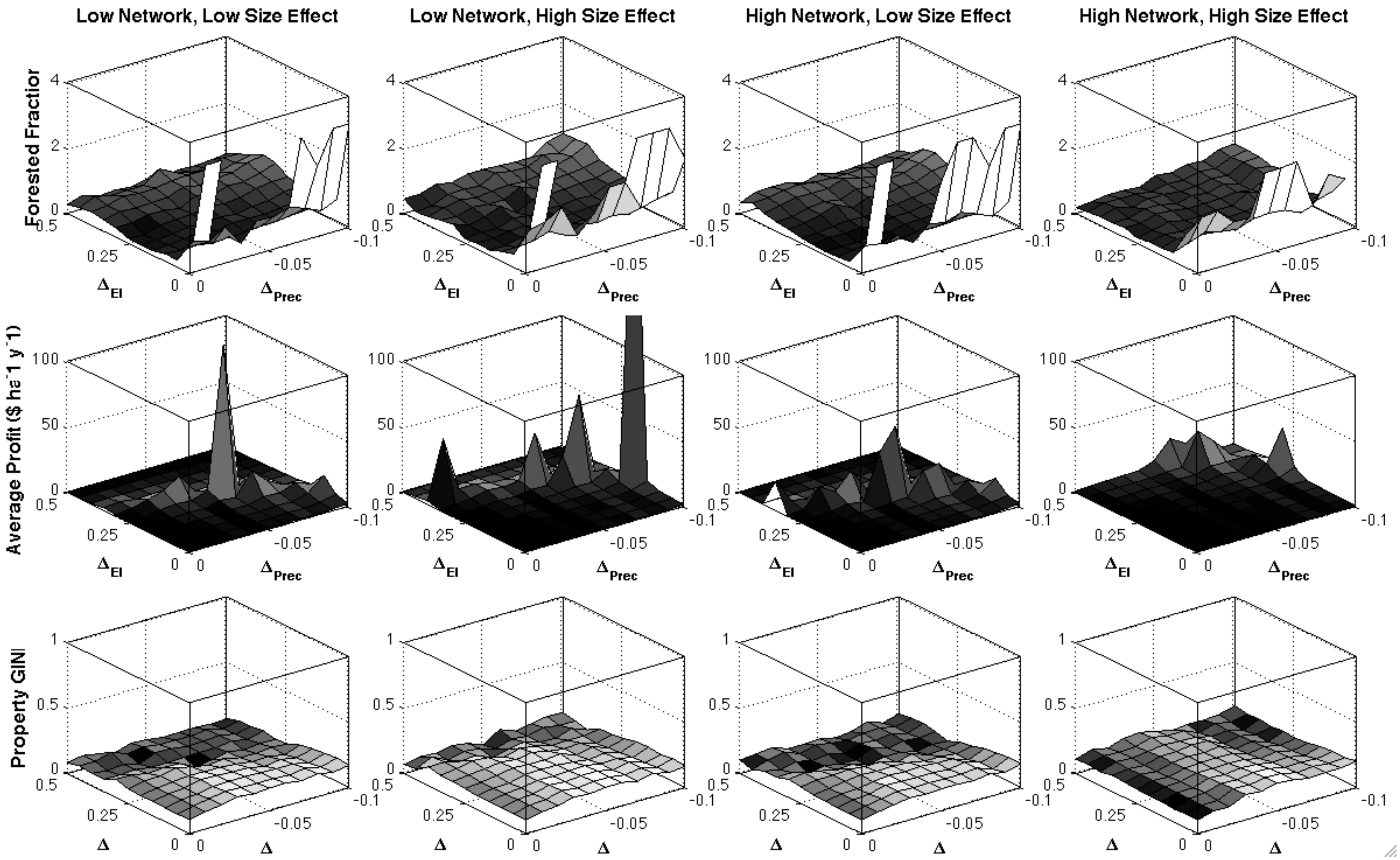

Figure D6: Relative standard deviations for response surfaces for Policy Scenario 2 – Sensitivity to change in expected income Δ_{EI} and in precipitation Δ_{Prec}, tiered environmental licensing. Surfaces in row 1 show standard deviation for forested fraction across the landscape; row 2 shows standard deviation for profit per hectare of property per year; row 3 shows the standard deviation for level of land aggregation measured by the property GINI coefficient. Each column represents a different scenario of rancher interaction. Values reflect the standard deviation across n replicates, divided by the mean across the n replicates.

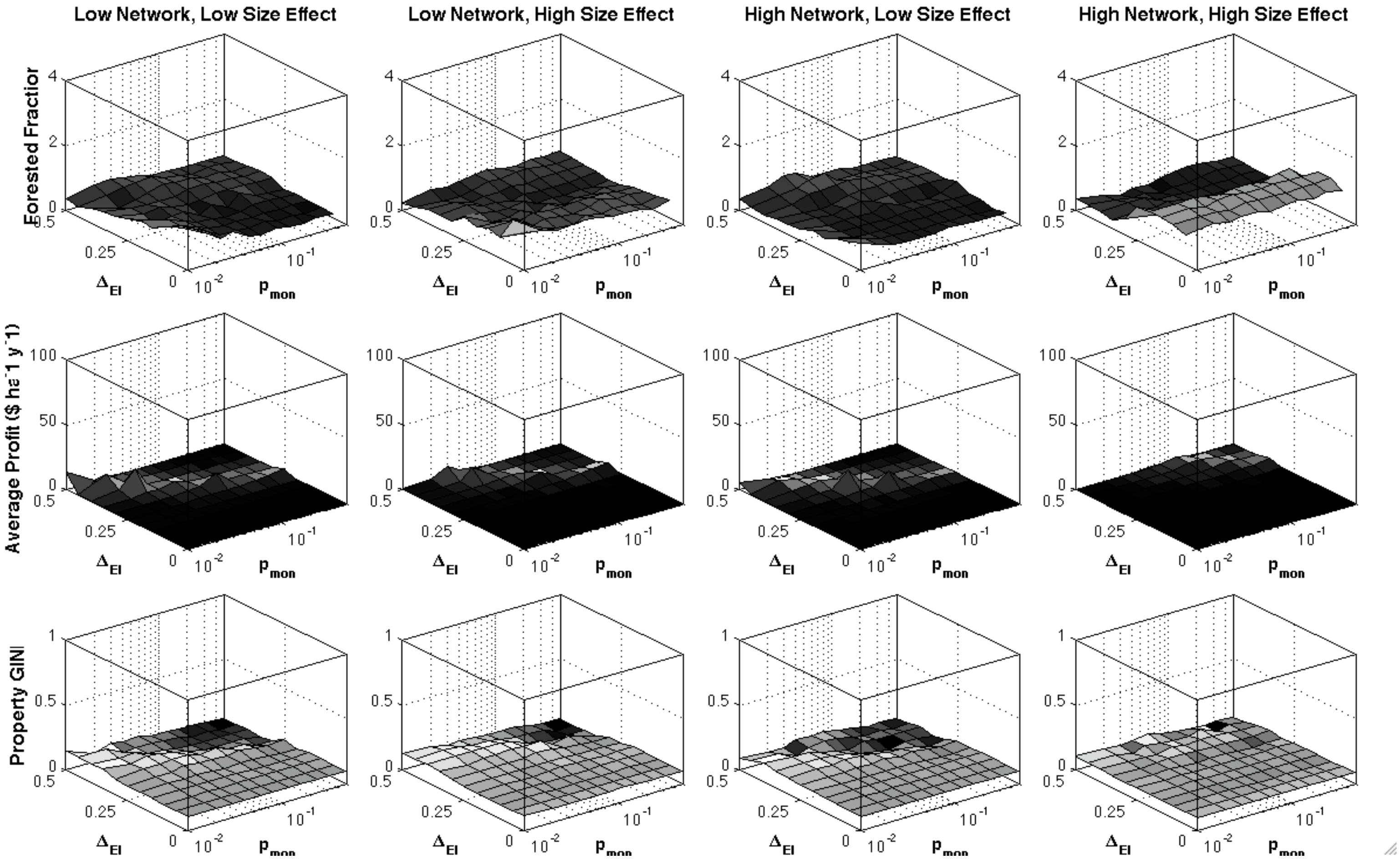

Figure D7: Standard deviations for response surfaces for Policy Scenario 3 – Sensitivity to change in expected income Δ_{EI} and in monitoring probability p_{mon}, non-tiered environmental licensing. Surfaces in row 1 show standard deviation for forested fraction across the landscape; row 2 shows standard deviation for profit per hectare of property per year; row 3 shows the standard deviation for level of land aggregation measured by the property GINI coefficient. Each column represents a different scenario of rancher interaction. Values reflect the standard deviation across n replicates, divided by the mean across the n replicates.