FOLLOWING THE RULES:
A BIOECONOMIC POLICY SIMULATION OF A BRAZILIAN FOREST CONCESSION

By

ALEXANDER JAMES MACPHERSON

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2007

To my wife, my children, and my parents

ACKNOWLEDGMENTS

I thank my doctoral advisor, Dr. Douglas Carter, for his complete support and intellectual guidance throughout my doctoral program. I would also like to thank the other members of my doctoral committee, Dr. Janaki Alavalapati, Dr. Charles Moss, Dr. Christine Staudhammer, and Dr. Daniel Zarin, for their excellent guidance through this tremendous challenge. I also thank the Working Forests in the Tropics program for its award of a National Science Foundation Integrated Graduate Education and Research Traineeship, which funded my doctoral education and research.

This study would not have been possible without the generous support of fellow researchers and students. At the Instituto do Homem e Meio Ambiente da Amazônia (IMAZON) in Belém, Brazil, I am extremely grateful to Paulo Barreto, Brenda Brito, Marco Lentini, Mark Schulze, Denis Valle, Beto Veríssimo, and Edson Vidal for sharing their time, data, and extensive knowledge. I am very fortunate to have received the continuous guidance of Mark Schulze and Marco Lentini, which was critical for this project's success. I hope the results of this study are valuable to IMAZON and that our collaboration continues in the future. I would like to thank my fellow student, Onil Banerjee, who gave me very helpful advice on this project. Fred Boltz of Conservation International broke a lot the ground with his research on production forests in Bolivia which greatly facilitated my work.

I owe the largest debt of gratitude to my loving family who shared the struggle every day. I could not have succeeded without them. My wife Natalie was willing to sacrifice an enormous amount so that I could achieve one of my dreams. My boys, Ewan and Lucas, have grown and learned along with me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

FOLLOWING THE RULES:
A BIOECONOMIC POLICY SIMULATION OF A BRAZILIAN FOREST CONCESSION

By

Alexander James Macpherson

December 2007

Chair: Douglas R. Carter
Major: Forest Resources and Conservation

After decades of difficult experiences with forest concessions, many countries continue to view concessions on public lands as a strategy to secure vulnerable lands while developing economic opportunities and raising government revenue. Brazil recently enacted the Public Forests Management Law, which focuses on the expansion and improved management of public forests, including the establishment of large areas of forest concessions. Using data from one of the longer running tropical forest experiments in the Eastern Brazilian Amazon region, my study develops a matrix growth and yield model which captures the dynamic effects of harvest system choice on forest structure and composition. The growth and yield model is embedded within a variety of optimization models parameterized with economic data from the Eastern Brazilian Amazon to study economic and forest condition outcomes as a function of policies such as current Brazilian regulations, sustainability constraints, enforcement mechanisms, and royalty systems. Results demonstrate that current regulations are unlikely to guarantee sustainable timber yields, even when regulations are followed and best logging practices are implemented. Inventory-based regulatory definitions of total volume and species-level sustainability are proposed and analyzed in order to estimate the viability and opportunity costs of additional harvest regulations. Results show that, under the proposed definitions, sustainable timber

inventories are likely viable but at significant opportunity costs. In a weak enforcement environment, audit pressure is unlikely to induce full compliance with harvest regulations, while performance bonds may potentially be more effective. The use of traditional royalty instruments such as the *ad valorem* and revenue-based royalties can effectively generate revenues and, in the case of revenue-based instruments, modify harvest behavior, but only under very limited circumstances. When critical variables change, such as the cost to implement reduced impact logging, the outcomes under the same instrument can vary dramatically. The optimal choice between applying a royalty-based strategy and a strategy based upon an area fee determined through a competitive or administrative process is crucial and is likely dependent upon the qualities and quantities of the forest resource, the characteristics of the logging firms, and regional institutional strength.

CHAPTER 1
INTRODUCTION

Brazilian Public Forests Management Law

In the 1960s and 1970s, government investment opened access to extensive portions of terra firme forests in inland regions of the Brazilian Amazon, mainly through the construction of roads. Improved forest access and subsidies for migrants to occupy and clear vast unclaimed areas promoted the creation of a highly predatory, extensive, and migratory logging industry (Lima et al., 2006; Stone, 1998a; Stone, 1998b; Uhl et al., 1997; Veríssimo et al., 1998; Veríssimo et al., 2002a). Today, in much of the Brazilian Amazon, the forest sector is dominated by insecure property rights and a rent-seeking, inefficient bureaucracy (Merry et al., 2006). The combination of high opportunity costs of capital and weak property rights increase the risks of forest investment, which compels loggers to have short-term, profit-maximizing objectives, leaving little incentive for managing for future harvests (Merry et al., 2006). Government inefficiency and corruption add to the disincentives of management, as oversight is often so lax or corrupt that illegal loggers gain a strategic advantage though bribery, while loggers wishing to follow the rules often cannot get management plans approved by the government (Merry et al., 2006). The result is that an estimated 43% of the Brazilian Amazon's timber supply is sourced by illegal logging (Lentini et al., 2005).

Land tenure instability poses the most significant constraint to increasing the area of managed forest in the Brazilian Amazon. Roughly 33% of the Brazilian Amazon, approximately 160 million hectares, is in *terras devolutas*, lands that are thought to be publicly-owned but are either subject to conflicting ownership claims or unclaimed and unsecured by a state presence. Because of the uncertain legal and ill-protected status of these lands, they are frequently used by loggers and ranchers for private gain (Lentini et al., 2005). The predatory use of these public lands creates a significant loss of the nonmarket benefits that should accrue the public. As well as maintaining ecological services and biodiversity, there is an enormous potential to use these forests to produce timber and non-timber forest products on a sustainable basis, generating increased governmental revenue and a wide range of social and economic benefits. Veríssimo et al. (2000) estimate there are 114 million hectares of forestlands, 28% of the Brazilian Amazon, with the potential to become sustainable multi-use production forests.

In 2006, Brazil enacted the Public Forests Management Law (Lei 11284/2006), which focuses on the expansion and improved management of public forests, including the establishment of large areas of forest concessions. The implementation of logging concessions on public lands is viewed as an ingredient toward correcting many of the failures of the current timber economy, at least on public lands (Veríssimo et al., 2002a; Veríssimo and Barreto, 2004). The new law arose from a long debate between public and non-governmental research institutions, state and federal governments, the private sector, and social movements. As well as asserting an overarching strategy for the sustainable multi-purpose use of public forests, the law approves the establishment of logging concessions in federal and state-administered public forests, the creation of a federal forest development fund (Fundo Nacional de Desenvolvimento Florestal) to financially support sustainable resource use, and the creation of a federal forestry agency (Serviço Florestal Brasileiro), which will manage the development fund and supervise the concessions.

Newly declared public lands will be allocated across the multiple forms of Brazilian conservation and sustainable land use categories at the state and federal levels, including strict protection, extractive reserves, lands allocated directly to traditional communities who prove historic use of the lands, and logging concessions. The law contains provisions that establish a framework for the decentralization of public land authority to the municipal and state-levels. These efforts are ongoing and parallel to the federal government devolving significant authority over forest policy to state environmental agencies. A forest destined to become a public forest under the new law must pass several legal tests and procedures, which is expected to require many years for many highly disputed areas.

As is typical with public policies, the new legislation is full of vague directives and goals to achieve in the future. Many of the procedural elements of the law have been left for rule-setting within the bureaucracy. In addition, the Public Forests Management Law (PFML) is, in a sense, a secondary law. In the general public forest case, designation under the new law depends upon other complex legal dynamics, such as land tenure reform, which also operate under their own sets of vague directives.

Many debates during the preparation of the law focused on the government's low institutional capacity to monitor and enforce contracts and appropriate environmental management and royalty payment requirements. As the PFML is implemented, the development of sound administrative procedures, revenue collection systems based on appropriate rates, enforcement capacity, and royalty distribution procedures will become crucial. There is significant controversy whether these multiple tasks can be achieved. For example, Merry and Amacher (2005) identify several potential problems with Brazilian concessions, many of which may be analogous to well-documented problems with concessions in other countries (see e.g. Gray, 2005; Repetto and Gillis, 1998). First, concessions may allow concessionaires artificially high rents because of poorly-designed revenue systems. As well as give away public resources, this problem may additionally stifle innovation and the longer term competitiveness of the Brazilian forest industry (Merry and Amacher, 2005). Second, the Brazilian government may become a rent-seeking government as a result of unexpectedly high costs of administering the concession system added to the possible nonpayment of royalties. In order to increase revenue, a rent-seeking government might seek to induce higher harvest rates by lowering tax or royalty rates away from the first-best rates that maximize economic efficiency. This effect, also discussed for concessions in general in Amacher (1999), Amacher and Brazee (1997), and Merry and Amacher (2005), can lead to an accelerated allocation of land into concessions, which risks compounding budgetary shortfalls.

The interaction between logging on public and logging on private land is a critical additional complexity, and it is difficult to foresee how the timber economy might evolve. Studies have shown that regional timber demand in the short and medium-term could be satisfied by low-intensity logging on smallholder properties, where social welfare and conservation gains are potentially large in comparison to concession logging (Campos and Nepstad, 2006; Lima et al., 2006; Nepstad et al., 2004). Most importantly, in order to avoid unintended consequences concession policies need to be designed using a broader view that includes revenue systems and interactions with timber markets in the larger economy (Merry and Amacher, 2005).

This introductory chapter develops these issues in more detail, drawing upon relevant research and discussions. The section that follows conceptualizes sustainability in the context of this study. The following section establishes the conceptual foundation underpinning this study by drawing upon the economics literature.

Sustainability

Given a political decision to contract out the management of public forest goods and services, fundamental questions about management objectives appear. The structure and outcomes of the concession system will vary dramatically according to the objective sought. The simplest form of concession is a harvest concession, where the ultimate objective is to convert the land to alternative uses. In the Sabah region of Malaysia, for example, the government largely treated forests as a nonrenewable resource to be mined for foreign exchange and employment, emphasizing the conversion of land to agricultural uses (Gillis, 1988). On the other end of the spectrum are the objectives of sustainable timber management (STM) and sustainable forest management (SFM). STM focuses on sustaining timber yields, while SFM focuses on the sustained delivery of multiple goods and services over long periods of time (Pearce et al., 2003). There may be many perspectives on management objectives along the spectrum between these extremes. In the Brazilian case, the legal definition of SFM is clearly presented in the PFML. Concessionaires are legally obligated to practice SFM, which is defined as "forest administration in order to gain economic, social, and environmental benefits, respecting the mechanisms that sustain the managed ecosystem and considering the use of multiple timber species, multiple non-timber products and sub-products, and other goods and services of natural forests" (Lei 11284/2006).

A central debate in the discussions about SFM is whether it is appropriate to include requirements for sustained timber yields (STY) within forest management requirements. On the surface, successfully implementing STY addresses the need for long-term timber supplies from managed sources, often viewed to be a critical ingredient to a stable forest sector that effectively contributes to economic development. In the absence of more complete information about the broad portfolio of forest ecosystem goods and services, as is typically the case, STY may also be viewed as an umbrella measure for forest processes more holistically. This use of STY as a proxy for SFM is very attractive to many stakeholders in the Amazon-region who are investing in forest management as a bulwark against the degradation and deforestation that dramatically reduces or destroys the bulk of the forests' functions.

However, Luckert and Williamson (2005) write that forest economists are increasingly viewing STY management requirements as economically detrimental. STY requirements do not promote economic stability and development as much as once thought, as the requirements can bind private actors into making suboptimal decisions when markets for forest goods and services are volatile (Luckert and Williamson, 2005). The authors debate whether strong STY constraints should have any role within SFM, arguing that timber perhaps should be viewed as one of a set of substitutable products within the forest. Viewed this way, forest managers are not constrained to harvest a given quantity over a set period of time. Rather, managers flexibly tradeoff forest goods and services in response to dynamic market conditions, increasing forest sector efficiency. At the same time, forest services that are either irreversible or public goods may additionally be managed under a precautionary principle (Luckert and Williamson, 2005).

Luckert and Williamson draw heavily upon the discourse within economics concerning strong and weak sustainability, pioneered largely by David Pearce in a series of publications (see e.g. Pearce et al. 1989). Whether an economy is strongly or weakly sustainable depends upon decisions about the substitutability of human-made capital for natural capital. In a weakly sustainable economy, human-made capital can be substituted for natural capital, the objective being to sustain non-declining utility into perpetuity (Pearce et al., 1989). In a strongly sustainable economy, utility and natural capital itself must be non-declining in time, a position frequently advocated within ecological economics (Daly, 1996). Many variations on these basic viewpoints are examined in detail in Heal (1998) and Neumayer (1999). In their article, Luckert and Williamson (2005) assert that STY requirements are a form of strong sustainability (no substitution between timber and other products) while SFM is a form of weak sustainability (substitution is permitted).

Luckert and Williamson's argument is compelling but is based upon the assumption that markets function well in the particular region under discussion, that the market's ability to assign prices to scarcity will generate an optimal allocation of forests which will persist into the foreseeable future. This assumption may be reasonable in the case of forested countries with well-functioning markets that have experienced a forest transition and are seeing forests rebound (Rudel et al., 2005), but may not be as appropriately applied within regions such as the Brazilian Amazon, where land tenure problems abound and rates of deforestation and forest degradation continue to be high (Foley et al., 2007). Markets and management information on non-timber forest ecosystem goods and services are also lacking in the region, preventing managers from making well-informed decisions about trade-offs between goods and services.

It is the position of this paper, then, that the continued examination and calculation of sustainable yield remains relevant for forest management in the Brazilian Amazon, particularly with respect to public lands planning. The limits of such an assessment should be identified at the outset, however. As Karsenty and Gourlet-Floury (2006) highlight, while estimating the timber harvests over multiple cutting cycles is valuable, reducing the assessment of sustainable management to the sustainable yields of a few, highly-valued species is problematic. Accepting the assertion that the calculation of sustainable yields remains relevant, the important discussion becomes about how STY is applied in practice. In much of the Brazilian Amazon, as a result of market failures, there is clear incentive to liquidate the entire merchantable timber stock, leaving behind commercially and ecologically degraded forests. Regulatory constraints and/or economic incentives are necessary to induce socially desired behavior.

Current forestry best practices are limited to reduced impact logging (RIL) systems which seek to minimize environmental impacts of harvest systems as compared to unplanned conventional logging (CL) systems which constitute about 90% of the region's harvests (Zarin et al., 2007). RIL typically requires the following practices, adapted from Dykstra (2002):

- Pre-harvest commercial tree inventories and maps
- Pre-harvest planning of roads, skid-trails and landings
- Pre-harvest vine cutting
- Employing directional felling, cutting stumps low to the ground, and optimal bucking of tree stems, all to reduce waste
- Construction of roads, landings and skid-trails that satisfy design guidelines
- Ensuring that skidders remain on the skid-trails by winching logs when feasible
- Conducting post-harvest assessments in order to provide feedback

In Brazil, firms are obliged to follow legal restrictions aimed at minimizing environmental damage and protecting the future productivity of the forest. These restrictions include minimum diameter cutting limits, upper bounds on harvest intensity, the retention of seed trees and individuals of rare species, and protection of riparian buffers and wildlife. However, the RIL system applied within the context of these legal restrictions is not guaranteed to induce STY (Zarin et al., 2007). An additional requirement that the harvest from any given cutting cycle be at or below a sustainable volume may be an additional policy instrument that proves appropriate in this environment. Further, regulators might consider imposing STY at the species-level. In fact, STY-type requirements are likely to be adopted within the PFML.

These types of rules are policy-determined approximations that are expected to achieve broad objectives yet are administratively simple to apply and monitor (Boscolo and Vincent, 2003). But, as is the case with virtually any form of regulation, one-size-fits-all policies are unlikely to optimally achieve multiple objectives within complex landscapes. Zarin et al. (2007) write that the size of the landholding and whether the land is publicly or privately-owned should influence management requirements. Private smallholders (typically with properties under 500 ha) should be expected to practice RIL, but given technical, legal, and financial constraints, these landowners should not be held to higher standards, such as sustainable production at the forest or species-level. These landholders often view timber harvests as a one-time event that finances economic activities, often the purchase of cattle, on the proportion of the land the owners are legally permitted to clear (Zarin et al., 2007). Maintaining forest cover on the residual land is challenging because of destructive reentry logging, fires escaped from adjacent lands, and clearings at the forest margin in an attempt to increase agricultural productivity (Zarin et al., 2007). Meanwhile, forest operations on mid-sized private and public lands typically larger than 3000 ha, Zarin et al. (2007) argue, are of sufficient scale that they should be required to sustain total commercial volume production. Silvicultural practices, cutting blocks, areas, and cycles should be appropriately be adjusted in response to forest conditions, information, and technology (Zarin et al., 2007).

Sustaining species-level harvested volumes is expected to be particularly challenging with high-valued timber species that are heavily logged and do not have the typical inverse J-distribution with a sizeable number of sub-merchantable stems poised to grow into the commercial size classes in time for future harvest entries, such ipê (*Tabebuia impetiginosa*), mahogany (*Swietenia macrophylla*), cumaru (*Dipteryx odorata*), and cedrela (*Cedrela odorata*) (Schulze, 2003; Schulze et al., 2005; Zarin et al., 2007). Some of these species are thought to benefit from, and perhaps require, large disturbance events for regeneration, indicating that the relatively flat size distributions seen today are likely to be from cohorts that established during a long ago disturbance (Fredericksen and Putz, 2003; Gullison et al., 1996; Snook, 1996; Zarin et al., 2007). Because of the expected silvicultural challenges and costs and the required spatial scales of sustaining these high-valued species, Zarin et al. (2007) advocate that sustaining volumes at the species-level should be required on large public lands, such as those destined to become logging concessions in Brazil.

Making the sustainability challenge more complex is the fact that logging impacts will inevitably lead to post-harvest floristic recomposition over the short and medium terms in logged-and-left stands and permanently in repeatedly logged stands under the relatively short cutting cycles typically used (Favrichon, 1998; Karsenty and Gourlet-Fleury, 2006; Sist et al., 2003b). This recombination tends to favor fast-growing, light-demanding species with very light, often not commercially valuable wood (Favrichon, 1998; Phillips et al., 2004; Valle et al., 2007; Van Gardingen et al., 2006). Sustaining species-level volumes over time, therefore, may be significantly more challenging than sustaining overall timber volumes in which substitutions among species to contribute to volume constraints is permitted.

Economic Approach

While the grey literature of consulting reports on the economics of tropical logging concessions flows relatively steadily (for reviews of a large number of studies, see e.g. Gray, 2005; Scholl, 2005), the peer-reviewed economics literature on tropical forest concessions appeared in two bursts. The first period, stimulated by the publication of Repetto and Gillis (1988), saw a prominent dialogue amongst economists on the influence of royalty instruments on economic efficiency and rent distribution (see e.g. Hyde and Sedjo, 1992; Vincent, 1990; Vincent, 1993). This literature is well-reviewed by Merry and Amacher (2005), who synthesize lessons for Brazil's emergent concession system and conclude that it is imperative to design concession policy instruments jointly with instruments that influence harvests on private lands. Merry and Amacher (2005) also caution that the concession system may expand too rapidly if concession polices and government revenue objectives are linked, a point echoing Amacher and

Brazee (1997). Perhaps motivated by the emergence of new logging concession policies in Latin America, a more recent round of concession economics literature places a stronger emphasis on the dynamics of illegal logging and corruption. For example, Amacher (2006) issued a challenge to economists to better integrate illegal logging and forest sector corruption into their research efforts (for examples, see e.g. in Amacher et al., 2006; Amacher et al,. 2007; Delacote, 2005; Palmer, 2003).

In a region as vast as the Brazilian Amazon, illegal logging and forest sector corruption assumes a multitude of forms. It is important to contextualize the very specific types of illegality studied here within the larger Brazilian forest economy. Illegal logging includes activities such as logging on illegally settled lands, logging without government approved management plans, logging outside the spatial boundaries of approved plans or within legally reserved areas. Illegal logging also includes logging greater volumes that management regulations permit and the harvest of rare and smaller diameter trees. Illegal logging also can include activities outside of the forest, such as the illegal acquisition of management authorizations, timber transportation permits, and other types of documentary falsifications. At the larger scale, there may be long-term agreements between timber firms and government officials to facilitate unlawful forest activities.

For many operators of forest products firms in the Brazilian Amazon, the legal environment is very ambiguous and uncertain (Rhodes et al., 2006). There is a large difference between operators of large enterprises who collude with law enforcement and purposefully flout national and international law and the much larger number of small-scale operators who, in order to survive in a difficult business climate, falsify documents and pay small bribes (Rhodes et al., 2006). From the regulator's perspective, it is difficult to distinguish between these very different types of businesspeople (Rhodes et al., 2006). Additionally, improved enforcement of misguided forest law might inhibit the rural poor from performing low-intensity timber operations by increasing transaction costs or, worse, by cutting off traditional access to forest resources, causing severe impacts on rural livelihoods (Kaimowitz, 2003).

In the limited forest economics literature that examines illegal logging, economists primarily examine the quantity of timber harvested (see e.g. Amacher et al., 2007) or the size of timber harvested (see e.g. Boscolo and Vincent, 2000). To a lesser extent, economists examine the possibly corrupt interactions between logger and regulators (see e.g. Delacote 2005). With the exception of Boscolo and Vincent (2000) and Leruth et al. (2001), economists have paid very little attention to logging techniques specifically or forest management more broadly.

This study adopts a confined definition of illegality. Building on the economics tradition of focusing on harvest volumes, this study examines the incentives to harvest over legal limits. While Brazilian regulations establish a general harvest limit on management plan authorizations, plans may in fact require harvests below this limit, based upon forest type, firm size, and cutting cycle length. This study examines the most general case of harvest limits (the 30 m^3/ha per harvest per cutting cycle entry), which is likely to reflect plans authorized for mid to large-scale firms operating under a 25 to 40 year cutting cycle.

Like Leruth et al. (2001), this study assumes that the negative externalities associated with selective logging have as much to do (or more) with management practices as with harvest intensities. In this study, the implementation of best logging practices, in the form of RIL, is treated as a proxy for forest management. Additionally, the implementation of RIL techniques is likely to be required on Brazilian forest concessions. Hence, the under-implementation of RIL is treated as a form of illegal logging.

To further motivate the conceptual approach of this study, Figure 1-1 modifies the diagrams discussed in Vincent (1990) and Hyde and Sedjo (1992) to include illegal logging. MC0 represents the illegal logger's marginal cost of harvesting timber volume V. In this highly simplified depiction, the illegal logger chooses to maximize private welfare and harvest at the level of V0 at the given market clearing timber price *p*. Next, V1 represents the harvest levels of the logger that follows current regulations. The additional marginal cost of operating legally is measured by MC1.

Crucially, as is often the case with one-size-fits-all environmental regulation, the set of rules driving the legal logger to produce at V1 are unlikely to be perfectly designed to protect the future productivity of the forest. Simultaneously, the rules are unlikely to induce the logger to internalize the social costs of logging, such as reductions in biodiversity, nontimber forest products, climate and disease regulation, and water quality that might be associated with logging impacts. The additional constraints on harvests that protect future productivity and internalize social costs are represented by adding MC2 and MC3, respectively, which further reduces the optimal harvest levels. However, as Vincent (1990) and Hyde and Sedjo (1992) discuss, the real rate of value growth in natural tropical forests may be so low that MC2 could equal zero, as there is little or no financial incentive to leave valuable timber standing or reduce damages to future stocks by reducing harvests or employing more costly harvest and silvicultural techniques.

In the presence of imperfect enforcement and incentives for breaking the rules, government agencies face the challenge of how to jointly develop enforcement and royalty systems that cost-effectively induce desired harvest levels and improved forest management. Depending on the agent's preferences over risk, the type of law, and the likelihood of being caught, the would-be rule-breaker generates a probabilistic expectation of gains and negative consequences of being caught and punished. In a simplified version of this story, if the expected profits with rule-breaking are higher than alternative legal opportunities, the agent will break the rules (Becker, 1968). Second, given the likelihood of criminal behavior, the law enforcement agency faces a resource allocation problem and must make a variety of decisions with respect to the definition of the potential crime, the public enforcement effort, and the level of the fines in order to identify an optimal solution under incentives for law-breaking behavior (Becker, 1968; Polinsky and Shavell, 1979; Polinsky and Shavell, 2000). The enforcement problem can be seen then as a form of market failure, where the social planner seeks to equate the marginal costs of controlling externalities with the marginal benefits of reducing the externality.

A representative logger's marginal profit as a function of volume harvested, $\frac{\partial \pi}{\partial V}$, is depicted as a downward sloping line in the simple schematic of Figure 1-2, which modifies a diagram from Sutinen and Andersen (1985) to include illegal logging. Under incentives for rule-breaking and failed enforcement, the logger will choose to operate at the level where marginal profit is zero, or V0 in Figure 1-1. The enforcement agency must allocate resources to push the logger toward producing at V1, the optimal production level under the current set of rules. But because enforcement is imperfect, the enforcement agency is unlikely to be successful. Where the fine is exogenously given at f (as is often the case with penalties for environmental crimes) and the probability of being caught performing illegal harvests is given by $\theta(V)$, where $\frac{\partial \theta}{\partial V} > 0$, the marginal expected fine is given by $f\frac{\partial \theta}{\partial V}$. The intersection between the two lines locates the logger's harvest choice at V* under imperfect enforcement when incentives for illegal behavior exist, most likely at a level somewhere between V0 and V1.

Increasing fines is one option to reduce illegality. In 1998, for example, Brazil, increased maximum fines under its environmental crimes law (Lei 9605-98), which includes a maximum fine for deforestation and illegal logging of $700/ha. Yet, a trivial mathematical solution to the enforcement problem when enforcement is costly is that fines should be made arbitrarily large while the probability of capture approaches zero (in order to minimize costs of enforcement effort), where the expected fine equates the marginal damage of the offence. Yet, economists pointed out soon after Becker's influential 1968 article that initiated the study of enforcement economics that fines above a firm's capacity to pay are often meaningless. For practical purposes, the expected fine should not exceed a firm's threshold for bankruptcy. Meanwhile, institutional barriers such as inadequate funding, professional capacity, and corruption may be pervasive within an enforcement system.

While enforcement pressure may induce regulatory compliance, royalty instruments, or taxation instruments more generally, some economists have argued, can be selectively applied to meet other harvest objectives, such as reducing harvest levels to the V2 or V3 levels in Figure 1-1. Much concessions economics research has focused on the fact that few countries have priced the forest resource well and provided appropriate economic incentives to the sustainable and efficient use of public forest resources (Gray, 2005). Problems include setting fees too low and collecting fees at relatively low rates (Gray, 2005).

Additionally, researchers in the concession economics literature have been concerned with rent capture and distribution (Amacher et al., 2001; Boltz, 2003; Boscolo and Vincent, 2000; Hyde and Sedjo, 1992; Vincent, 1990). Rent capture appeals to the idea that the state is the true owner of the land and should recover the full economic rent associated with concession logging, the area *p1pc* in the regulated logger of Figure 1-1, for example. Distribution refers to how much of the rent is captured by the government and how much is retained by the concessionaire, the common concession experience being that the concessionaire retains too large a proportion of the rent (Repetto and Gillis, 1988). Meanwhile, even if the government is able to fully capture legal levels of rent, the logger may hide rents obtained through illegal harvests, depicted in Figure 1-1 by the area *ap0p1c*.

However, rent distribution says little about economic efficiency (Hyde and Sedjo, 1992; Vincent, 1993). On one extreme, depending on how firms reinvest the rents, disproportionate private sector rent capture may lead to more local-scale economic gains than rent captured and dissipated by an inefficient government (Hyde and Sedjo, 1992). On the other extreme, private sector rent might accrue predominantly to national and international elites, with few positive impacts poverty or forest sector development (Hyde and Sedjo, 1992).

In this study, in addition to the opportunity to collect fines when the concessionaire is caught breaking the rules, two types of royalty charges are investigated. First, a percentage *ad valorem* rate is charged against the marginal profit, or the added-value, of harvesting a tree. In other words, a percentage of the difference between the price of a tree and the costs to harvest the tree is charged under the *ad valorem* royalty. Second, a percentage revenue-based royalty rate is charged against just the price of the harvested tree. For either instrument, the royalty rate is applied only against trees that were legally harvested. As has been shown in previous work, the *ad valorem* royalty system as typically applied is a non-distortionary instrument that will not influence marginal harvest decisions (Hyde and Sedjo, 1992).

However, given the analysis here includes the potential of illegal logging, where no royalties are paid on the illegal portion of the harvest, the *ad valorem* royalty may not be non-distortionary across its feasible range, as high rates may induce illegal logging. Meanwhile, the revenue-based royalty charged will reduce the relative profitability of harvesting the tree, distorting harvest decisions on the margin, creating the possibility of inducing lower harvest levels, which may or may not be a desirable effect, given the government's objectives. The same risk of high rates inducing illegal harvests may also be present with the revenue-based royalty. Also, as it is commonly practiced, the *ad valorem* royalty requires relatively high monitoring costs relative to the revenue-based royalty because firm revenues and costs need to be monitored, rather than only the revenues. Under imperfect monitoring, the firm may seek to exaggerate costs, reducing the overall *ad valorem* charge.

An area fee is also studied as a possible revenue instrument. Area fees, as used in this analysis, are also non-distortionary in terms of harvest decisions, although at a larger scale they may help determine what lands are profitable for harvest. This occurred in the Bolivian concession system as large areas of less productive forests were taken out of the concession system under an annual area fee (Merry and Amacher, 2005). In practice, the area fee can be determined via a competitive or administrative process.

An additional policy choice to be examined in this study is the use of harvest performance bonds. Performance bonds function differently than the previous instruments in that, in one form of the bond, loggers deposit money with the government before harvest and then, upon execution of the harvest, are refunded a quantity proportional to the satisfaction of required performance measurements. The use of performance bond mechanisms is often proposed as a royalty or enforcement instrument and has been the subject of several studies (Boltz, 2003; Boscolo and Vincent, 2000; Leruth et al., 2001; Sun, 1997), yet there is very little practical experience with the instrument in tropical country concessions. The logger, for example, may deposit the area $ap0p1c$ with the government in order to get final approval to proceed with harvests (Figure 1-1).

If the rule-abiding harvest is not performed, the government will keep the appropriate proportion to compensate for losses associated with the rule-breaking.

Leruth et al. (2001) find that performance bonds combined with traditional enforcement measures are more likely to be effective at protecting forest resources than approaches that rely upon royalty instruments. They argue that the negative externalities associated with logging have very little relationship with harvest volumes. Rather, the externalities are largely a result of the quality of management practices, such as whether RIL or post-harvest silviculture is implemented. A timber tax is unlikely to successfully function as Pigovian-type instrument which taxes the externality in order to better align social and private costs (Leruth et al., 2001). In fact, Leruth et al. (2001) argue, timber taxation can actually induce more damage to the forest resource than no taxes at all by encouraging lower overall harvests at higher rates of collateral damage.

In this study, the logger will be assumed to pay royalties only on legal portion of the harvest. This shirking of payments adds to the already significant incentive to operate illegally. Revenue systems have little or no influence within the area between the MC0 and MC0 + MC1 curves on Figure 1-1. In fact, there is severe discontinuity at the threshold between legal and illegal logging intensities; the royalty instantaneously goes to zero. Meanwhile, there are critical forest activities that are unaffected directly in the short-term by royalty policies, such as RIL or post-harvest silviculture, which may have significant economic and ecological implications over the long-term. The position of this paper is that enforcement and royalty systems are intertwined, a point theoretically shown in Leruth (2001) and Amacher et al. (2007). In other words, command and control policies must be mixed with royalty instruments in order to foster more sustainable harvest and management practices.

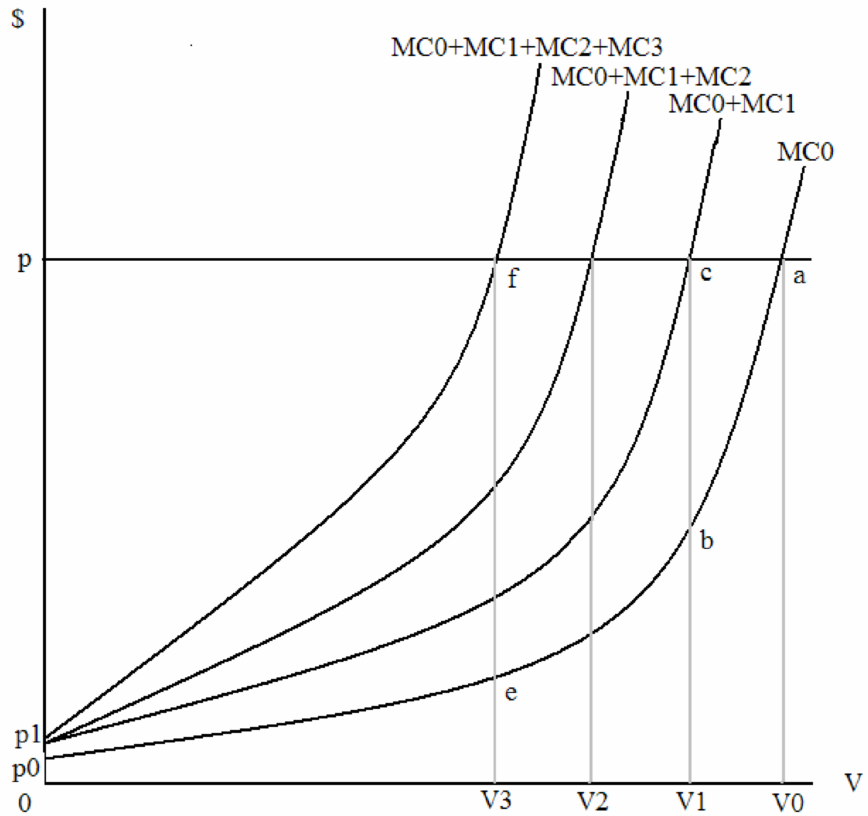


Figure 1-1. Comparative harvest profiles (modified from Hyde and Sedjo, 1992). MC0 represents the marginal costs of harvesting illegally. MC1 represents the additional marginal costs of operating within the current set of rules. MC2 represents the additional marginal costs of investing to protect the future productivity of the stand. MC3 represents the additional marginal costs of internalizing environmental externalities.

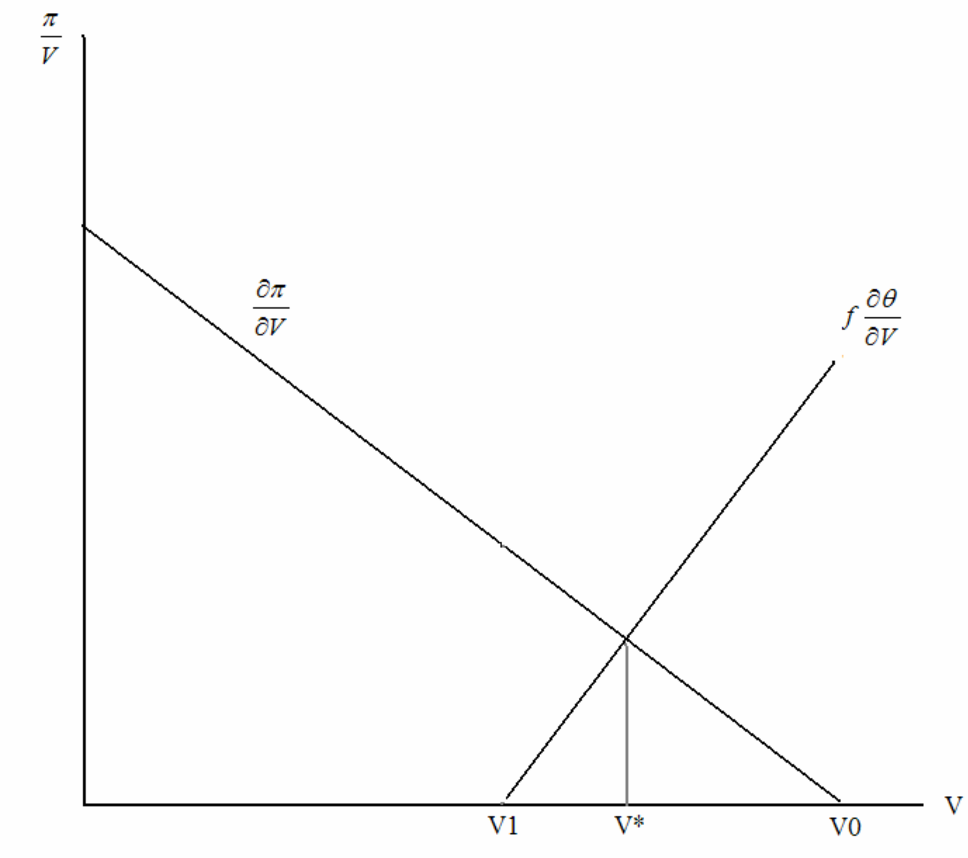


Figure 1-2. Simple application of a penalty function (modified from Sutinen and Andersen, 1985)

CHAPTER 2
A MATRIX-BASED GROWTH AND YIELD MODEL OF AN EASTERN AMAZONIAN FOREST UNDER HARVEST PRESSURE

Introduction

Matrix models of forest growth and yield are robust predictors of aggregate stand characteristics such as density, basal area, and diameter distribution, while being mathematically tractable (Picard et al., 2002; Sist et al., 2003a; Vanclay, 2001). Matrix models are particularly advantageous in that they can be used to simulate a range of conditions based upon minimal data requirements (Gourlet-Fleury et al., 2005). A pair of observations of the diameter distribution will often be sufficient to construct the transition matrix (Buongiorno and Michie, 1980; Michie and Buongiorno, 1984). Analysis may be performed at smaller scales, as in the many studies that examine a representative forest area, such as a hectare or acre (Boltz, 2003; Boscolo and Vincent, 2000; Buongiorno and Michie, 1980), or at the landscape-level (Lin and Buongiorno, 1998; Lin and Buongiorno, 1999a; Lin and Buongiorno, 1999b) Because of analytical tractability, minimal data requirements, and scalability, matrix models are often used in forest economics, particularly in tropical contexts (Boltz, 2003; Boscolo et al., 1997; Boscolo and Vincent, 2000; Favrichon, 1998; Mendoza and Setyarso, 1986; Önal, 1997; Sist et al., 2003b).

Estimation of tropical forest growth and yield models is typically very difficult because of the lack of data on such complex forests. Adequately representing the dynamics of species interactions, recruitment, and response to disturbance is even more difficult when the objective is to develop management plans (Boltz and Carter, 2006). The response to disturbance, usually a harvest, is often treated non-explicitly by mixing data from control and logged sites to estimate growth and recruitment parameters. The main limitation of the approach of estimating a single growth matrix from data that mixes control and disturbed treatments is the poor incorporation of how the forest responds in the short and long-term to relatively high levels of disturbance.

For the Eastern Amazonian forest of this study, the harvest system employed has a strong effect on damage to the residual stand and future growth rates of the stand, although these effects may be short-term. For some species in certain contexts, harvest disturbance can create a favorable environment for growth (Fredericksen and Putz, 2003). For others, the harvest disturbance may create an environment that is unfavorable, particularly if combined with heavy harvest pressure, as is the case with many highly valuable species in the Amazon region (Schulze, 2003). As matrix models are often used to project logged stands into the far future in which logging is performed over multi-decade cycles, repeated application of a growth matrix estimated on data collected over a relatively short post-harvest period creates a risk of bias, as the post-harvest growth response is projected for several decades, whereas the available evidence indicates that the post-logging growth pulse lasts for a decade or less (De Graaf et al., 1999; Dekker and De Graaf, 2003; Silva et al., 1995; Valle et al., 2007; Vidal, 2004). Estimating matrix transition parameters including trees killed inadvertently during harvest is also problematic because these trees do not observe any of the possible transitions.

While other authors have examined the implications of reduced impact logging (RIL) on economic and ecological outcomes (Boscolo et al., 1997; Boscolo and Vincent, 2000; Favrichon, 1998; Sist et al., 2003b), only Boscolo and Vincent (2000) have developed a management-oriented matrix model that gives the forest manager an endogenous choice of logging technique and, hence, the consequent type and level of damage. The forest manager, often under highly imperfect information, will evaluate costs and benefits of various actions and then choose a decision path that best meets particular objectives within relevant institutional and ecological constraints.

The decision to adopt improved harvest practices resides not at the extremes of to fully adopt RIL or not, but is situated somewhere in the continuum between. Within an actual logging environment, some practices are more costly than others while some are more easily shirked than others. Simple oversight or lack of training may also cause firms to fail to adopt particular RIL guidelines. For example, in a study of two large certified companies in the Brazilian Amazon, Pokorny et al. (2005) note that about one-third of a set of 61 RIL guidelines were not fully implemented. The lack of sufficient monitoring, training, and equipment explains many of the failures to meet guidelines (Pokorny et al., 2005).

This work seeks to advance the use of matrix models in tropical forestry policy analysis on two fronts: first, by improving the capacity of the model to capture the dynamic effects of harvest on forest structure and composition; and, second, by endogenizing the choice of harvest system that allows the manager to best meet objectives. In doing so, this study extends the multi-species uneven-aged forest management models of Lu and Buongiorno (1993), Lin et al. (1996), and Buongiorno et al. (1995) to a tropical forest context. The model also improves the incorporation of harvest damage in a manner similar to Boscolo and Vincent (2000). The study also draws on and extends Boltz and Carter (2006) by using multinomial logit regression (MNL) to estimate the matrix transition probabilities. The model incorporates a recruitment function that models recruitment as a function of stand density and logging treatment type.

To display the utility of the modeling approach, the model will be used to compare the long-run structure and composition of the forest arising from the choice of implementing either RIL or conventional logging (CL), contrasted against a baseline projection of an unlogged forest. The framework of the managers harvest system choice will be established in this chapter, but examined in more detail in subsequent chapters.

Methods

Study Site

The matrix model was estimated from data collected from a 205 ha forest block in the Paragominas region of Pará, Brazil $\left(3^{\circ}\mathrm{S}\ 47.5^{\circ}\mathrm{W}\right)$, one of the principal Amazonian logging centers during the region's logging boom period of the 1980s and 1990s. The annual rainfall in the area is on average 1700 mm, occurring mostly between December and May. While on level terrain with no obvious differences in soil types (oxisols or ultisols), the evergreen study forest displays wide structural variation (Schulze, 2003; Vidal et al., 1997). Forests form a mosaic of high, medium and low stature patches, which can vary over very short distances (Schulze, 2003; Vidal et al., 1997). High stature patch trees are 30-45 m tall, while in the low, early-building phase forests, trees are generally less than 10 m tall with frequent, dense vine cover (Vidal et al., 1997).

The forest block of the experiment is a part of what is known as Fazenda Sete, a large, privately-owned forest fragment (2,500 ha) embedded within a landscape of cattle-ranches, agricultural fields and forests that have been logged and, in many areas, burned (Gerwing, 2002; Schulze, 2003). The bulk of the Fazenda Sete forest was logged in the early 1990s using CL, except for the area used in the logging experiment that generated the data used in this and several other studies on forest ecology and management (Barreto et al., 1998; Johns et al., 1996; Schulze, 2003; Valle et al., 2007; Vidal et al., 1997; Vidal, 2004). The forest block, which contains more than 350 tree species, was subjected to three treatments in 1993: an unlogged 25 ha control plot, a 75 ha plot logged using CL by a typical, locally-recruited logging crew, and a plot logged using RIL by a well-trained crew (Barreto et al., 1998; Johns et al., 1996; Vidal, 2004). The overall harvest intensities were approximately the same within the two treatment areas, but the amount of residual stand damage varied dramatically (Barreto et al., 1998; Johns et al., 1996; Valle et al., 2007; Vidal, 2004).

The Fazenda Sete experiment has been the source of several papers on the financial and ecological aspects of RIL. Johns et al. (1996) quantified the relative damage incurred by CL in comparison to RIL, also generating estimates of the benefits that would accrue to loggers employing RIL. Barreto et al. (1998) examined the relative costs and benefits of following best logging practices and found substantial economic benefit from implementing RIL rather than performing the typical unplanned logging operations prevalent in the region. The study site has been the source of ecological studies on vines (Gerwing and Vidal, 2002; Vidal et al., 1997) and post-harvest regeneration (Schulze, 2003; Vidal, 2004). Valle et al. (2007) use the Fazenda Sete data to calibrate the spatially-explicit SYMFOR model to study questions of yield regulation.

The data used in this study were collected within 24.5 ha areas within each treatment area. Within each treatment, two sampling strategies were followed. First, all trees with diameter at breast height $(\mathrm{DBH}) \geq 10$ cm were measured within 5.25 ha (700 m x 75 m) plots within each 24.5 ha treatment area. Second, for the remaining 19.25 ha, trees of commercial species with $\mathrm{DBH} \geq 10$ cm were measured, while only trees of non-commercial species with $\mathrm{DBH} \geq 25$ cm were measured. This study largely uses data from the extensively sampled plots to derive model coefficients. In addition to pre-harvest measurements, the plots have been measured several times over irregular intervals; this study draws on measurements from 1993 and 2003. A range of measurements were been performed, including recruitment of new trees, species identification, DBH, vine density, stem form, crown form, and whether the trees were damaged or killed during logging or died of natural causes.

In terms of trees felled, harvest intensities in the logging treatment plots were similar. In the RIL plot, 4.6 trees/ha (2.1 m^2/ha in basal area and 29.3 m^3/ha in volume) were harvested. In comparison, in the CL plot, 4.8 trees/ha (2.2 m^2/ha basal area and 29.9 m^3/ha in volume) were harvested. Meanwhile, the number of trees accidentally killed during each harvest diverged. In the RIL plot, 81.3 trees/ha (1.7 m^2/ha in basal area and 18.5 m^3/ha in volume) were killed inadvertently during harvest, while 86.9 trees/ha (2.2 m^2/ha in basal area and 24.5 m^3/ha in volume) were killed inadvertently in the CL plot. The damage figures indicate that, while the number of trees inadvertently killed per tree harvested was roughly equivalent across treatments, the basal area and volume damaged was about 30% higher in the CL plot. It is very important to note that these figures capture trees identified as trees killed immediately during harvest (essentially destroyed) and do not include trees that were damaged and died in subsequent years, or at least suffered reduce post-harvest growth. These trees which were likely to have been identified as damaged in Johns et al. (1996).

Of the 6571 trees with $DBH \geq 10$ cm that were not killed during harvest, 6351 (96.7%) were used to estimate the growth model. Trees that could not be identified to species were excluded from the model estimation, as in Boltz (2006). In the simulations, however, these trees are proportionally allocated across species groups in order to provide more accurate predictions of aggregate variables such as basal area and merchantable volumes. Annual diameter increments ranged from 0.00 to 2.69 cm/year, the average rate being 0.28 cm/year with a standard deviation 0.33 cm/year. 80.7% of the post-harvest residual trees survived the 10-year period.

Meanwhile, the recruitment data includes trees that grew to $DBH \geq 10$ cm during the 10-year interval. 2627 trees (166.8 trees/ha) recruited during this period, 2449 (93.3%) of which were identified to species. The subset of trees with identified species was retained for the estimation of the recruitment function. Trees which were recruited and then died before observation in the tenth post-harvest year re-measurement were excluded from the recruitment model.

Classification of Species Groups

Species classifications provide a simplified representation of the considerable ecological variation among species, which is a necessary simplification in many studies because data limitations and modeling constraints necessitate a small number of species groups (Vanclay, 2001). Two strategies are possible in this context: the analyst can make expert judgments of the relationship or data can be aggregated so relationships can be estimated at the group-level (Vanclay, 2001). Some simple models aggregate species based upon economic criteria alone, a risky strategy that may bear little resemblance to true forest dynamics. It is preferable to use ecological information in the grouping decision (Vanclay, 2001).

In this study, species were clustered into five groups based on ecological traits, such as seed size, seedling shade tolerance, growth potential, wood density, and maximum adult size (see Appendix A for a complete list of species classifications). The classification system used here provides a workable synthesis of published information on the ecological traits of neotropical species, field observations made by three experienced researchers with over a combined 45 years study history of eastern Amazonian forests, and patterns in the Fazenda Sete plot data.

At one end of the spectrum were pioneer species, characterized by small seeds, early reproduction, aggressive colonization of canopy openings, rapid growth, high mortality rates, low wood density, and relatively small adult size (most species did not reach 100 cm DBH). Embaúba species (e.g., *Cecropia obtusa* and *C. sciadophylla*) are common is this group. Pioneers include some commercial species but most are low-value lightwoods used primarily for plywood. The shade-tolerant group was composed of species with generally large seeds, seedlings capable of prolonged survival in the shaded forest understory, high density wood, and low mean and maximum growth rates. Commercial species in this group, such as maçaranduba (*Manilkara huberi*), are used primarily for sawnwood and have medium to high commercial value.

Two species groups fell in between the pioneer - shade-tolerant ecological extremes. Light-demanding species, those with shade intolerant seedlings and capable of rapid growth under high light, but without classic pioneer characters such as copious and early seed production and small adult stature, include many plywood and a few sawnwood timber species, such as freijo branco (*Cordia bicolor*) and tacacazeira (*Sterculia speciosa*). The intermediate group includes species that have less abundant advance seedling regeneration in the forest understory than shade-tolerant species and generally lower wood density and higher mean or maximum growth rates. Intermediates include species like muiracatiara (*Astronium lecointei*) and louro preto (*Ocotea caudata*) that combine shade-tolerant (e.g., diameter distributions approaching an inverse J-distribution) and light-demanding (e.g., rapid growth in high light) characteristics.

A fifth group was created for a group of species with a unique suite of traits, the light-demanding emergents. These species are characterized by highly left-skewed diameter distributions, with very large and very old adults accounting for a large percentage of the standing population, and high density wood. Seedlings display shade intolerance, but grow relatively slowly compared with pioneers and light-demanding species. Researchers have hypothesized that some emergent species are dependent on large-scale disturbance for replacement of adults and population persistence (Gullison et al., 1996; Snook, 1996). The emergent group includes some of the highest value timbers, such as ipê (*Tabebuia impetiginosa*) and jatobá (*Hymenaea courbaril*), and some of the most difficult to manage sustainably (Schulze, 2003; Schulze et al., 2005; Zarin et al., 2007).

Growth and Yield Model

Despite the initial divergence in growth patterns caused by the choice of logging treatment, at some point in the future, the growth dynamics of the forest under different treatments is likely to re-converge to the dynamics of the unlogged forest, a phenomenon observed by researchers working in the Tapajós National Forest in the Brazilian Amazon (Silva et al., 1995), in the Fazenda Sete forest studied here (Valle et al., 2007; Vidal, 2004), and in Suriname (De Graaf et al., 1999; Dekker and De Graaf, 2003). The trajectories resulting from each treatment can be represented by a unique cycle of transition matrices, which can be reduced to a single transition matrix (Winston, 1991). The benefit of this single matrix, then, is its easy incorporation into the classic economic optimization models, such as those that followed Buongiorno and Michie (1980).

The Fazenda Sete growth and yield model is based upon a characterization of forest structure and composition using tree diameter distributions and species groups. The pre-harvest stand state is given by the vector $\mathbf{y}_t = \left[y_{ijt} \right]$ where y_{ijt} is the number of trees per ha in species group $i\ (=1,..,m)$ and size class $j\ (=1,..,n)$ at time *t*. In this application of the model, the size classes are dominated in 10 cm DBH ranges beginning with 10-20 cm DBH. The highest range includes all trees greater than 100 cm DBH. Hence, there are 10 size classes. For example, the 10-20 cm DBH size class is indexed by $j=1$, 20-30 cm DBH is indexed by $j=2$, and so on until the highest DBH class, > 100 cm DBH, which is indexed by $j=10$.

At each time t, the forest manager will choose (or by policy or management objective be constrained) to harvest trees or not. The harvest from species group i and size j at time t is given by $\mathbf{h}_t = \left[h_{ijt} \right]$. If the decision is to harvest at time t, the manager will harvest using a RIL or CL system, the choice of which will influence rates of damage, growth, and recruitment. Let s index the choice of harvest system, where s = 0 indicates no harvest occurs, s = 1 indicates a harvest using RIL, and s = 2 which indicates a harvest using CL. The damage to the residual stand is assumed to be a function of overall harvest intensity and is represented by the mn x 1 vector, $\mathbf{d}_{st}$:

$$\mathbf{d}_{st} = \left(\sum_{i=1}^{m} \sum_{j=1}^{n} h_{ijt} \right) \mathbf{D}_s \mathbf{y}_t \tag{2-1}$$

where $\mathbf{D}_s$ is a mn x mn matrix whose diagonal contains the logging damage coefficient for trees in each species group i and size j under harvest system type s. The damage coefficients are estimated as a percentage of trees killed per tree harvested within each species group i and size j under harvest system s. The damage vector includes trees killed immediately upon harvest and does not include trees which were damaged during harvest operations and later died. When there is no harvest, $\mathbf{D}_0$ is an empty matrix.

In addition to different rates of damage, the model is constructed to test whether post-harvest forests respond differently to harvest volumes and type of logging system employed. The choice of one type of harvest system over another is likely to result in different residual stand damages and competitive environments. On one hand, some trees are damaged during harvests but not killed. One would expect relatively lower growth and higher mortality rates for these trees. On the other hand, harvest disturbance creates large gaps in the forest, changing the competitive environment. These changes are likely to favor some species over others. Consequently, a growth matrix for a forest logged using a well-executed RIL system is not likely to result in the same growth matrix as the highly damaged forest logged with no planning or regard to future commercial trees. Both of these growth matrices are likely to be different than the matrix derived from data on unlogged stands.

Given a growth interval, θ, the stand state at $t+\theta$ is determined by the population, harvest, and damage at time t according to a modification of the multi-species uneven-aged matrix model presented in Lu and Buongiorno (1993), Lin et al. (1996), and Buongiorno et al. (1995):

$$\mathbf{y}_{t+\theta} = \mathbf{G}_s\left(\mathbf{y}_t - \mathbf{h}_t - \mathbf{d}_{st}\right) + \mathbf{r}_s \tag{2-2}$$

where $\mathbf{G}_s = \mathbf{A}_s + \mathbf{R}$, in which $\mathbf{A}_s$ is the transition matrix for treatment type s, $\mathbf{R}$ is the ingrowth matrix that introduces the density dependent component of recruitment, and $\mathbf{r}_s$ captures the fixed component of recruitment as a function of species group and treatment. The matrices and vectors are defined as:

$$\mathbf{A}_s = \begin{bmatrix} \mathbf{A}_{1s} & & \\ & \ddots & \\ & & \mathbf{A}_{ms} \end{bmatrix} \tag{2-3}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{11} & \cdots & \mathbf{R}_{1m} \\ \vdots & \ddots & \vdots \\ \mathbf{R}_{m1} & \cdots & \mathbf{R}_{mm} \end{bmatrix} \tag{2-4}$$

$$\mathbf{y}_t = \begin{bmatrix} \mathbf{y}_{1t} \\ \vdots \\ \mathbf{y}_{mt} \end{bmatrix}, \mathbf{h}_t = \begin{bmatrix} \mathbf{h}_{1t} \\ \vdots \\ \mathbf{h}_{mt} \end{bmatrix}, \mathbf{r}_s = \begin{bmatrix} \mathbf{r}_{1s} \\ \vdots \\ \mathbf{r}_{ms} \end{bmatrix}. \tag{2-5}$$

Each matrix $\mathbf{A}_{is}$ contains the transition probabilities for each species group i under harvest system s:

$$
\mathbf{A}_{is} = \begin{bmatrix} a_{i1s} & & & & \\ b_{i2s} & a_{i2s} & & & \\ & b_{i2s} & a_{i3s} & & \\ & & \ddots & \ddots & \\ & & & b_{ins} & a_{ins} \end{bmatrix} \tag{2-6}
$$

where a_{ijs} is the probability that a tree in species group i and size j under harvest system s will remain alive in size j during the interval t to $t+\theta$,and b_{ijs} is the probability that a tree in species group i and size $j-1$ under harvest system s will remain alive and grow into j from size $j-1$ during the interval t to $t+\theta$.

A myriad of procedures exist to estimate the growth matrix transitions. As in Boltz and Carter (2006), multinomial logit regression was used to estimate the transition probabilities over a 10-year period. Mortality includes both natural death and death from harvest damage that did not immediately kill the tree as identified in the immediate post-harvest inventory of the stands. Where c_{ijs} is the probability that a tree in species group i and diameter class j under harvest system s will die during the interval t to $t+\theta$, the following must hold true:

$$
\begin{aligned} & a_{ijs} + b_{ijs} + c_{ijs} = 1 \quad \forall i, s, \text{ and } j < n \\ & a_{ijs} + c_{ijs} = 1 \quad \forall i, s \text{ and } j = n \end{aligned} \tag{2-7}
$$

Where $v=1$ is defined as mortality, $v=2$ is defined as stability, and $v=3$ is defined as upgrowth, the probability that any given tree u will transition to state v is a function of a set of parameters, β_v , given by:

$$
\text{Prob}(Tree_u = v) = \frac{e^{\beta_v' x_u}}{\sum_{v=1}^{3} e^{\beta_v' x_u}}. \tag{2-8}
$$

The transition probabilities are estimated using maximum likelihood as a function of tree attributes and harvest system employed. The first independent variable, diameter at breast height, *DBH*, reflects the relative dominance of each tree in its immediate forest context. SG_i, a series of dummy variables representing species group $i\ (=1,...,4)$, where $SG_i = 0$ if species group is not *i* and 1 otherwise, is included to incorporate growth and mortality differences across species group as compared to the base species group, the emergent species. An interaction between tree diameter and species group, $SG_i \times DBH$, is included to incorporate differences across species groups and tree size. Finally, a set of dummy variables, T_s where $T_s = 0$ if the harvest system employed is not *s* and 1 otherwise, are included to incorporate the impact of logging technique as compared to the base control plot treatment.

It is assumed that the data do not violate the Independence of Irrelevant Alternatives (IIA) property, which requires that the ratio of the probability of choosing between any two alternatives is independent of the presence or absence of any other alternative in the choice set (Hausman and McFadden, 1984). In the case of the MNL estimation in this study, this property implies, for example, that the ratio of the upgrowth and stability probabilities for any given tree is not dependent upon whether mortality is included as an outcome in the model, a reasonable assumption for the purposes of this model.

The recruitment of new trees is expected to be negatively related to the total number of post-harvest trees per ha at time *t*, TPH_t. Where *k* (=1,…, *m*-1) now indexes a set of dummy variables representing species groups, an interaction term between species group and trees per ha, $SG_k \times TPH_t$, is added to reflect species-group level recruitment response to stand density. The fixed component of recruitment is hypothesized to be a function of species group and an interaction between species group and harvest system employed, $SG_k \times T_s$, to reflect differential responses to harvest across species groups. Where I_{it} equals the number of newly recruited trees of species group *i* at time *t,* the recruitment equation can be written as:

$$I_{it} = c_0 + \sum_{k=1}^{m-1} c_k SG_k + eTPH_t + \sum_{k=1}^{m-1} f_k SG_k \times TPH_t + \sum_{k=1}^{m-1}\sum_{s=1}^{2} g_{ks} SG_k \times T_s \qquad \forall i \qquad \text{(2-9)}$$

where $c_{0,}$, c_k, e, f_k, and g_{ks} are parameters to be estimated using ordinary least squares regression.

To build each submatrix $\mathbf{R}_{ik}$, let *i* and *k* again index the full set of species group, $i, k = 1, ..., m$. Each submatrix $\mathbf{R}_{ik}$ in Equation 2-4 incorporates the density-dependent effect of the trees of species *k* on the recruitment of trees of species group *i*, including, when $i = k$, own-effects of species group *i*. The matrix entries for c_k, f_k, and g_{ks} are equal to zero for the reference species group in Equation 2-9, or when $i, k = m$. Using the estimated coefficients of Equation 2-9, each submatrix $\mathbf{R}_{ik}$ is constructed in the following manner:

$$\mathbf{R}_{ik} = \begin{bmatrix} e + f_k & e + f_k & \cdots & e + f_k \\ 0 & 0 & \cdots & 0 \\ \vdots & \cdots & \cdots & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix}. \qquad \text{(2-10)}$$

Meanwhile, the fixed component of recruitment for species group *i*, which depends on species group but not overall stand density, is entered in vector form as follows:

$$\mathbf{r}_{is} = \begin{bmatrix} c_0 + c_i + g_{is} \\ 0 \\ \vdots \\ 0 \end{bmatrix}. \qquad \text{(2-11)}$$

Now, imagine two types of forest stand, one that is logged strictly according to a cutting cycle and a stand that is logged at $t = 0$ and never logged again. For the repeatedly logged stand, the length of the cutting cycle is denominated by $\gamma\theta$, where γ represents the number of growth periods between entries. As an example, the evolution of the diameter distribution of a stand repeatedly logged using RIL (s = 1) would be determined by the following iterative procedure:

$$\begin{aligned}
&\mathbf{y}_{\theta} = \mathbf{G}_1\left(\mathbf{y}_0 - \mathbf{h}_0 - \mathbf{d}_{1,0}\right) + \mathbf{r}_1 \\
&\mathbf{y}_{2\theta} = \mathbf{G}_0\mathbf{y}_{\theta} + \mathbf{r}_0 \\
&\ldots \\
&\mathbf{y}_{\gamma\theta} = \mathbf{G}_0\mathbf{y}_{(\gamma-1)\theta} + \mathbf{r}_0 \\
&\mathbf{y}_{(\gamma+1)\theta} = \mathbf{G}_1\left(\mathbf{y}_{\gamma\theta} - \mathbf{h}_{\gamma\theta} - \mathbf{d}_{1,\gamma\theta}\right) + \mathbf{r}_1.
\end{aligned} \tag{2-12}$$

To project the stand repeatedly logged using CL, simply replace the RIL growth matrix and the damage and recruitment vectors with those derived from the CL treatment.

Meanwhile, where μ equals the number of growth periods projected into the future, the projections for the “logged and left” stand using RIL is determined iteratively by the procedure:

$$\begin{aligned}
&\mathbf{y}_{\theta} = \mathbf{G}_1\left(\mathbf{y}_0 - \mathbf{h}_0 - \mathbf{d}_{1,0}\right) + \mathbf{r}_1 \\
&\mathbf{y}_{2\theta} = \mathbf{G}_0\mathbf{y}_{\theta} + \mathbf{r}_0 \\
&\ldots \\
&\mathbf{y}_{\mu\theta} = \mathbf{G}_0^{\mu-1}\left(\mathbf{y}_{\theta}\right) + \sum_{i=0}^{\mu-2}\mathbf{G}_0^{i}\mathbf{r}_0.
\end{aligned} \tag{2-13}$$

This formulation is equivalent to the projection of an unlogged stand, only with the initial diameter distribution determined by the post-logged forest, rather than the distribution of the unlogged stand. As in the classical model of Buongiorno and Michie (1980), the projected stand will approach a steady state, where $\mathbf{y}_{t+\theta} = \mathbf{y}_t = \mathbf{y}^*$ and $\mathbf{y}^*$ is the equilibrium distribution, which is found using:

$$\mathbf{y}^* = \left(\mathbf{I} - \mathbf{G}_0\right)^{-1}\mathbf{r}_0. \tag{2-14}$$

While it appears a strong assumption that the unlogged and logged stands will ultimately converge, it is important to note that this convergence may require extremely long periods of time, depending on the characteristics of harvest, damage, growth, and recruitment.

Estimation Results

Growth Model

Using data from the full 73.5 ha study site, the MNL estimation of Equation 2-9 resulted in a significant model ($p < 0.001$). Results are presented in Table 2-1. The Nagelkerke Pseudo-R^2 = 0.331, which is relatively high for a discrete choice model, indicates an overall good fit to the data. However, largely because of the fact there are significantly more observations at lower sizes than in the higher sizes, some observations at higher diameters exert relatively high leverage over the parameter estimates. Pearson's goodness-of-fit test returns a significant chi-square score, indicating the model does not fit the data well throughout the dataset, even though the global pseudo R-square measure is high, highlighting the problem at higher diameters.

Most of the variables in the model proved to be significant predictors of transition probabilities. DBH was not significant for the upgrowth transition, while it was strongly significant for stability. The first-order parameters for each of the species groups were significant. The interaction between species group and DBH were significant for the stability transition, while only the interaction between pioneer species and diameter was significant for the upgrowth transition. The RIL treatment was significant for the both the upgrowth and stability categories, although weakly for the stability transition. Meanwhile, the CL treatment was significant for the stability parameter only.

Damage

The damage vector was estimated from the 49 ha logged area (24.5 ha in the RIL and CL treatments, respectively). However, in the larger plot area only the commercial trees were measured within the 10-25 cm DBH range. The damage estimates within this size range are drawn from the intensively measured 5.25 ha smaller plots. Each element of damage vector, $\mathbf{d}_s$, is estimated as the percentage of trees killed in species group *i* and size *j* under treatment *s* per tree harvested within treatment *s*. While a model that estimates damage according to the size or species of the tree that has been felled is more appropriate, the damages observed in the dataset are not recorded as arising from a specific tree being felled. Consequently, the vector estimated here best uses the available data. Tables 2-2 and 2-3 present the estimated damage across species groups, size, and logging treatments. It is evident from these tables that the intermediate, shade-tolerant, and emergent species groups were more heavily damaged in the CL treatment. Also, larger trees incurred relatively more damage in the CL area. These comparisons reveal that management activities, such as vine-cutting and directional felling, better protect the residual stand. Particularly important is the reduction in residual damage to the emergent species group, as they are by a large margin the most economically valuable group.

Recruitment

In order to generate the data required to estimate the effects of stand density on recruitment, the three 5.25 ha treatment areas were each divided into 10 equally-sized and shaped units, a strategy similar to that of Buongiorno et al. (1997). *TPH* was then calculated for the 30 subplots, creating the data to estimate Equation 2-9. As Table 2-4 shows, the overall recruitment model is significant ($p < 0.001$) with an adjusted R-square of 0.54. As expected, recruitment is negatively related to total stand density. With the exception of the pioneer species group, species group is also significantly related to recruitment. In the case of the pioneer species, however, a strong positive relationship emerges in the pioneer species interactions with harvest system type, an expected relationship as pioneer species tend to thrive in the post-logged forest environment.

No other species group and harvest system interaction was significant; these interactions are excluded from the recruitment model. Additionally, the only species group and stand density interaction that proved significant was the interaction for the intermediate species; the other interactions are also withheld from the model.

In early trials of the model, a problem emerged with recruitment with the emergent species group. Recruitment into the emergent class was low over the 10 year observation period, 1.1 stems/ha in the control area, 1.2 stems/ha in the RIL area, and 0.7 stems/ha in the CL area. Because the predicted TPH can oscillate over 30% depending on the intensity of harvests, TPH could become sufficiently high such that the emergent recruitment could be suppressed to a negative number, clearly impossible. A recruitment function that eliminated this problem could not be found. Therefore, the recruitment function was over-ridden for the emergent species group and replaced with the observed recruitment just mentioned, an unfortunate but necessary calibration. The resulting growth matrices for each treatment are presented in Tables 2-5, 2-6, and 2-7.

Discussion

Validity

Ideally, model predictions should be compared to outcomes independent of the data used to estimate the model. However, no data of this sort currently exists and the best validation technique available is to assess the quality of the predictions with the actual state of the Fazenda Sete stand after 10 years, as shown in Figure 2-1. The predicted stands are the result of projecting each treatment area of the site after incorporating the actual harvest and damage incurred during the experiment. The overall projected diameter distributions for the unlogged and CL stands appear to be reasonably close, while the RIL appears to under-predict at lower diameters. Examination at the species-group level bears out these observations. The under-prediction at the lower diameters in the RIL simulation is largely due to the under-prediction of newly recruited trees from the shade-tolerant group. Attempts at improving the performance of the recruitment function to predict shade-tolerant recruitment under RIL were unsuccessful.

"Log and Leave" Scenarios

To exhibit the use of the model, three 100-year simulations were performed based upon identical initial conditions, the average condition across the Fazenda Sete site. In the first simulation, no harvest was performed, so the projection is simply that of the unlogged stand 100 years into the future. This simulation presents a richer context for the harvest scenarios. An identical harvest was simulated in the RIL and CL scenarios in order to compare the post-harvest trajectories of the three stands. The simulated harvest volume was set at 30 m^3/ha and the minimum DBH was set at 50 cm to reflect current regulations. Brazilian regulations requiring retention of at least 10% of merchantable trees per species for seed trees were applied at the species group-level, as necessitated by the model's structure.

Since the initial forest contains 41.0 m^3/ha of merchantable timber (non-hollow timber of good form from commercial species), the harvest was performed such that the most valuable stems were removed first, to simulate the behavior of a profit-maximizing forest manager. Table 2-8 shows the simulated distribution of the harvest and stems killed by harvest damage distributed across species groups. While 5.8 stems/ha were harvested in both the RIL and CL scenarios, 113.5 stems/ha were inadvertently killed in the CL harvest operation compared to the 83.8 stems/ha killed in the RIL operation, representing a 26% reduction in direct harvest damage when RIL is adopted.

Figure 2-2 shows the simulated trajectories at the species-level for the three differentiated treatment types. Particularly evident is the dramatic jump in pioneer species in the post-harvest environment. The jump in pioneers is strongest in the CL scenario, which is likely due to larger gaps and greater damage to understory vegetation created by the relatively careless logging operation. Many, but not all, pioneer species are short-lived so while the surge occurs in the first 10 years of the simulation, the wave of pioneers still has not cleared from the system after 100 years.

As the large pioneer population causes a strong negative effect of recruitment on other species, the projections portray a strong floristic shift as the stand, at the species-level, recovers unevenly. Other species-groups do not shift as dramatically as the pioneer group but generally take decades to recover. The light-demanding group, which loses about 20% of its population during logging, surges in the first 10 years to levels near or above the levels of the unlogged site, as would be expected given the group’s ecological characteristics. Yet, this group suffers an increase in mortality in the first few decades to drop the population below that of the unlogged site. The population of the intermediate species-group declined in the unlogged scenario, which indicates that the unlogged forest was unlikely to have been in equilibrium when the experiment began.

While the shade-tolerant group contains a relatively low proportion of commercial species, the commercial component of this group was heavily harvested. Additionally, the large shade-tolerant species group received heavy damage during the harvest, particularly in the CL scenario. Valuable shade-tolerant species like maçaranduba can compose a large proportion of the commercial harvest, so damage to this species group can have significant impacts upon future harvests. Again, after 100 years, the population of this group is still approaching that of the unlogged forest from below.

In contrast to the shade-tolerant species, all emergent species have high economic values. Consequently, all permissible merchantable timber is logged from the emergent species group first. Since the initial population distribution is relatively flat and recruitment of these species is low, the emergent species are unlikely to recover their initial merchantable volume within a reasonable management horizon.

Aggregate projections of basal area (Figure 2-3) shows that the stand logged using RIL will recover its basal area rapidly, within 20 to 30 years, while the CL stand requires at least 50 years to recover a total basal area approximating that of the unlogged site. Yet, as an indication of the shift in species composition, merchantable volumes do not recover within the 100-year horizon of the analysis, indicating a switch away from commercial species (Figure 2-4). The recovery of merchantable timber is relatively slow in both the RIL and CL cases. If the RIL logger returned in 30 years, a typical cutting cycle length in the Eastern Amazon-region, only 18.3 m^3/ha of merchantable timber would be available, assuming the same suite of species were commercial then as now. The CL logger would encounter a merchantable volume of 15.6 m^3/ha.

The chapters that follow will examine timber yields in great detail, but it is important to note here that the model is depicting a dynamic that is becoming well-known, that logging induces large shifts in floristic composition while commercial volumes are unlikely to recover within a typical management time-frame (Dauber et al., 2006; Karsenty and Gourlet-Fleury, 2006; Keller et al., 2007; Sist and Ferreira, 2007; Van Gardingen et al., 2006). In this simulation, the RIL logger would need to wait about 80 years to repeat a 30 m^3/ha harvest. The CL logger would need to wait up to 100 years. The results call into question the sustainability of expected timber yields from permanent production forests under the current set of regulations in Brazil.

The results reaffirm findings of other recent Eastern Amazon forest growth and yield studies. In the Tapajós National Forest, Van Gardingen et al. (2006) estimate a maximum annual commercial increment of 0.33 m^3/ha/year for a forest logged using RIL. Meanwhile, the annual commercial increments estimated in Valle et al. (2007) for the same Fazenda Sete forest after accounting for defects is about 0.30 m^3/ha/year for a forest logged using RIL and 0.20 m^3/ha/year for a forest logged using CL. The average annual commercial increment estimated using this matrix model is 0.42 m^3/ha/year in the first ten years of the RIL simulation and 0.27 m^3/ha/year in the first ten years of the CL simulation (Figure 2-5). The increment declines over time for the RIL stand, while the increment for the CL stand increases slightly from year 40 to year 70 before decreasing again.

Conclusion

The growth model was estimated using a discrete choice model with data for a 10-year-old logging experiment in one of the older logging frontiers of the Brazilian Amazon. To make the model tractable for economic and policy analysis, the model is based upon extensions of the classic density-dependent Buongiorno and Michie (1980) model that is often used in forest economics and management research. Two adaptations were made to the basic model. First, logging damage sensitive to the intensity of the harvest was included. Second, to better reflect the growth trajectory of a logged forest, growth matrices were estimated as a function of logging type. It is expected that these modifications will improve the performance of the matrix model within a tropical forestry context.

The adoption of RIL and improved forest management practices is crucial for the long term sustainability of working forests in the tropics. Using this model within an optimization framework, it will be relatively straightforward to allow the logger a choice over the logging system to incorporate, as a function of economic incentives and regulation. Understanding how incentives and regulations affect this decisionmaking is an important ingredient for tropical forest policy analysis.

If the objective is to manage forest resources sustainably, policymakers and planners need to be explicit not only about the sustainable yields in an absolute sense, but the sustainability of components of the dynamic system. It is clear that logging influences the floristic composition of the forest, both through selective economic pressure on high-value timber species and through complex ecological interactions which are driven by intense harvest disturbances. While detailed examination of this issue is left for the chapter that follows, the simple simulations shown in this study show the depletion of the higher-value timber species.

Table 2-1. Maximum likelihood estimates of transition parameters

	MLE parameter					
	Upgrowth			Stability		
Variable	B	S.E.		B	S.E.	
DBH	0.076	0.056	*	0.406	0.049	
Pioneer	0.910	0.188		0.799	0.179	
Light-demanding	-0.345	0.104		0.234	0.090	
Intermediate	-0.219	0.110		0.905	0.092	
Shade-tolerant	-0.262	0.091		1.782	0.071	
DBH x pioneer	-0.376	0.093		-0.479	0.083	
DBH x light-demanding	-0.049	0.073	*	-0.274	0.063	
DBH x intermediate	-0.001	0.068	*	-0.308	0.060	
DBH x shade-tolerant	-0.069	0.065	*	-0.520	0.056	
RIL treatment	0.698	0.064		0.083	0.055	x
CL treatment	0.021	0.067	*	-0.156	0.054	
N = 6351						
Chi-square = 4964.1 (df = 22)						
-2 log likelihood = 1260.4						
Nagelkerke pseudo R^2 = 0.33						

Notes: * Not significant. x Significant at $p < 0.15$. All other values are significant at $P < 0.05$.

Table 2-2. Proportion of population per species group and size killed per tree harvested under RIL treatment

Size	Pioneer	Light-demanding	Inter-mediate	Shade-tolerant	Emergent
10-20 cm	0.06	0.04	0.04	0.04	0.02
20-30 cm	0.02	0.01	0.01	0.01	0.02
30-40 cm	0.02	0.02	0.01	0.01	0.00
40-50 cm	0.00	0.00	0.01	0.00	0.02
50-60 cm	0.00	0.03	0.00	0.00	0.00
60-70 cm	0.00	0.03	0.00	0.00	0.00
70-80 cm	0.00	0.00	0.00	0.00	0.00
80-90 cm	0.00	0.00	0.00	0.00	0.00
90-100 cm	0.00	0.06	0.00	0.00	0.00
>100 cm	0.00	0.00	0.00	0.00	0.00

Table 2-3. Proportion of population per species group and size killed per tree harvested under CL treatment

Size	Pioneer	Light-demanding	Inter-mediate	Shade-tolerant	Emergent
10-20 cm	0.03	0.03	0.04	0.05	0.01
20-30 cm	0.03	0.03	0.04	0.04	0.03
30-40 cm	0.02	0.02	0.02	0.02	0.01
40-50 cm	0.01	0.03	0.02	0.02	0.06
50-60 cm	0.03	0.01	0.01	0.02	0.00
60-70 cm	0.00	0.00	0.00	0.01	0.00
70-80 cm	0.00	0.03	0.00	0.01	0.00
80-90 cm	0.00	0.06	0.00	0.03	0.00
90-100 cm	0.00	0.06	0.00	0.00	0.00
>100 cm	0.00	0.00	0.00	0.00	0.00

Table 2-4. Ordinary least squares estimates of the recruitment parameters

Variable	Parameter	St. Dev.
Constant	55.975	13.893
TPH	-0.119	0.032
Pioneer	7.260	8.457 *
Light-demanding	25.984	5.541
Intermediate	-47.453	33.063 x
Shade-tolerant	42.619	5.541
RIL x Pioneer	56.816	11.056
CL x Pioneer	86.403	11.153
TPH x Intermediate	0.130	0.078 +
N =150		
Adjusted R-square = 0.54		
F = 30.41		

Notes: * Not significant. + Significant at P < .10. x Significant at p < 0.15. All other values are significant at P < 0.05.

Table 2.5. No harvest growth matrix $\mathbf{G_0}$

		1				2				3			
Species-group	DBH (cm)	10-20	20-30	…	> 100	10-20	20-30	…	> 100	10-20	20-30	…	> 100
1	10-20	0.30	-0.12	…	-0.12	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.38	0.45	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.32	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.49	0.00	0.00	…	0.00	0.00	0.00	…	0.00
2	10-20	-0.12	-0.12	…	-0.12	0.34	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.23	0.49	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.22	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.71	0.00	0.00	…	0.00
3	10-20	0.01	0.01	…	0.01	0.01	0.01	…	0.01	0.60	0.01	…	0.01
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.19	0.61	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.19	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.71
4	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
5	10-20	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00

Notes: Species group 1 = pioneer, 2 = light-demanding, 3 = intermediate, 4 = shade-tolerant, 5 = emergent.

Table 2.5. Continued

		4				5			
Species-group	DBH (cm)	10-20	20-30	…	> 100	10-20	20-30	…	> 100
1	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
2	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
3	10-20	0.01	0.01	…	0.01	0.01	0.01	…	0.01
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
4	10-20	0.63	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.11	0.73	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.12	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.51	0.00	0.00	…	0.00
5	10-20	0.00	0.00	…	0.00	0.42	0.00	…	0.00
	20-30	0.00	0.00	…	0.00	0.30	0.51	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.26	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.95

Notes: Species group 1 = pioneer, 2 = light-demanding, 3 = intermediate, 4 = shade-tolerant, 5 = emergent.

Table 2-6. RIL growth matrix $\mathbf{G_1}$

		1				2				3			
Species-group	DBH (cm)	10-20	20-30	…	> 100	10-20	20-30	…	> 100	10-20	20-30	…	> 100
1	10-20	0.20	-0.12	…	-0.12	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.53	0.36	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.47	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.48	0.00	0.00	…	0.00	0.00	0.00	…	0.00
2	10-20	-0.12	-0.12	…	-0.12	0.27	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.36	0.42	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.35	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.64	0.00	0.00	…	0.00
3	10-20	0.01	0.01	…	0.01	0.01	0.01	…	0.01	0.53	0.01	…	0.01
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.31	0.53	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.31	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.62
4	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
5	10-20	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00

Notes: Species group 1 = pioneer, 2 = light-demanding, 3 = intermediate, 4 = shade-tolerant, 5 = emergent.

Table 2.6. Continued

		4				5			
Species-group	DBH (cm)	10-20	20-30	…	> 100	10-20	20-30	…	> 100
1	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
2	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
3	10-20	0.01	0.01	…	0.01	0.01	0.01	…	0.01
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
4	10-20	0.57	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.19	0.67	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.20	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.44	0.00	0.00	…	0.00
5	10-20	0.00	0.00	…	0.00	0.34	0.00	…	0.00
	20-30	0.00	0.00	…	0.00	0.45	0.42	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.40	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.92

Notes: Species group 1 = pioneer, 2 = light-demanding, 3 = intermediate, 4 = shade-tolerant, 5 = emergent.

Table 2.7. CL growth matrix $\mathbf{G_2}$

		1				2				3			
Species-group	DBH (cm)	10-20	20-30	…	> 100	10-20	20-30	…	> 100	10-20	20-30	…	> 100
1	10-20	0.26	-0.12	…	-0.12	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.40	0.41	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.34	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.45	0.00	0.00	…	0.00	0.00	0.00	…	0.00
2	10-20	-0.12	-0.12	…	-0.12	0.30	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.25	0.44	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.24	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.68	0.00	0.00	…	0.00
3	10-20	0.01	0.01	…	0.01	0.01	0.01	…	0.01	0.56	0.01	…	0.01
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.21	0.57	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.21	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.67
4	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
5	10-20	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00	0.00	0.00	…	0.00

Notes: Species group 1 = pioneer, 2 = light-demanding, 3 = intermediate, 4 = shade-tolerant, 5 = emergent.

Table 2.7. Continued

		4				5			
Species-group	DBH (cm)	10-20	20-30	…	> 100	10-20	20-30	…	> 100
1	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
2	10-20	-0.12	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
3	10-20	0.01	0.01	…	0.01	0.01	0.01	…	0.01
	20-30	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.00
4	10-20	0.60	-0.12	…	-0.12	-0.12	-0.12	…	-0.12
	20-30	0.12	0.69	…	0.00	0.00	0.00	…	0.00
	30-40	0.00	0.14	…	0.00	0.00	0.00	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.47	0.00	0.00	…	0.00
5	10-20	0.00	0.00	…	0.00	0.38	0.00	…	0.00
	20-30	0.00	0.00	…	0.00	0.33	0.47	…	0.00
	30-40	0.00	0.00	…	0.00	0.00	0.29	…	0.00
	…	…	…	…	…	…	…	…	…
	> 100	0.00	0.00	…	0.00	0.00	0.00	…	0.94

Notes: Species group 1 = pioneer, 2 = light-demanding, 3 = intermediate, 4 = shade-tolerant, 5 = emergent.

Table 2-8. Simulated harvest and damage across species groups and harvest system

Species group	RIL and CL harvest (stems/ha)	Killed by damage, RIL (stems/ha)	Killed by damage, CL (stems/ha)
Pioneer	0.3	6.0	4.7
Light-demanding	0.0	14.7	16.6
Intermediate	2.6	14.0	19.3
Shade-tolerant	1.5	48.6	72.3
Emergent	1.4	0.5	0.6
Total	5.8	83.8	113.5

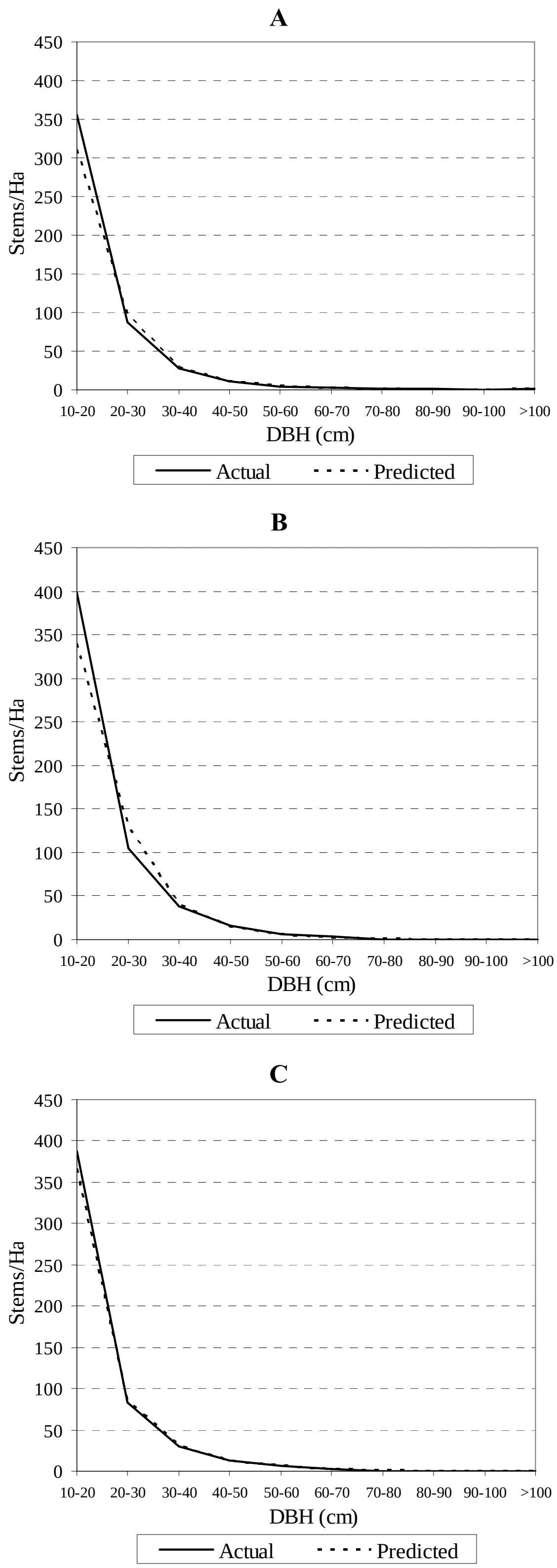


Figure 2-1. Actual and predicted 10-year diameter distributions (stems/ha). A) Control area. B) RIL area. C) CL Area

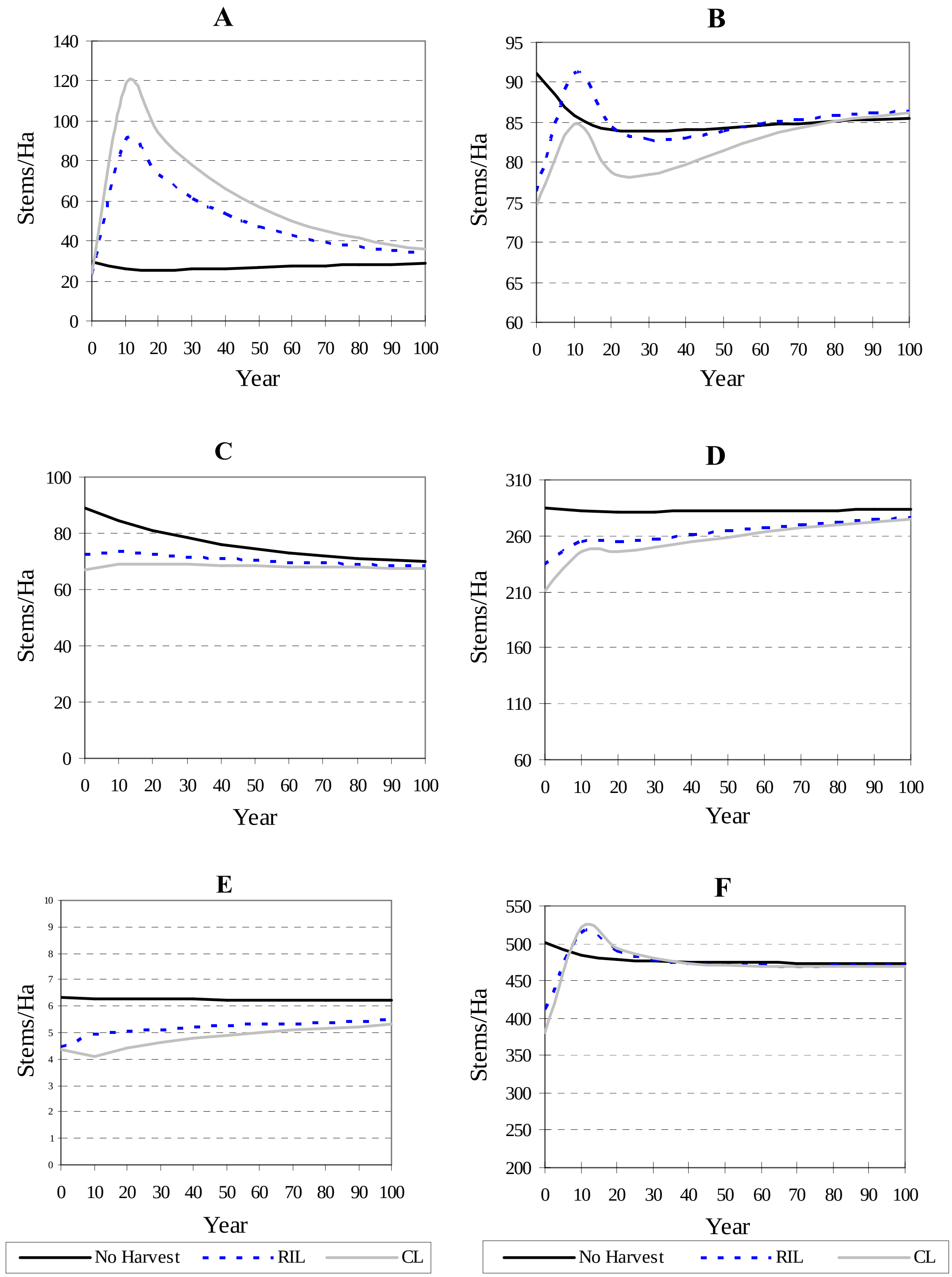


Figure 2-2. 100-year post-harvest projections across harvest system and species groups (stems/ha). A) Pioneer. B) Light-demanding. C) Intermediate. D) Shade-tolerant. E) Emergent. F) All species.

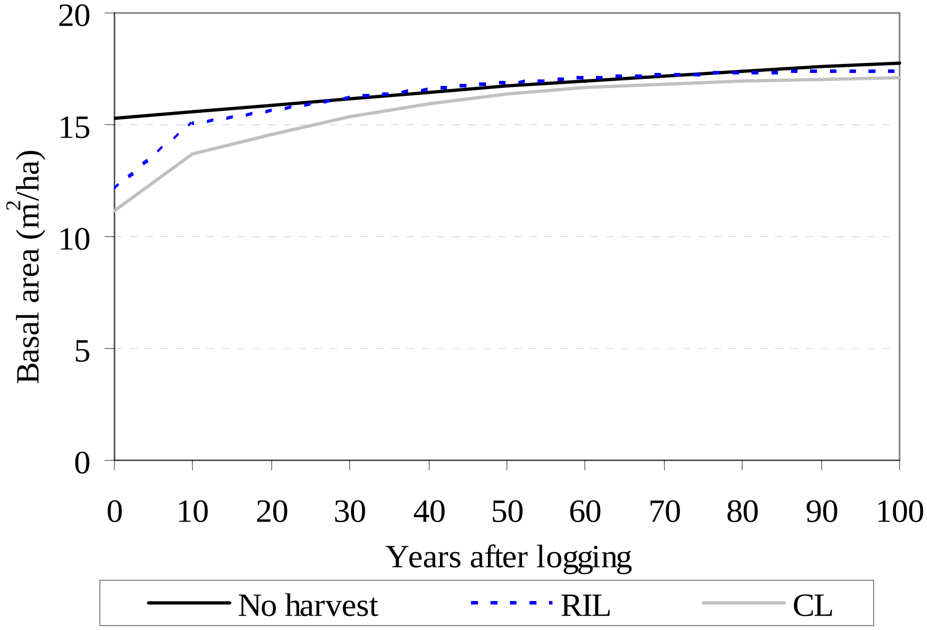


Figure 2-3. 100-year post-harvest projection of basal area (m^2/ha of stems > 10 cm DBH)

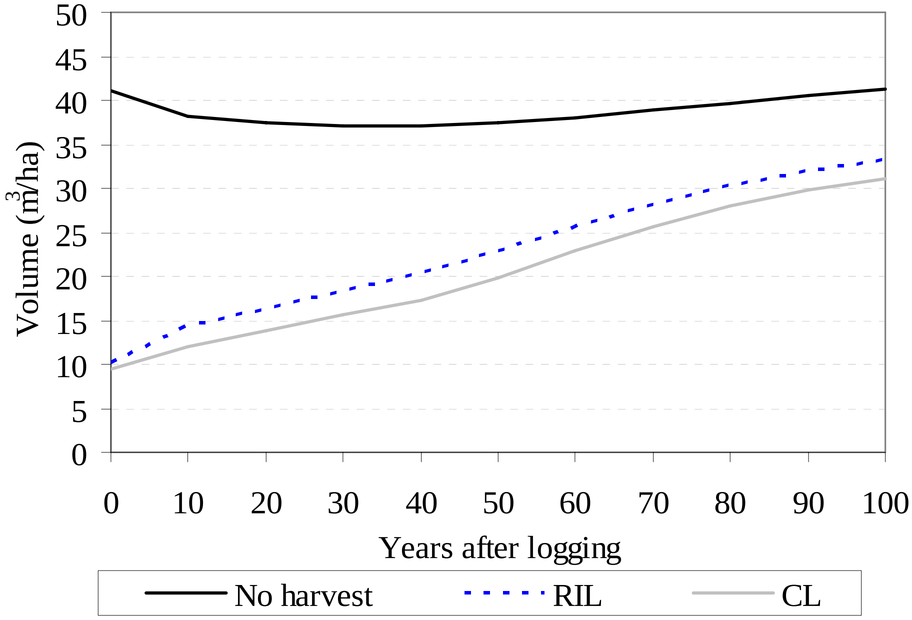


Figure 2-4. 100-year post-harvest projection of merchantable volume (m^3/ha of merchantable stems > 50 cm DBH)

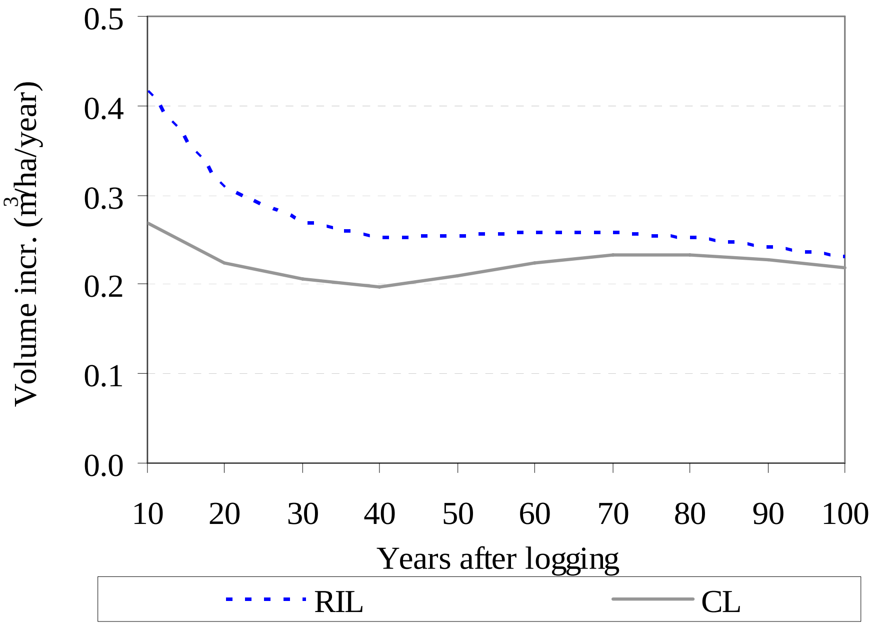


Figure 2-5. Projection of average annual increment (m^3/ha/year of merchantable stems > 50 cm DBH

CHAPTER 3
THE SUSTAINABILITY OF TIMBER PRODUCTION FROM AN EASTERN AMAZONIAN FOREST

Introduction

Current timber production best practices are limited to reduced impact logging (RIL) systems which seek to minimize environmental impacts compared to conventional logging (CL) systems which constitute about 90% of the region's harvests (Zarin et al., 2007). In Brazil, firms are obliged to follow legal restrictions aimed at minimizing environmental damage and protecting the future productivity of the forest. These restrictions include minimum diameter cutting limits, upper bounds on harvest intensity, the retention of seed trees and individuals of rare species, and protection of riparian buffers and wildlife. These types of simple harvest rules are policy-determined approximations that are expected to achieve broad objectives yet be administratively simple to apply and monitor (Boscolo and Vincent, 2003). There are serious questions as to whether the current set of forest management regulations combined with best harvest practices are adequate to ensure sustained timber production (Schulze et al., 2005; Valle et al., 2007; Van Gardingen et al., 2006; Zarin et al., 2007). Meanwhile, Brazilian policy is likely to require sustainable yields as a matter of policy. Further, regulators might consider imposing sustained-yield requirements at the species-level, an added layer of complexity.

Yet, while many call for sustainable timber harvests, few have attempted to establish quantitative management objectives that can be applied in practice in Brazil. A notable exception includes Van Gardingen et al. (2006) who examine a variety of yield regulation scenarios in the Tapajós National Forest, arriving at the recommendation that to achieve sustainable yields for that region's forests, loggers must not harvest more timber than accumulates at a rate of 0.33 m^3/ha/year in combination with no more than one-third of the commercial stock being removed during any single harvest. Van Gardingen et al. (2006) also state that management must adapt to local tenure and ecological conditions as well as varying management objectives.

While estimates based on ecological models are extremely important, particularly in regions such as the Brazilian Amazon where relatively little is known about forest dynamics under harvest pressure, the studies typically exclude economic perspectives. Yields such as those recommended in Van Gardingen et al. (2006) may in fact be ecologically feasible, but if followed may not be profitable. Economic studies of the cost-effectiveness of forest management have been limited to a few influential studies of RIL projects (Bacha and Rodriguez, 2007; Barreto et al., 1998; Holmes et al., 2002). However, these studies are static in that they evaluated the costs and benefits over short periods of time for harvests that remove nearly all merchantable volume. Meanwhile, the underlying problem is dynamic. How do forests respond to different harvest intensities and types and how do decisions and constraints in the present time influence the opportunities in future periods?

Objectives of the Study

The objective of this chapter is to quantitatively analyze the dynamic cost-effectiveness of best logging practices and sustainable yield constraints using a dynamic optimization model. While sustainability can be viewed as a function of perspectives and values (Karsenty and Gourlet-Fleury, 2006), the paper proposes two new operational definitions, weakly sustained inventory (WSI) and strongly sustained inventory (SSI). These definitions of sustainability focus on sustaining standing timber inventories across cutting cycle entries, rather than on sustaining harvest yields, as is typically the case. WSI, a variation on stand-level sustainability, requires that the overall standing volume of merchantable timber at each harvest cycle be non-declining into perpetuity. SSI, a variation on species-level sustainability, requires that the standing volume of merchantable timber at the species-group level at each harvest cycle be non-declining in perpetuity. By using this terminology, this study draws upon the discourse within economics concerning the substitutability of capital, where a weakly sustainable economy permits substitution between human-made and natural capital to sustain utility levels while a strongly sustainable economy must additionally sustain natural capital stock (Heal, 1998; Pearce et al., 1989).

Identifying the optimal harvest paths under the proposed sustainability constraints requires a two-stage optimization process. First, the harvests and standing timber stocks are found for a maximum sustainable economic yield problem, independent of initial conditions. This stage is achieved by applying an innovation to the classic Buongiorno and Michie (1980) uneven-aged forest management optimization model. The innovation incorporates an equilibrium condition that improves the model's ability to dynamically account for commercial hollow and defective trees left standing, an important concern in tropical forestry. The results of this optimization step produce the species-group and stand-level timber inventories that quantify the sustainability constraints, which are then used in the simulations to assess the cost-effectiveness of applying the constraints.

After the model is further developed, results comparing a series of simulations will be presented. To form a baseline reference for the regulatory simulations, RIL and CL harvests in which the loggers are not bound by any regulations are first presented. RIL and CL harvests under the current set of Brazilian forest management regulations are then simulated to evaluate how well the regulations induce sustainable yields. Harvests by a RIL logger under the WSI constraint and under the SSI constraint are then compared to the outcomes in the baseline and regulatory scenarios. The closing discussion will bring together the analysis and discussion above to offer insights into the challenges of defining and applying sustainability constraints in practice.

The Model

The model used in this chapter is based upon the density-dependent multinomial logit-based matrix model developed in Chapter 2. The basic model is a tropical forest extension of the multi-species uneven-aged matrix model presented in Lu and Buongiorno (1993), Lin et al. (1996), and Buongiorno et al. (1995). The model also more fully accounts for the relationship between the choice of harvest method and damage than the method first presented in Boscolo and Vincent (2000). To perform the analysis in this chapter, the model requires further development in terms of the introduction of merchantability restrictions, harvest regulations, economic factors, and, in certain scenarios, harvest restrictions designed to achieve sustainability objectives.

Merchantability Restrictions

A typical forest area in the Eastern Amazon may contain more than 300 tree species and, depending on local and regional timber markets and species distributions, will have anywhere from a few to over 100 commercially valuable species (Lentini et al., 2005; Veríssimo et al., 1998). The list of commercially valuable species varies in time, according to species availability, markets, and milling technology, among other factors. Additionally, many commercially valuable mill-sized trees have stem defects and/or hollow stems, rendering them effectively valueless to the logger (Holmes et al., 2002; Schulze, 2003; Valle et al., 2006; Vidal, 2004). In this study, there is a clear distinction between the commercial status of any given tree and its merchantability. If a given tree comes from a commercial species, the tree must be sufficiently large, of good stem form, and not hollow to be purchased and processed by a mill. A tree that passes these tests is considered merchantable.

If the logger selects against hollows and defective stems, the model must incorporate a mechanism to ensure that the logger harvests only non-hollow commercial stems with good form, or projected volumes will be over-estimated (Valle et al., 2006). In terms of growth, the residual hollow and defective stems are assumed to persist at the same rates as other trees in the stand. The model must also account for the fact that future recruiting trees will also have some likelihood of becoming hollow or defective.

In the model, the merchantability of any given tree is a function of three factors, the commercial status of the species, the form of the stem, and whether the tree is hollow. Let $\mathbf{S}$ be a *mn* x *mn* diagonal matrix whose elements represent the proportion of the stems from commercial species within each species group $i\ (=1,..,m)$ and size class $j\ (=1,..,n)$. The matrix $\mathbf{Q}$ is a *mn* x *mn* diagonal matrix whose elements represent the proportion of trees in each species group *i* and size *j* with stem form appropriate for milling. The matrix $\mathbf{H}$ is a *mn* x *mn* diagonal matrix whose elements represent the proportion of stems in each species group *i* and size *j* thought to be hollow. While the model is developed to accommodate these estimates as a function of the species group and size, the values for this study (Table 3-1) were estimated at the species group-level, as in Boltz (2003).

Given that large hollow stemmed trees in the unlogged forest are likely to be very old, the merchantability formulation can be modified to allow for the possibility that the relatively younger trees that recruit into the larger size classes during the simulation may have a lower likelihood of being hollow simply because they are likely to be harvested before becoming very old. These adjustments are reflected in Table 3-1, as $H0_i$ represents the proportion of initially standing trees per species group that are hollow, while $H1_i$ represents the proportion of newly recruited trees that are hollow.

Now enters a crucial behavioral distinction between the RIL and CL loggers. While both types of logger will reject stems with poor form, the RIL sawyer will test target trees by making a vertical incision in the tree with the chainsaw. This cut is sufficient to give the sawyer a sense of whether the tree is hollow and the diameter of the hollow, enough information to avoid felling the tree if the hollow is significant. Meanwhile, the CL sawyer is assumed to be able to visually identify that a proportion of the hollow trees are in fact hollow and avoid cutting them down, but will not perform the same tests as the RIL sawyer. Consequently, the CL sawyer will make mistakes and cut some, but not all, hollow trees. Let the proportion of hollow trees *not* identified as hollow (i.e. mistakes) be represented by, ϕ_s. For the RIL logger, $\phi_1 = 0$, and, for the CL logger, $\phi_2 \in [0,1]$. Hence, where s = 1 for the RIL logger, s = 2 for the CL logger, and **I** is the identity matrix, the *perceived* merchantable proportion for each species group i and size j is placed within the diagonal of the mn x mn matrix $\mathbf{M}_s$ according to the equation:

$$\mathbf{M}_s = \mathbf{S} \times \mathbf{Q} \times \left(\mathbf{I} - (1 - \phi_s)\mathbf{H}\right). \qquad (3\text{-}1)$$

In this study it is assumed that $\phi_2 = 0.5$. The assumed values for ϕ_s imply that the CL logger will perceive a slightly inflated stock of merchantable timber. Table 3-1 shows the complete set of merchantability factors for the loggers.

Where $\mathbf{y}_0$ represents the initial unlogged distribution of the stand, the initial pre-harvest perceived standing stock of merchantable timber, $\mathbf{y}_0^m$, is calculated as:

$$\mathbf{y}_0^m = \mathbf{M}_s \mathbf{y}_0. \qquad (3\text{-}2)$$

During the first entry either of the loggers will honor the following constraint and not harvest and kill by damage more than the logger perceives is merchantable:

$$\mathbf{h}_0 + \mathbf{d}_{s0}^m \le \mathbf{y}_0^m \qquad (3\text{-}3)$$

where $\mathbf{d}_{st}^{m}$ contains the merchantable trees killed accidentally during harvest. The CL logger will not gain revenues by felling hollow trees, only incur variable costs.

Recruitment is also likely to generate new hollows or trees of poor form. Over many harvest cycles, the stand is likely to accumulate a proportion of non-merchantable trees far exceeding the proportion of non-merchantable trees in the initial stand (Valle et al., 2007; Valle et al., 2006). In fact, Valle et al. (2007) predict that the commercial volume of a stand logged under RIL will be almost entirely composed by defective stems after 60 years under a 30-year cutting cycle. About one-third of the commercial volume in a comparable stand logged using CL will be composed of defective stems as the CL logger is less selective and removes hollow trees (Valle et al., 2007). With the exception of Boltz (2003), it is unclear whether similar matrix model-based economic studies adequately incorporate this dynamic.

If $\mathbf{h}_0 > 0$, the merchantable stock, $\mathbf{y}_t^m$, at time $t > 0$, is comprised of the growing stock of residual merchantable stems remaining after harvest plus any upgrowth into this merchantable stock during the cutting cycle interval. Where $\mathbf{G}_s$ is defined in Equation 2-2 and letting $\mathbf{G}_s^* = \mathbf{G}_0^{\gamma-1}\mathbf{G}_s$ indicate the cycle of growth matrix applications that arise from the logger's choice of harvest system, $\mathbf{y}_t^m$ at the next cutting cycle is given by:

$$\mathbf{y}_t^m = \mathbf{G}_s^*\left(\mathbf{y}_{t-\gamma\theta}^m - \mathbf{h}_{t-\gamma\theta} - \mathbf{d}_{st-\gamma\theta}^m\right) + \sum_{i=0}^{\gamma-2}\mathbf{G}_0^i\mathbf{M}_s\mathbf{r}_0 + \mathbf{G}_0^{\gamma-1}\mathbf{M}_s\mathbf{r}_s\,. \qquad (3\text{-}4)$$

Written as a constraint upon harvests at $t > 0$, the logger cannot harvest and kill by damage at time t more merchantable stems than are perceived to exist at time t:

$$\mathbf{h}_t + \mathbf{d}_{st}^m \leq \mathbf{y}_t^m\,. \qquad (3\text{-}5)$$

Equilibrium Dynamics

Now, assume that all harvests across time are identical, such that $\mathbf{h}_t = \mathbf{h}_{t+\gamma\theta} = \mathbf{h}^*$ and performed with a constant logging system according to a strict cutting cycle. Drawing on the seminal analysis of Buongiorno and Michie (1980), previous multi-species multi-age studies examining steady-state dynamics, such as Boltz (2003), assumed that the overall stand must maintain an equilibrium diameter distribution (i.e. $\mathbf{y}_t = \mathbf{y}_{t+\gamma\theta} = \mathbf{y}^*$) in order to sustain the equilibrium harvest. Solving for a steady-state harvest in this model, however, requires considering the merchantable proportion of the stand as its own sub-stand and solving for an equilibrium diameter distribution of merchantable trees, or $\mathbf{y}_t^m = \mathbf{y}_{t+\gamma\theta}^m = \mathbf{y}^{m*}$. Under this solution, the overall stand is allowed to vary from cutting cycle to cutting cycle to accommodate the constant supply of merchantable timber. To capture the dynamics of the merchantable stand, it is necessary to modify the equilibrium growth constraint of the Buongiorno and Michie (1980) model to impose the equilibrium conditions of the merchantable sub-stand:

$$\mathbf{G}_s^*\left(\mathbf{h}^* + \mathbf{d}_{st}^{m^*}\right) + \left(\mathbf{I} - \mathbf{G}_s^*\right)\mathbf{y}^{m*} = \sum_{i=0}^{\gamma-2}\mathbf{G}_0^i\mathbf{M}_s\mathbf{r}_0 + \mathbf{G}_0^{\gamma-1}\mathbf{M}_s\mathbf{r}_s \qquad (3\text{-}6)$$

In words, the equation states that the sum of harvest, harvest damage, and mortality must equal recruitment over any given cutting cycle interval at the given choices of $\mathbf{h}^*$ and $\mathbf{y}^{m*}$.

Brazilian Regulatory Policy

The regulatory agency has available a set of simple rules that it can use to try to induce desired logging behavior. In this chapter, the logger is assumed to perfectly comply with these rules, an assumption loosened in the next chapter. The regulatory agency may apply diameter cutting limits, harvest volume intensity limits (at the overall stand and species-level), and provisions for leaving seed and rare trees standing. The regulations are assumed to remain fixed throughout the horizon of the scenario. The scenario in which only these standard regulations are applied is called the Brazilian Regulatory Policy (BRP) case, and the specific parameters are drawn from a set of forest management regulations enacted in 2006 (Instrução Normativa 05/2006).

While the diameter cutting limit may be determined at the species group-level, the diameter cutting limit constraint used in this study is set at 50 cm DBH across all species-groups to reflect the most general case of the currently proposed regulations in Brazil:

$$\sum_{j=1}^{4} h_{ij} = 0 \ \forall i \tag{3-7}$$

In some circumstances, this constraint can be considered a merchantability constraint, as mills generally will accept logs over a certain size. The commercial volume of stems greater than or equal to commercial size was calculated by applying the commercial volume equations (with bark) reported in Silva et al. (1984) to the commercial trees in the permanent sample plot (PSP) data. Given the unlogged stand may contain very large commercial trees which will be logged upon first entry, to minimize the risk of overstating the available commercial timber, it is necessary to reduce the volume in the largest diameter class in future entries since insufficient time is likely to pass between cutting cycles to allow commercial trees to grow to the very large sizes found in the largest diameter class in the initial stand. The predicted volumes were averaged across species groups and size and placed into the mn x 1 vector $\boldsymbol{\psi}$, the elements of which are shown in Table 3-2. During the second harvest and beyond, the commercial volume of trees > 100 cm DBH is assumed to be equal to the volume of a 110 cm DBH tree in order to account for the above concern with over-stating commercial volumes for very large trees. The merchantable volume at any time t is found by multiplying the transpose of the commercial volume vector against the harvest vector at time t , or $\boldsymbol{\psi}'\mathbf{h}_t$. The harvest intensity regulatory constraint, 30 m^3/ha per entry, is written as:

$$\boldsymbol{\psi}'\mathbf{h}_t \leq 30 \ \forall t \tag{3-8}$$

To retain seed trees, management standards obligate the logger to retain at least 10% of the stems of any given species that would otherwise be authorized for logging, or:

$$\sum_{j=5}^{10} h_{ijt} \leq 0.9 \sum_{j=5}^{10} y_{ijt} \ \forall i,t \tag{3-9}$$

While Brazilian forest regulations are unclear on whether the practice is permissible, forest managers may often satisfy this constraint by the retention of hollow stems or stems of poor form that are permissible to log, but in practice are left standing. In this study, the logger is able use non-merchantable trees to satisfy the constraint.

Sustainability Constraints

As discussed in the introduction, sustainability can be viewed as a matter of perspective and analytical judgment. In the study forest, for example, the rate at which the harvest volume recovers after the first harvest is, as would be expected, very much a function of the harvest intensity. Figure 3-1 shows estimates of volume growth after first harvests ranging from 15m^3/ha to 40m^3/ha, implementing RIL in each case. Higher harvest intensities lead to more rapid growth. If the sustained yield goal is simply to harvest the growth, then the rules will be highly dependent upon the choice of first harvest and cutting cycle length, for which an unlimited number of combinations exist in practice. Additionally, the decision to harvest what is grown is essentially non-economic, a function of the growth potential of the stand alone, rather than the growth of value. The specific quantitative definitions of sustainability in this study are generated from within the bioeconomic system as a function of the maximum sustainable economic yield, rather than the maximum sustainable accumulation of a physical characteristic of the system, such as the commercial volume or number of commercial-sized trees.

As mentioned earlier, sustainable yield constraints assume two definitions: weakly sustained inventory (WSI) and strongly sustained inventory (SSI). WSI, a variation on stand-level sustainability, requires that the overall standing volume of merchantable timber at each harvest cycle be non-declining into perpetuity, without respect to the maintenance of volumes of any particular species group. SSI, a variation on species-level sustainability, requires that the standing volume of merchantable timber at the species-group level at each harvest cycle be non-declining in perpetuity. While it would be more appropriate to apply the SSI constraint at the individual species-level, targeting the constraints at the group-level is a simplification required by the model's design.

The problem can be solved for the equilibrium harvest, $\mathbf{h}_t = \mathbf{h}_{t+\gamma\theta} = \mathbf{h}^*$, and size distribution, $\mathbf{y}_t^m = \mathbf{y}_{t+\gamma\theta}^m = \mathbf{y}^{m*}$ that maximizes an economic objective. This solution determines the maximum sustained economic yield (MSY), but this yield estimate is independent of the initial conditions of the stand, a limitation discussed in detail in Boltz (2003). Given an initial stand size distribution and a feasible target distribution, the series of regulation harvests that lead to this steady state can be identified and optimized (Buongiorno, 2001). Given the initial unregulated condition of a typical forest in the region, this period of regulation may require such a long period of time that it is uninteresting for the policy context of the study. Similarities between the constrained harvests of the WSI and SSI harvests and the regulation cuts required to achieve a steady state may emerge indirectly, but modeling the regulation cuts directly is not an explicit objective here.

If the first harvest is performed at $t = 0$, where z indexes the number of cutting cycles, and the pre-harvest merchantable volume is found at any time t by the matrix operation $\boldsymbol{\psi}'\mathbf{y}_t^m$, WSI requires that the pre-harvest stand-level merchantable timber never diminishes below the equilibrium pre-harvest merchantable volume found by solving the MSY problem:

$$\boldsymbol{\psi}'\mathbf{y}_{\gamma\theta}^m \geq \ldots \geq \boldsymbol{\psi}'\mathbf{y}_{z\gamma\theta}^m \geq \boldsymbol{\psi}'\mathbf{y}^{m*} \text{ as } z \to \infty . \qquad (3\text{-}10)$$

Note that this constraint exempts the merchantable stock of the initial stand and proposes nothing directly about harvest-levels. Meanwhile, exempting the merchantable stock of the initial stand, the SSI constraint requires that the merchantable timber never diminishes at the species-group level:

$$\sum_{j=1}^{n} \psi_{ij} y_{ij,\gamma\theta}^m \geq \ldots \geq \sum_{j=1}^{n} \psi_{ij} y_{ij,z\gamma\theta}^m \geq \sum_{j=1}^{n} \psi_{ij} y_{ij}^{m*} \text{ as } z \to \infty \; \forall i \qquad (3\text{-}11)$$

There may be situations in which the sustainability of a given species or group of species is not a management challenge, exempting the species or group of species from the constraint. In the Eastern Amazon, for example, pioneer species with little or no commercial value thrive in the post-harvest environment and, hence, are by definition sustainably managed within a repeatedly logged stand. Additionally, the surge of pioneers can out-compete the juveniles of more valuable timber species. In practical terms here, the SSI constraint will not be applied to pioneer species.

The SSI constraint is not likely to produce the biologically most rapid approach path to the maximum sustained economic yield. However, it is asserted but not proved here that the combination of the yield constraints and profit maximizing behavior, applied over many cutting cycles, will iteratively yield harvest and standing merchantable diameters approaching the MSY distributions. Additionally, satisfying the sustainability requirement in either case does not necessarily imply that harvest intensity is non-declining. In fact, depending on the stand’s population structure and dynamics and the length of the cutting cycle, harvest intensity may oscillate, or even be zero if this is what is required to satisfy the inventory requirements.

Because the overall study is concerned with logging concession agreements of finite length, two simplifications of the WSI and SSI constraints are necessary for this work. For example, say a contract specifies two harvest entries under a fixed cutting cycle, permitting entries at $t = 0$ and $t = \gamma\theta$, where θ is the time-step of the matrix model and γ is the number of time-steps between harvest entries. Assuming similar terms will define the future contract, assuming one is issued, the terminal merchantability constraint could maintain the economic conditions of the stand for the first entry of the subsequent contract at $t = 2\gamma\theta$ to that of the first contract. The modified constraint for the WSI case is written:

$$\boldsymbol{\psi}'\mathbf{y}^{m}_{\gamma\theta} \geq \boldsymbol{\psi}'\mathbf{y}^{m}_{2\gamma\theta} \geq \boldsymbol{\psi}'\mathbf{y}^{m*} \tag{3-12}$$

and, where $i = 1$ for the pioneers species group, for the SSI case is written:

$$\sum_{j=1}^{n} \psi_{ij} y^{m}_{ij,\gamma\theta} \geq \sum_{j=1}^{n} \psi_{ij} y^{m}_{ij,2\gamma\theta} \geq \sum_{j=1}^{n} \psi_{ij} y^{m*}_{ij} \quad \forall i \neq 1 \tag{3-13}$$

Economic Variables

For this analysis, the unit values of prices and costs are assumed to be fixed throughout the time horizon and are expressed throughout the study in US\$2004. The price of a tree, p_{ij}, in from species group *i* in size *j* is presented in Table 3-3. These values were calculated based upon the mill gate Free On Board prices in the Paragominas region, according to economic surveys of mill owners and operators (Lentini et al., 2005). Management costs Free On Board forest mill are classified as either variable or fixed costs and are drawn from Barreto et al. (1998) and Lentini et al. (2005). Variable costs of harvesting a tree in species group *i* and size *j* under harvest system *s* is represented by vc_{ijs} and includes the costs associated with felling, skidding and log deck operations, and transportation costs incurred relative to the level of harvest intensity and harvest system choice s. The costs are estimated at \$15.64/m^3 for the RIL logger and \$13.48/m^3 for the CL logger, and the per-tree costs are shown in Table 3-4. Fixed costs in \$/ha, represented by fc_s, are incurred regardless of harvest intensity at each cutting cycle entry for planning, capital costs, and transaction costs and are estimated at \$50.56/ha for the RIL logger and \$13.91/ha for the CL logger. A constant real discount rate, r, of 9.75% was applied throughout the analysis. This rate was based upon the long term real interest rate reported for the bulk of 2004 by Brazil's National Bank of Economic and Social Development (Banco Nacional de Desenvolvimento Econômico e Social - BNDES, 2007).

Waste

The benefits of implementing RIL, in particular from operational planning improvements, extend beyond the reduction of damage to the residual stand and minimizing the felling of hollow trees (Barreto et al., 1998; Boltz et al., 2003; Holmes et al., 2002). In the unplanned logging operation, the skidder operator will generally find felled trees by driving the skidder through the forest to logging gaps the operator visually identifies. RIL operators, in comparison, develop detailed maps that show the locations of felled trees, minimizing the loss of valuable timber, reducing expensive machine-time, and reducing the damage incurred during the skidder operator's search for felled trees. The RIL felling team will also waste relatively less commercial volume though improved felling and bucking techniques. In the model, wood waste of this form is incorporated after trees have been felled by deducting harvest revenues, while not deducting costs. Table 3-5 shows the rate at which deductions are applied against the RIL and CL loggers' revenues to calculate the variable $waste_s$, where s indexes the choice of harvest system employed, based upon estimates in Holmes et al. (2002).

Concessionaire Objectives

In each of the scenarios that follow, the concessionaire will be allowed two logging entries, the timing of which is strictly defined by the cutting cycle with the first harvest at $t = 0$. The cutting cycle length, $\gamma\theta$, varies from 30 to 60 years. For each cutting cycle length, seven scenarios are presented:

- Maximum sustainable economic yield (MSY) harvests for the RIL logger (from which the sustainability restrictions on the WSI and SSI cases are estimated)
- Unconstrained harvests (U) for the RIL and the CL logger, the baseline harvests in which the logger is not bound by any regulations
- Brazilian regulatory policy (BRP) harvests for the RIL and the CL logger
- Weakly sustainable inventory (WSI) harvests for the RIL logger
- Strongly sustainable inventory (SSI) harvests for the RIL logger

In each case, the logger will seek to maximize the net present value (NPV) of two harvest cycles with the first harvest at *t* = 0. The profit at time *t*, π_t, is calculated as:

$$\pi_t = \sum_{ij}\left(\left(1 - waste_s\right) p_{ij} h_{ijt} - vc_{ijs} h_{ijt}\right) - fc_s . \qquad (3\text{-}14)$$

Where *T* equals the length of the concession contract and $\delta = \dfrac{1}{1+r}$ represents the discount function, the net present value (NPV) of returns is then written:

$$\text{NPV} = \sum_{t=0}^{T} \delta^t \pi_t . \qquad (3\text{-}15)$$

As mentioned earlier, the vector $\mathbf{y}^{m*}$ that defines the pair of sustainability constraints is found by solving the MSY problem, independent of initial conditions. The objective function of the MSY scenario reflects that the logger seeks to choose the steady state harvest, $\mathbf{h}^*$, and pre-harvest merchantable stock , $\mathbf{y}^{m*}$, which maximize the economic objective while satisfying the equilibrium merchantable growth constraint (Equation 3-17), the merchantable harvest constraint (Equation 3-18), the regulatory constraints (Equations 3-19, 3-20 and 3-21), and the non-negativity constraint (Equation 3-22):

$$\max_{\mathbf{h}^*, \mathbf{y}^{m*}} \text{NPV} = \sum_{t=0}^{T} \delta^t \pi_t \tag{3-16}$$

subject to:

$$\mathbf{G}_s^* \left(\mathbf{h}^* + \mathbf{d}_{st}^{m*} \right) + \left(\mathbf{I} - \mathbf{G}_s^* \right) \mathbf{y}^{m*} = \sum_{i=0}^{\gamma-2} \mathbf{G}_0^i \mathbf{M}_s \mathbf{r}_0 + \mathbf{G}_0^{\gamma-1} \mathbf{M}_s \mathbf{r}_s \tag{3-17}$$

$$\mathbf{h}^* + \mathbf{d}_t^m \le \mathbf{y}^{m*} \tag{3-18}$$

$$\sum_{j=1}^{4} h_{ij} = 0 \tag{3-19}$$

$$\boldsymbol{\psi}' \mathbf{h}_t \le 30 \ \forall t \tag{3-20}$$

$$\sum_{j=5}^{10} h_{ij}^* \le 0.9 \sum_{j=5}^{10} y_{ij} \ \ \forall i, t \tag{3-21}$$

$$\mathbf{h}^*, \mathbf{y}^{m*} \ge 0 \tag{3-22}$$

In both RIL and CL cases for the U scenarios, the logger will be constrained by the growth model (Equation 3-24), the size restrictions on merchantable stems (Equation 3-25), the merchantable harvest constraint (Equation 3-26), the initial condition of the stand (Equation 3-27), and the non-negativity constraint (Equation 3-28):

$$\max_{\mathbf{h}_t} \text{NPV} = \sum_{t=0}^{T} \delta^t \pi_t \tag{3-23}$$

$$\mathbf{y}_{t+\theta} = \mathbf{G}_s \left(\mathbf{y}_t - \mathbf{h}_t - \mathbf{d}_{st} \right) + \mathbf{r}_s \tag{3-24}$$

$$\sum_{j=1}^{4} h_{ij} = 0 \tag{3-25}$$

$$\mathbf{y}_t^m \ge \mathbf{h}_t + \mathbf{d}_t^m \tag{3-26}$$

$$\mathbf{y}_0 = \mathbf{y}_{actual} \tag{3-27}$$

$$\mathbf{h}_t, \mathbf{y}_t \geq 0 \tag{3-28}$$

The BRP logger is additionally constrained by the harvest intensity limit (Equation 3-29) and limits on harvesting all trees within any species group (Equation 3-30):

$$\boldsymbol{\psi}'\mathbf{h}_t \leq 30 \; \forall t \tag{3-29}$$

$$\sum_{j=5}^{10} h_{ijt} \leq 0.9 \sum_{j=5}^{10} y_{ijt} \;\; \forall i, t \tag{3-30}$$

The WSI logger will be constrained by Equations 3-24 through 3-30 and will be additionally constrained by the sustainability constraint on overall merchantability stocks:

$$\boldsymbol{\psi}'\mathbf{y}^m_{\gamma\theta} \geq \boldsymbol{\psi}'\mathbf{y}^m_{2\gamma\theta} \geq \boldsymbol{\psi}'\mathbf{y}^{m*} \tag{3-31}$$

The SSI logger will be constrained by Equation 3-24 though 3-30 and will be additionally constrained by the sustainability constraint on species-level stocks of merchantable timber:

$$\sum_{j=1}^{n} \psi_{ij} y^m_{ij,\gamma\theta} \geq \sum_{j=1}^{n} \psi_{ij} y^m_{ij,2\gamma\theta} \geq \sum_{j=1}^{n} \psi_{ij} y^{m*}_{ij} \quad \forall i \neq 1 \tag{3-32}$$

Recall that the constraint for pioneer species is removed in the SSI simulations.

Results

Maximum Sustainable Yield Harvests

In order to compare the baseline (U) and policy (BRP) scenarios with the WSI and SSI scenarios, it is necessary to first solve the MSY problem to identify the values of the sustainability constraints WSI and SSI. Table 3-6 shows the distribution of pre-harvest standing merchantable stock and harvests at the species group-level in terms of trees and volumes, across cutting cycle lengths. The table shows the relative dominance of the pioneer species group in the standing stock and harvest. While the highly-valuable emergent class has the most standing merchantable volume at the solution in each case, the equilibrium harvests are very low, from about 7 to 10% of the standing stock of emergents. Meanwhile, because of the large number of trees from the pioneer group in the post-harvest stand and the fact that some of the pioneer species capable of reaching larger sizes are commercial, harvests from the pioneer group compose more than one-third of the equilibrium harvest at each cycle length. The light-demanding, intermediate, and shade-tolerant groups assume similar intermediate proportions in the optimally regulated stand. Because the large role of pioneer species in the post-harvest stand is one of the dominant practical management problems, the contribution of pioneer species in the maximum economic yield problem should be viewed with caution and definitely should not become a goal of management. As will be seen in subsequent sections, the pioneer component of the SSI solution will be removed to address this management concern.

The volumes harvested from each stand at the aggregate and species-level provide the values for the WSI and SSI constraints, with the exception of pioneer species. Notice that the aggregate volumes harvested at the MSY solution, from 22.7 m^3/ha under the 30-year cycle to 28.6 m^3/ha under the 60-year cycle are not constrained by the 30 m^3/ha limit prescribed by Brazilian law.

Unconstrained and Brazilian Regulatory Policy Harvests

Table 3-7 shows the timber volumes harvested and recovered during the first harvest entry at t = 0 and during the second entry of the concession term for each of the scenarios. The table also shows the pre-harvest merchantable volume at the first and second entries, as well as at the time of the third entry, assuming the same cutting cycle length. Because the unconstrained CL sawyer cuts hollow trees, the total harvest volume exceeds that of the standing merchantable stock in the first harvest, while the unconstrained RIL logger harvests slightly less than the merchantable timber because some of the valuable timber is lost to damage.

For each of the U and BRP scenarios, the first harvest for each cutting cycle was essentially the same, to remove all merchantable timber in the unconstrained case and the most valuable permissible timber in the BRP scenarios. The value growth rate of no species was sufficient to leave permissible timber standing to grow into the next harvest period. The very high degree of waste in the CL case is evident as the RIL logger is able to recover about 16% more timber, even though the RIL logger logs slightly less. This result is consistent with Barreto et al. (1998) and Holmes (2002), and the reduction in waste and damage, as will soon be seen, will resonate strongly though financial returns and available timber in future harvests.

The benefits in adopting RIL to reduce harvest waste are significant across all cutting cycle lengths. Also, the benefits of reduced damages in the first harvest resonate in future harvests. In the unconstrained scenarios, the logger who adopts RIL will have about 3-4 m^3/ha more merchantable volume in the second harvest than the CL logger. The logger who adopts RIL under the BRP scenario will be able to harvest about 2 m^3/ha more timber in the second harvest. While these volumes are not large in an absolute sense, especially considering the effects of discounting over long periods of time, from the future perspective of the logger, these differences are important.

Assuming the harvest system adoption is consistent between the first and second harvests, there is little difference between U and BRP scenarios in terms of available timber for the third harvest. Meanwhile, the adoption of RIL makes a significant difference. This outcome is likely from the fact that in the first harvest, the BRP loggers are constrained to leave (the lowest-valued) merchantable volume standing. But, in the second harvest, this additional timber is now harvested, incurring relatively more damage in the stand, which, in a sense, permits the BRP-constrained loggers to “catch up” with their unconstrained counterparts.

For each cutting cycle length, the pre-harvest merchantable volume is higher for the third entry than the second. There is a pair of likely contributors to this trend. First, the growth “surge” stimulated by intense first harvests has, by the third entry, pushed through the system and is attaining commercial size. Second, because the second harvest was relatively light compared to the first harvest, damage rates are relatively low, while the stand will still receive a relatively strong positive growth and regeneration effect because of the disturbance. This dynamic raises the possibility that, over time, the harvests arising in the unconstrained and Brazilian policy cases will oscillate. However, there is the possibility that the growth model overstates growth and recruitment after harvests of relatively low intensity, as the RIL and CL growth matrices were based upon harvests of about 30m^3/ha. The density-dependence of recruitment is likely to reduce this risk, but is unlikely to fully remove the risk.

Figure 3-2 shows the species-group composition of the total harvest for the first and second harvests and available merchantable stock for the first and second and the hypothetical third harvest, but only for a 40-year cutting cycle for graphical convenience. In the U scenario for the CL logger, the logger harvests more than is available because the CL sawyer fells hollow trees, which are not skidded from the forest. For the U and BRP cases for both types of logger, the charts show how the composition of the harvest by species group shifts across harvests. The merchantable volume from the valuable emergent group is fully extinguished in the first harvest in the unregulated and regulated cases. As discussed earlier, because of regeneration challenges and relatively flat diameter distributions in the initial stand, when under periodic harvest pressure, the emergents are unlikely to ever regain volumes that approximate the initial condition. The distributions depict the differences between the initial condition of the emergent species group and the post-logging condition (Figure 3-3).

The shade-tolerant, intermediate, and light-demanding groups are each diminished significantly from the first to second harvest, but the intermediate and light-demanding species recover a larger proportion of their initial volume than do the emergent species. The dramatic shift in commercial composition toward pioneer species is clearly evident in the chart, with pioneers increasing from about 4% of the harvest to almost 40% in the unconstrained cases. Figure 3-3 shows the diameter distribution of pioneer trees under each scenario with a cutting cycle of 40 years. The harvest-induced ingrowth of pioneer trees causes waves of pioneers to push through the diameter distribution. Decreasing harvest pressure by increasing constraints reduces the amplitude of the waves but they none-the-less deform the distribution away from the typical inverse J-distribution. Clearly, this shift has economic implications. Future harvests are likely to be small in comparison to the first harvest and will simultaneously be less valuable per m^3 extracted on an undiscounted basis, which has strong implications for the sustainability of economic timber yields.

Harvests under Weakly Sustainable Inventories

Given RIL will be required on Brazilian public lands, the WSI and SSI scenarios were modeled for the RIL logger only. The WSI and SSI solutions are constructed such that the merchantable volume at the time of logging entry does not decrease below that defined by the MSY solution. For example, for a 40-year cutting cycle, the merchantable volume at time of logging entry cannot decrease below 35.1 m^3/ha. Harvests can vary over time to accommodate this constraint. For the WSI scenarios, in order to satisfy the constraint, the first harvests are light relative to the first U and BRP harvests. By the second harvest, with the exception for the 30-year cutting cycles, the WSI harvests are larger than the U and BRP harvests (Table 3-7). At that point, the WSI logger is still constrained by the sustainability harvest, which prevents the logger from liquidating the forest, but the harvest is such that the constraint is again met by the hypothetical third harvest. Continuing to use the 40 year cycle as an example, the WSI logger will encounter 75% more merchantable standing in the second entry than the BRP counterpart and about 33% more at the time of the third hypothetical entry.

The WSI harvests at the species-group level tell a slightly different story than the U and BRP harvests. The contribution of the emergent species is higher in the second WSI harvest than that of the U and BRP harvests (Figure 3-2). Although, it is evident that, by the third harvest, the commercial volume of emergent species is approaching the same low levels as the scenarios not constrained by sustainability concerns. The pioneer group is also assuming a larger role in the harvests. The future quantities of light-demanding and shade-tolerant species under WSI also persist at relatively the same rate as under the BRP set of policies. The difference in species dynamics between the scenarios is that intermediate species receive very light harvests relative to the available volume, implying that the WSI logger's strategy is to use the low-value intermediate species to satisfy the constraint, while the emergent class is gradually eliminated.

Note as an example that the idealized MSY logger applying a 40-year cutting cycle harvests 24.8 m^3/ha of 35.1 m^3/ha standing at each entry for perpetuity. The WSI logger extracts 13.1 m^3/ha of 41.0 m^3/ha in the first entry, then 21.8 m^3/ha of 35.1 m^3/ha in the second entry. In future entries, this harvest is likely to increase gradually until the MSY solution is approximated, implying that, while the WSI logger is a constrained profit maximizer, the extraction path the logger is following is also one that is regulating the stand toward a long-term MSY equilibrium. Comparison of the dynamics of the emergent species under the WSI and MSY solutions at year 80 for the 40-year cutting cycle shows that this period of regulation may take a very long period of time. In the MSY case, while the available merchantable volume of the emergent species group stands over 10 m^3/ha, which permits a small but sustainable harvest of the high-valued species, the emergents of the WSI solution stands at around 2 m^3/ha.

In the 40-year cutting cycle example just discussed, the logger may be able to extract high volumes of lower value species and satisfy the biological constraints but may not extract as much profit from the stand. As can be seen in Table 3-7, the intensity of the first harvest rises relatively slowly as the cutting cycle lengthens. Because more valuable species tend to grow more slowly, the optimizing logger seems to be making (slight) trade-offs between volume and value. Yet, as a result of the second harvest being discounted farther into the future, the second harvest becomes less valuable, more-or-less eliminating these gains.

Harvests under Strongly Sustainable Inventories

For each cutting cycle length, the first harvest under the SSI constraint exceeds the first harvest under the WSI constraint (Table 3-7). Also, for the 30 and 40-year cutting cycle lengths, the second SSI-constrained harvest exceeds the second harvest under the WSI constraint (Table 3-7). In fact, the second SSI-constrained harvest volumes under 30 and 40-year cutting cycles exceed the second harvests of all of the scenarios which are constrained by the initial standing stock. This result is interesting in that it highlights the importance of using an economic perspective in this type of analysis. In the U and BRP scenarios, the concessionaire harvests the most valuable timber first, caring very little about future growth. Under the WSI constraint, the concessionaire harvests valuable but slow growing timber, knowing that lower value species will grow sufficiently to satisfy the stand-level inventory volume constraint. Under the SSI solution, this substitution is not possible, so lower value but fast-growing timber is harvested first, with very little of the valuable emergent class being removed.

In fact, the emergent species group becomes more-or-less protected under the SSI constraint. For example, under a 40-year cutting cycles, no emergent stems are harvested in the first harvest. In the second harvest, about .7 m^3/ha is removed from a standing stock of about 10 m^3/ha, approximately the same harvest rate as the MSY solution. Figure 3-3 shows that the pre-harvest emergent distribution at years 40 and 80 has not changed significantly from the initial distribution, while the surge of pioneer species is muted in comparison with other scenarios.

Earlier in this chapter, it was asserted that the harvest path generated by a profit-maximizing concessionaire under the sustainability constraints would approach the harvest path derived under the MSY solution. Figure 3-2 provides visual evidence of this assertion, as the distribution of the pre-harvest merchantable volume across species groups under SSI constraints closely resembles that of the MSY solution.

Financial Returns

As highlighted in Barreto et al. (1998), Boltz et al. (2003), and Holmes et al. (2002), the comparison of financial returns (Table 3-8) depends greatly upon the relative amounts of waste. While the CL loggers harvest more than their RIL counterparts, almost 20% less timber volume actually leaves the forest. For example, the unconstrained CL logger achieves an NPV of $479/ha when applying a 40-year cutting cycle, while the RIL logger earns an NPV of $604/ha, the difference between the two essentially being a result of loss within the forest. Meanwhile, the difference between the loggers' respective returns is compounded by the fact that the CL logger incurs marginal harvests costs by harvesting timber that produces no revenues. Given the impact of the high levels of waste on the CL logger, both the RIL U and BRP scenarios have higher NPVs than the unconstrained CL logger.

This observation connects this analysis to the larger question of why a logger would not adopt RIL practices if the financial benefit is incentive compatible. One possible answer to this issue is that RIL is cost-effective in some circumstances, but not all. Putz et al. (2000) write that RIL may be not be cost-effective when loggers are restricted from accessing steep slopes or when ground yarding of timber is not permitted during wet conditions. Because the terrain at the experimental forest of this study is relatively flat and the study area also did not include any stream buffer areas that firms are required to set aside as reserves, there is a risk that benefits of RIL are over-stated because the estimated costs do not account for these factors. For example, according to a study of certification reports for certified timber firms operating in the Brazilian Amazon, the firms set aside about 9% of total forest area as permanent buffer area (Schulze et al., 2007a).

In cases where the benefits of adoption may otherwise be unambiguous, institutional constraints can also preclude adoption. Survey research on logging in the Brazilian Amazon revealed that many conventional loggers recognize that RIL, or forest management practices more generally, better protects forest values and, under certain circumstances, is cost effective, yet still do not adopt improved practices (Sabogal et al., 2006). Land tenure insecurity may prevent firms from pursuing improved environmental practices. Firms are unlikely to invest in practices that improve the economic value in future decades if they do not expect to have access to those forests decades in the future. Appropriate training, labor, and equipment may also be scarce (Sabogal et al., 2006). Institutional barriers, such as government corruption or inefficiency, may also exist that make operating conventionally or illegally the only option for operators (Merry et al., 2006; Sabogal et al., 2006). In any case, a type of technological path dependency can emerge where there has been historical distrust between loggers and government officials, particularly where government has been perceived to be indifferent to long term timber management (Smith et al., 2006). In this environment, norms that promote poor management practices emerge, which may require long periods of time to change under improved enforcement and incentive systems (Smith et al., 2006).

With the exception of the SSI-constrained scenario, NPV is mostly invariant to cutting cycle length for the simple reason that, for each cutting cycle length of the unconstrained and Brazilian policy scenarios, the logger harvests all (in the unconstrained case) or the most valuable (in the policy case) merchantable timber. Lengthening the cutting cycle does not change anything with respect to the first harvest. The discounted second harvest contributes very little to the NPV, regardless of volumes harvested. For the WSI scenarios, NPV falls then rises with cutting length because the longer periods of time between harvests permits increases in the allowable cuts in each harvest, shifting slightly toward slow-growing but more valuable species, but exchanges the gains for second harvest returns discounted farther into the future. For the SSI scenario, the NPV increases with the length of the cutting cycle, as the increasing length permits the concessionaire to harvest more valuable timber in the first harvest, knowing that the volume can recover by the next entry to satisfy the constraint.

For the RIL logger under a 40 year cycle, following Brazilian policy generates about $80/ha in opportunity costs. The WSI scenario presents opportunity costs of about $240/ha compared to the BRP RIL scenario and $320/ha to the U RIL scenario. The SSI scenario presents opportunity costs of about $360/ha compared to the BRP scenario and $440/ha to the U scenario. While the NPV is calculated from the present perspective of the logger, imagine the dynamic perspective of the future logger as the logger approaches the time of the second harvest. The WSI and SSI logger will encounter a significantly richer stand then the counterpart U and BRP loggers. But to maintain the sustainability-constrained stands in perpetuity will always generate opportunity costs and risks of timber trespass.

As mentioned before, the concessionaire who is governed by the SSI constraint is able to harvest more volume than the WSI-constrained concessionaire, but that volume is from relatively low value species. Under a 30-year cutting cycle, the NPV under the SSI constraint is about half of that of the WSI concessionaire. Under a 60-year cutting cycles, the NPV under the SSI constraint is just over two-thirds of the NPV under the WSI constraint. Given the SSI harvest is approaching that of the MSY solution, the trade-off between short-term gains and achieving a dynamically optimal and, hence, sustainable path is clear.

Discussion

While demonstrating the dynamic benefits of RIL, model results exhibit how current best logging practices and current regulatory policies do not guarantee the sustainability of timber harvests. The study also shows the difficulty associated with operationalizing sustainability in practice; sustaining timber yields at the stand-level led to significant opportunity costs while still leading to a stand that is changed in species composition and economically degraded. Over two cutting cycles, the harvests under the proposed definition of sustainability at the species-level were profitable and led to a species group-level merchantable volume distribution approaching the distribution of the maximum sustainable economic yield. To achieve this, the SSI solution essentially protects valuable but slow-growing timber species from harvest, which again creates high opportunity costs and strong incentives for breaking the rules when enforcement is imperfect. These are clearly results derived within a simulation of a representative stand, while the “on-the-ground” reality of the Brazilian Amazon is extremely complex. The following discussion will discuss a set of approaches that have been proposed to help induce sustainability and reduce opportunity costs of increased regulation.

Silviculture

A variety of silvicultural practices are currently performed in the Brazilian Amazon. Walters et al. (2005) surveyed the practices of a wide range of landowners, from smallholders to larger industrial firms, to identify that factors that influence adoption of silvicultural practices.

Practices currently include single or mixed-species reforestation on agricultural, pasture, or secondary forest lands, enrichment planting in logging gaps, secondary forest and the reserve areas of private landholdings, and tending commercially valuable trees (Walters et al., 2005). The dominant reasons for adopting silviculture include guaranteeing future timber supplies, complying with regulations, and reforesting land. The principle barriers to adoption include lack of technical skills or assistance, problems with pests, and seedling supply difficulties. Curiously, lack of incentives is a relatively minor barrier.

Because of the lack data on the dynamics of silvicultural treatments within this particular site, this study could not incorporate silvicultural practices above and beyond the practices already included in RIL, such as vine-cutting. Research on the costs and benefits of silvicultural practices that enhance regeneration and upgrowth of valuable species, such as enrichment planting and liberation thinning, is ongoing. The financial cost-effectiveness of such activities, considering the length of relevant managerial time-frames under reasonable discount rates, is uncertain but promising. For example, Wadsworth and Zweede (2006) performed liberation thinning in a forest similar to the Fazenda Sete site, finding that the diameter increment of the liberated trees was 20% greater than the comparison trees during the six post-treatment years. The extra harvest merchantable volume generated by the liberation thinning would have paid for the liberation, without considering the increased volumes likely to be available for future harvests (Wadsworth and Zweede, 2006).

Future efforts with this model should try to augment the transition matrices and recruitment vectors to account for silvicultural treatments. Assuming public preferences for sustaining individual species exist, such activities may need to be required on public lands, which may also merit public incentives. Improved analysis of the long term costs and benefits of silviculture would greatly assist in public forests planning.

Role of Currently Non-Commercial Species

It is possible that increasing the number of species extracted from tropical forests for commercial purposes is likely to increase the economic value of the forest, reduce impacts upon heavily harvested high-valued species, and reduce the pressure to expand timber production into new forest lands (Barany et al., 2003; Buschbacher, 1990; Plumptre, 1996; Youngs and Hammett, 2001). The increase in species over time is likely to arise from market changes and increased wood processing efficiency improvements (Karsenty and Gourlet-Fleury, 2006). Critics argue that the diversification of harvested species leads to increased rates of exploitation without diminishing pressure on high-valued species or increasing the likelihood the land will remain under forest cover (Rice et al., 2001). However, there is little empirical evidence to support either view, and the costs and benefits of valorizing new species depends in a complex fashion upon prices, regulations, and management objectives (Pearce et al., 2003).

As the Paragominas region was central to the early expansion of logging in the Eastern Amazon during the 1980s, regional transportation and forest sector infrastructure is relatively well-developed, implying that the number species harvested in this region is likely to be relatively high compared to most of the Brazilian Amazon. In fact, about 75% of the stems > 50 cm DBH in the Sete experimental forest are of commercial species. While evaluating the historical trends of timber species use is difficult because of ambiguities in the species names of low-valued species with few individuals, the increase in the number of species processed in local Paragominas mills of the study region appears negligible during the 12-year study period. Rather than the commercial species list in this region lengthening over time, as the local industry becomes exhausted, loggers are reentering logged forests to obtain smaller diameter and defective stems before land conversion.

Assuming increased land security, as in permanently secured state and national forests, to what extent would future commercialization of currently lesser known species affect economic viability of forest management? From the present-oriented NPV-maximizing perspective of a concessionaire, optimistic commercialization scenarios make little difference. For example, while the detailed results are not presented here, assuming a 40-year cutting cycle managed under RIL with 20% of the non-commercial trees species becoming merchantable by the second entry, less than $2/ha is added to the NPV, although commercial harvests clearly increase in the future. These numbers assume that prices remain constant and that no new high-valued species will emerge in the future, an assumption that seems reasonable given the strongly valued wood qualities of the high-valued species. The scenario also assumes that no species are "de-commercialized" in time.

Ways to Compensate Opportunity Costs of Additional Management

While international transfers to protect biodiversity hotspots have been an important element in forest conservation strategies in recent decades, many commentators have expressed cautious excitement about the potential for emerging payments for ecosystem service schemes to mobilize global resources to achieve long-term conservation and economic development (Chomitz et al., 2007; Wunder, 2006; Wunder, 2007). Recent Kyoto Protocol negotiations have looked more favorably upon forested developing countries to include averted deforestation, or compensated reduction, into the Protocol (Gullison et al., 2007). The central idea of compensated reduction is that countries can chose to reduce national deforestation levels below historical levels and receive payments upon accomplishing targeted reductions, which would create significant incentives to reduce deforestation (Santilli et al., 2005). Under particular proposals, the incentives are directed toward decreases in overall deforestation rates, not toward particular projects, freeing governments to seek the gains with the lowest marginal costs. Given that the establishment of state and national forests is a significant component of the Brazilian national forest-sector strategy and that the carbon sequestration benefits of reduced impact logging have been demonstrated by previous studies (Boscolo et al., 1997; Boscolo and Buongiorno, 1997; Pinard and Putz, 1996; Smith and Applegate, 2004), resources could be directed at securing and improving long-term management of public production forests, Brazil could choose to direct international payments toward grassroots management, silvicultural, and enforcement capacity building.

Matters of Scale: Spatial and Temporal Landscape Management

Considering a landscape as a summation of stand-level projects potentially yields misleading results by failing to include variables that incorporate economic gradients across space and time (Boyland, 2006). For example, the results presented here do not discuss the possibility of spatial and temporal zoning of timber harvests to meet long term objectives. With respect to sustaining populations of high-value species that, because of population structures and low recruitment rates, are difficult or perhaps impossible to manage sustainably, a reasonable conclusion of this study is that logging will need to be located within an appropriately designed and enforced reserve network. The Public Forests Management Law (PFML) requires that 5% of all allocated concessions be held in absolute reserve for biodiversity preservation and monitoring, and that the relevant government agency can determine the boundaries of this reserve area. Difficult to manage species should receive consideration in this decisionmaking processes.

The reserve network may also be designed temporally. For example, a forest concession may be logged twice according to a given cutting cycle then put aside for productive purposes for an equivalent length of time in order to regenerate timber stocks while protecting the non-timber values of the forest. Costly enforcement must be sustained during the period of dormant timber production. This approach would give future decisionmakers a policy variant of the "log and leave" scenario advocated by Rice et al. (2001) should land use priorities shift in the future.

Public forest timber production occurs over extremely long time horizons, and adaptive management requires the building of capacity to change management objectives or prescriptions in the future. That said, decisionmakers are currently planning national and state forests in the Brazilian Amazon and need accurate projections of future timber supplies and demands (Lentini, 2007; Veríssimo et al., 2006). Under current regulations, estimates of supply should account for diminished timber volumes and values in future harvests, rather than assume optimistically that timber volumes are sustainable perpetually at maximum permitted volumes. Realistic projections of timber supply are critical in evaluating how the natural capital of the unlogged forest is converted into economic development, the key issue being whether logging in public forests, or particular areas within larger forests, should be viewed as a one-shot event or as a repeating series of sustained harvests.

Conclusion

While it is again shown under the conditions of the study site that RIL is cost-effective to implement, the bulk of the financial gains are due to harvest planning improvements over conventional techniques, rather than through protection of the forest resource. RIL is shown to marginally increase the volumes of merchantable timber available in future harvests, but does not significantly change what is now well-known about logged forests; the structure and composition of the managed forests will be different than that of the primary forest. Perhaps silvicultural techniques in addition to continued development of improved logging techniques will prove to ameliorate this effect in the future. However, given the likelihood that certain RIL practices may be more financially beneficial than others, such as testing hollows or reducing wood waste and skidder-time in the forest, reveals the possibility that RIL may more often be partially implemented, as managers determine the relative costs and benefits of shirking certain cost-ineffective activities.

While volumes of merchantable timber predicted to be available for the second and third harvests are significantly lower than the available timber in the primary forests, the second and third harvests are projected to be profitable and appear to have the potential for sustainability at the stand-level and species-group level. The WSI scenario showed that stand-level sustainability is likely to be possible at lower volumes and lower economic value, but that sustainable management by the criteria driving that scenario is viable. The harvests under species group-level sustainability constraints were profitable, but at the expense of harvesting very little of the most valuable timber.

While this study is performed with the intent to provide analytical support to public forest planning, there is no reason that the results should apply exclusively to public lands. The bioeconomic results apply to private lands equally, although the policy implications may differ across tenures, depending on over-arching management objectives for the different lands and public preferences for goods and services delivered from public lands. That said, perhaps the most important implication of the results presented here, which is not original to this study (see e.g. Karsenty and Gourlet-Floury, 2006, and Van Gardingen 2006), is that the public, forest sector, decisionmakers, and other stakeholders such as non-governmental organizations and certifying bodies, should reflect and revise their visions for the likely financial and ecological outcomes of multi-cyclic management of natural forests in the Eastern Amazon region.

Table 3-1. Merchantability criteria by species group.

Logging system	Species group	S_i	Q_i	$H0_i$	$H1_i$	τ_s	$M0_{is}$	$M1_{is}$
RIL	Pioneer	0.56	0.91	0.20	0.05	1.00	0.40	0.48
	Light-demanding	0.69	0.71	0.20	0.05	1.00	0.39	0.46
	Intermediate	0.96	0.80	0.20	0.05	1.00	0.61	0.73
	Shade-tolerant	0.42	0.93	0.20	0.05	1.00	0.32	0.38
	Emergent	1.00	1.00	0.20	0.05	1.00	0.80	0.95
CL	Pioneer	0.56	0.91	0.20	0.05	0.50	0.45	0.49
	Light-demanding	0.69	0.71	0.20	0.05	0.50	0.44	0.48
	Intermediate	0.96	0.80	0.20	0.05	0.50	0.69	0.75
	Shade-tolerant	0.42	0.93	0.20	0.05	0.50	0.36	0.39
	Emergent	1.00	1.00	0.20	0.05	0.50	0.90	0.98

Notes: S_i = proportion of stems in species group *i* composed of commercial species. Q_i = proportion of stems in species group *i* composed of stems of good form. $H0_i$ = proportion of hollow stems in species group *i* at initial harvest. $H1_i$ = proportion of hollow recruited stems in species group *i*. τ = proportion of hollow stems identified by logger under harvest system *s*. $M0_i$ = proportion of perceived merchantable stems for species group *i* under harvest system *s* at initial harvest. $M1_i$ = proportion of perceived merchantable stems for species group *i* under harvest system *s* at subsequent harvest.

Table 3-2. Commercial volume (m^3/stem) by species group and DBH

Species group	50-60 cm	60-70 cm	70-80 cm	80-90 cm	90-100 cm	>100 cm initial harvest	>100 cm subs. harvests
Pioneer	3.0	4.1	6.0	8.3	9.6	11.9	11.9
Light-demanding	3.0	4.1	5.8	7.9	10.2	21.3	13.8
Intermediate	2.9	4.4	6.0	8.1	9.6	17.0	13.8
Shade-tolerant	3.0	4.3	6.6	8.4	10.4	15.2	13.8
Emergent	3.0	4.4	6.1	8.1	10.8	19.6	13.8

Notes: Volumes estimated using volume equations in Silva et. al (1984).

Table 3-3. Price/tree (price/m^3 multiplied by volume/tree) by species group and size (DBH)

Species group	50-60 cm	60-70 cm	70-80 cm	80-90 cm	90-100 cm	>100 cm initial harvest	>100 cm subs. harvests
Pioneer	86.5	114.3	234.7	344.3	418.4	475.7	475.7
Light-demanding	84.5	110.8	156.4	205.4	275.4	537.5	348.2
Intermediate	79.7	113.5	153.7	224.3	261.3	490.1	397.8
Shade-tolerant	87.1	129.9	196.6	275.6	390.0	538.6	489.0
Emergent	120.3	200.2	282.1	333.9	514.4	1313.0	924.5

Table 3-4. Variable cost/tree (cost/m3 multiplied by volume/tree) by species group and size (DBH)

Harvest system	Species group	50-60 cm	60-70 cm	70-80 cm	80-90 cm	90-100 cm	>100 cm initial harvest	>100 cm subs. harvests
RIL	Pioneer	46.9	64.1	93.8	129.8	150.1	186.1	186.1
	Light-demanding	46.9	64.1	90.7	123.6	159.5	333.1	215.8
	Intermediate	45.4	68.8	93.8	126.7	150.1	265.9	215.8
	Shade-tolerant	46.9	67.3	103.2	131.4	162.7	237.7	215.8
	Emergent	46.9	68.8	95.4	126.7	168.9	306.5	215.8
CL	Pioneer	40.4	55.3	80.9	111.9	129.4	160.4	160.4
	Light-demanding	40.4	55.3	78.2	106.5	137.5	287.1	186.0
	Intermediate	39.1	59.3	80.9	109.2	129.4	229.2	186.0
	Shade-tolerant	40.4	58.0	89.0	113.2	140.2	204.9	186.0
	Emergent	40.4	59.3	82.2	109.2	145.6	264.2	186.0

Table 3-5. Components of waste across logging systems

Harvest treatment	Cut hollows	Poor felling and bucking[1]	Lost trees[1]	$waste_s$
RIL	0.000	0.039	0.003	0.042
CL initial harvest	0.100	0.123	0.038	0.261
CL subsequent harvests	0.025	0.123	0.038	0.186

[1]Values found in Holmes et al. (2002).

Table 3-6. Solution of the MSY program at the species group-level (tree/ha and m^3/ha)

		Cutting cycle (years)							
		30		40		50		60	
Variable	Species group	(trees/ha)	(m^3/ha)	(trees/ha)	(m^3/ha)	(trees/ha)	(m^3/ha)	(trees/ha)	(m^3/ha)
Pre-harvest stock									
	Pioneer	2.8	9.3	2.6	8.7	2.4	8.3	2.3	8.2
	Light-dem.	1.5	5.1	1.6	5.7	1.7	6.3	1.8	6.8
	Intermediate	1.4	4.8	1.6	5.6	1.8	6.6	2.0	7.5
	Shade-tol.	1.3	4.3	1.5	5.1	1.7	5.8	1.8	6.4
	Emergent	1.7	10.5	1.6	10.0	1.6	9.7	1.5	9.6
	Total	8.7	34.0	8.9	35.1	9.2	36.8	9.5	38.6
Harvest									
	Pioneer	2.8	9.2	2.6	8.7	2.4	8.3	2.3	8.2
	Light-dem.	1.2	4.0	1.3	4.6	1.4	5.1	1.4	5.6
	Intermediate	1.4	4.5	1.6	5.6	1.8	6.6	2.0	7.5
	Shade-tol.	1.3	4.3	1.5	5.1	1.7	5.8	1.8	6.4
	Emergent	0.0	0.7	0.1	0.7	0.1	0.8	0.1	0.9
	Total	6.7	22.7	7.0	24.8	7.3	26.7	7.7	28.6

Table 3-7. Pre-harvest standing stock, total harvest, and recovered timber for all cutting cycles (m^3/ha)

		1st entry			2nd entry			3rd entry
Cutting cycle (years)	Scenario	Timber avail. (m^3/ha)	Harvest (m^3/ha)	Recovered (m^3/ha)	Timber avail. (m^3/ha)	Harvest (m^3/ha)	Recovered (m^3/ha)	Timber avail. (m^3/ha)
30	CL U	41.0	43.4	32.1	8.3	8.1	6.6	12.1
	RIL U	41.0	39.8	38.1	11.4	11.1	10.6	17.7
	CL BRP	41.0	30.0	24.4	16.9	16.8	13.7	12.2
	RIL BRP	41.0	30.0	28.7	18.3	17.9	17.1	17.8
	RIL WSI	41.0	13.1	12.6	34.0	15.0	14.4	34.0
	RIL SSI	41.0	14.9	14.3	31.5	19.2	18.3	29.0
	RIL MSY*	34.0	22.7	21.8	34.0	22.7	21.8	34.0
40	CL U	41.0	43.4	32.9	10.4	10.3	8.5	18.2
	RIL U	41.0	39.8	38.1	14.2	13.8	13.2	24.3
	CL BRP	41.0	30.0	22.2	18.3	18.1	14.7	18.2
	RIL BRP	41.0	30.0	28.7	20.3	19.8	19.0	24.4
	RIL WSI	41.0	13.7	13.1	35.1	21.8	20.9	35.1
	RIL SSI	41.0	15.0	14.3	32.9	22.3	21.4	33.6
	RIL MSY*	35.1	24.8	23.8	35.1	24.8	23.8	35.1
50	CL U	41.0	43.4	32.1	13.7	13.3	10.8	22.7
	RIL U	41.0	39.7	38.0	17.7	17.1	16.4	28.8
	CL BRP	41.0	30.0	22.2	20.9	20.5	16.7	22.5
	RIL BRP	41.0	30.0	28.7	23.1	22.5	21.5	28.8
	RIL WSI	41.0	13.9	13.3	36.8	25.9	24.9	36.8
	RIL SSI	41.0	19.3	18.4	34.3	16.1	15.4	37.8
	RIL MSY*	36.8	26.7	25.6	36.8	26.7	25.6	36.8
60	CL U	41.0	43.3	32.0	17.8	17.1	13.9	26.0
	RIL U	41.0	39.6	38.0	21.6	20.9	20.0	31.9
	CL BRP	41.0	30.0	22.2	24.3	22.6	16.7	26.1
	RIL BRP	41.0	30.0	28.7	26.4	25.6	24.5	31.9
	RIL WSI	41.0	15.4	14.8	38.6	26.6	25.5	38.6
	RIL SSI	41.0	19.0	18.2	34.3	16.1	15.4	37.8
	RIL MSY*	38.6	28.6	27.4	38.6	28.6	27.4	38.6

MSY scenario is independent of initial conditions

Table 3-8. NPV of scenarios ($/ha)

	Cutting cycle (years)			
Scenario	30	40	50	60
CL U	481.1	479.2	478.8	478.1
RIL U	606.1	603.7	602.1	600.8
CL BRP	416.7	411.9	410.3	409.6
RIL BRP	526.9	522.4	520.3	519.3
WSI	295.2	286.9	290.3	304.5
SSI	148.1	160.4	212.9	220.5
MSY*	278.9	279.4	303.4	328.7

* MSY scenario is independent of initial conditions

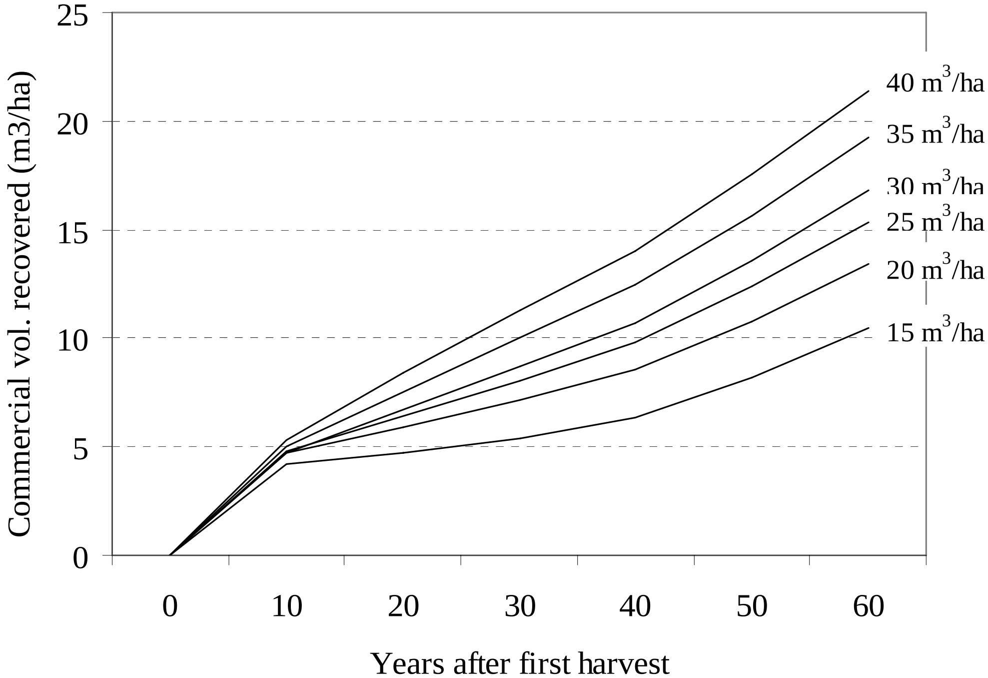


Figure 3-1. Commercial volume recovery (m^3/ha) after initial RIL harvest of increasing intensity (15 to 40 m^3/ha)

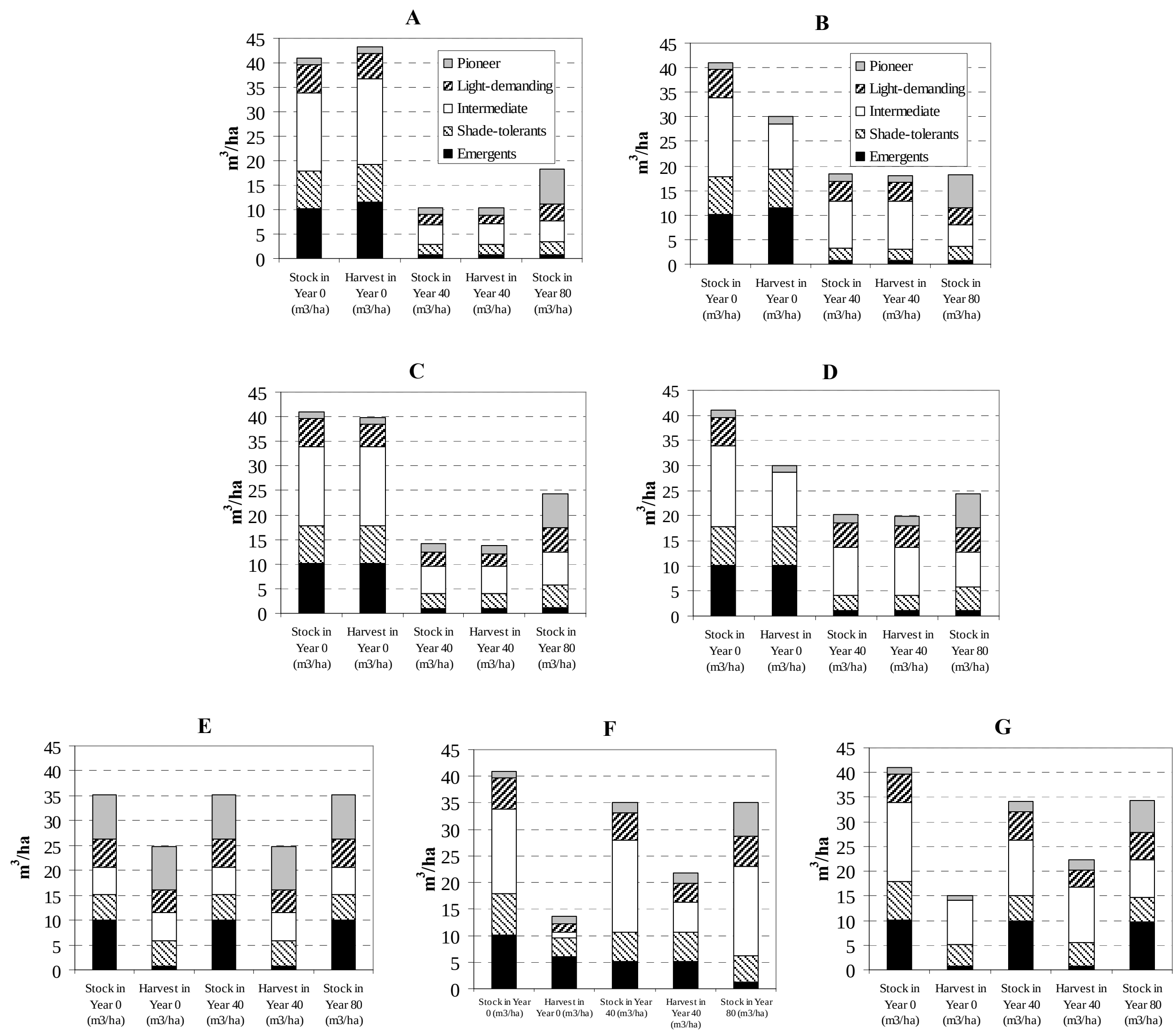


Figure 3-2. Dynamics of pre-harvest standing stock and total harvest by species group (40-year cutting cycle). A) CL unconstrained. B) CL Brazilian regulatory policy. C) RIL unconstrained. D) RIL Brazilian regulatory policy. E) RIL maximum sustainable yield solution. F) RIL weakly sustainable inventories. G) RIL strongly sustainable inventories.

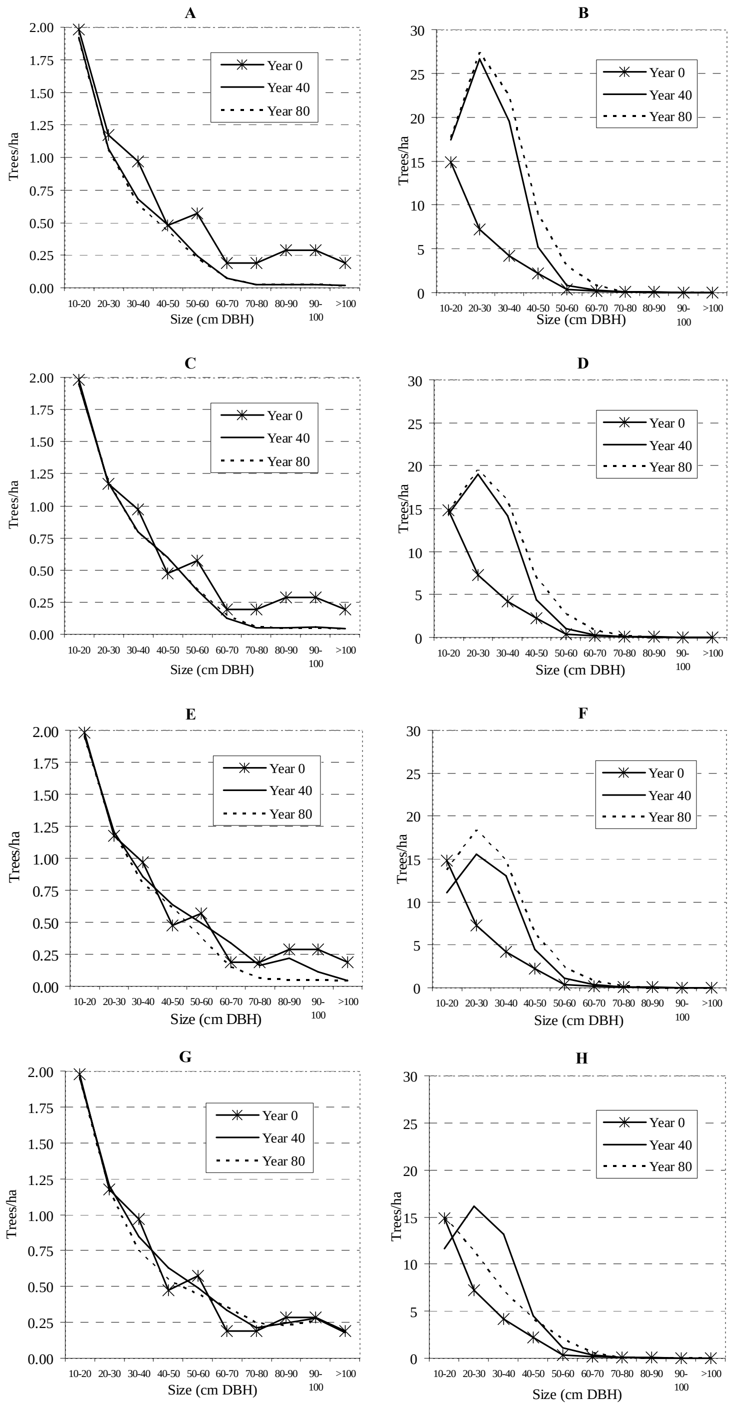


Figure 3-3. Size distributions of emergent and pioneer species groups across scenarios (40-year cutting cycle). A) Emergent species under CL U. B) Pioneer species under CL BRP. C) Emergent species under RIL U. D) Pioneer species under RIL BRP. E) Emergent species under RIL WSI. F) Pioneer species under RIL WSI. G) Emergent species under RIL SSI. H) Pioneer species under RIL SSI.

CHAPTER 4
A POLICY SIMULATION OF A BRAZILIAN LOGGING CONCESSION UNDER IMPERFECT ENFORCEMENT AND ROYALTIES

Introduction

Supporters of Brazil's new Public Forests Management Law (Lei 11284/2006) are optimistic that concessions will provide economic development opportunities and help modernize the natural forest products industry, while improving the capacity of the state to protect lands from incursions and degradation (Veríssimo et al., 2002a; Veríssimo and Barreto, 2004). While a logged forest may deliver lower quantities or qualities of environmental services, it is argued that the lower ecological qualities of the forests are likely to be offset by the economic and control functions the concessions will perform. The overall supply of ecosystem services will be protected by the appropriate land being allocated toward stronger forms of protection.

However, many debates during the preparation of the Public Forests Management Law (PFML) focused on the government's low institutional capacity to manage the concession system and to monitor and enforce the concession contracts and appropriate environmental management requirements. As the PFML is implemented, the development of sound administrative procedures, revenue collection systems based on appropriate rates, enforcement capacity, and royalty distribution procedures will become crucial. There is significant controversy whether these multiple tasks can be achieved. For example, Merry and Amacher (2005) identify several potential problems with Brazilian concessions, many of which are analogous to well-documented problems with concessions in other countries (Gray, 2005; Repetto and Gillis, 1988). First, concessions may allow concessionaires artificially high rents because of poorly designed revenue systems. As well as give away public resources, this problem may additionally stifle innovation and the longer term competitiveness of the Brazilian forest industry (Merry and Amacher, 2005).

Second, the Brazilian government may become a rent-seeking government as a result of unexpectedly high costs of administering the concession system added to the possible nonpayment of royalties. In order to increases revenue, a rent-seeking government might seek to induce higher harvest rates by lowering tax or royalty rates away from the first-best rates that maximize economic efficiency. This effect, also discussed for concessions in general in Amacher (1999), Amacher and Brazee (1997), and Merry and Amacher (2005), can lead to an accelerated allocation of land into concessions which may simply compound budgetary shortfalls.

Meanwhile Leruth et al. (2001) find that royalty instruments do not reinforce or substitute for command and control enforcement approaches. The negative externalities associated with logging have very little relationship with harvest volumes, which is typically the target of timber tax instruments. Rather, the externalities are largely a result of the quality of management practices, such as whether RIL or post-harvest silviculture is implemented. A timber tax is unlikely to successfully function as Pigovian-type instrument which taxes the externality in order to better align social and private costs (Leruth et al., 2001). In fact, Leruth et al. (2001) argue, timber taxation can actually induce more damage to the forest resource than no taxes at all by encouraging lower overall harvests at higher rates of collateral damage. As a corrective instrument, Leruth et al. (2001) advocate a performance bond instrument combined with strengthened enforcement over royalty instruments. Performance bonds are also found to be effective instruments in the simulation-based studies of Boltz (2003) and Boscolo and Vincent (2000).

Objectives of the Study

Within this fast-moving political-economic environment, empirical efforts that examine the viability of concessions under imperfect enforcement can provide critical information to decisionmakers. Using an optimization model parameterized with data from the Eastern Amazon, this research investigates the effectiveness of renewability audits and performance bonds in inducing compliance with requirements regarding harvest volume limits and the implementation of RIL.

The contracts emerging in larger-scale Brazilian concessions have a maximum length of 40 years under a variable cutting cycle that is typically 35 or more years. Hence, a typical concessionaire can be expected to plan for a single harvest from each cutting block. In absence of policies that give concessionaire's equity in the forest beyond the concession contract, each entry from the concessionaire's perspective can be considered a static optimization problem. This assertion is bolstered by the evidence presented in the previous chapter, as the discounted value of future harvests is extremely low, regardless of damage incurred to the forest. The optimal harvest under current regulations and discount rate removes the most valuable timber possible until constraints are binding, without respect to the potential growth of any given tree.

The concessionaire of this chapter will solve a harvest problem similar to the imperfect enforcement problem discussed in Amacher et al. (2007), which examined tax and fine structures when the logger was able to harvest more timber than legally allowed. The model of this chapter, however, permits the logger to also shirk RIL requirements as well as harvest illegal timber volumes, defined as harvested timber volume above the legal limit of 30 m^3/ha. In order to examine the response of the concessionaire to periodic audit pressure, the paper adopts the sequential harvest framework of Boscolo and Vincent (2000), which simulates the annual harvest of different stands with identical initial conditions over the course of a concession contract. In the model, if the concessionaire fails an audit, the concessionaire will not be able to operate on the concession for the remainder of the time horizon of the contract. As in the Boscolo and

Vincent (2000) sequential harvest problem, a second harvest of any management unit is not permitted.

The model will be used to examine the incentives for implementing reduced impact logging techniques (RIL) and observing legal harvest volume intensity regulations. In the model, the decisions to implement RIL and perform illegal harvests are seen as discrete decisions. For example, the concessionaire can fully implement RIL while logging illegal volumes.

The model is developed in the form of a classic principal agent problem. Royalty rates and enforcement pressure will be examined when the government is subject to a revenue constraint and the logger is subject to a participation constraint, which requires that the logger earn a rate of return equivalent or higher than a typical rate of return to forestry on private lands. The government has at its disposal a set of harvest regulations, imperfect audit abilities, systems to generate royalty payments from the concessionaire, and the possibility of charging pre-harvest performance bonds, which are returned to the concessionaire in proportion to the concessionaire's compliance with regulations.

Two types of royalty charges are investigated here. First, a percentage *ad valorem* rate is charged against the marginal profit, or the added-value, of harvesting a tree. In other words, a percentage of the difference between the price of a tree and the marginal costs to harvest the tree is charged under the *ad valorem* royalty. Second, a percentage revenue-based royalty rate is charged against just the price of the harvested tree. For either instrument, the royalty rate is applied only against trees that were legally harvested. As has been shown in previous work, the *ad valorem* royalty system as typically applied is a non-distortionary instrument that will not influence marginal harvest decisions (Hyde and Sedjo, 1992). However, given the analysis here includes the potential of illegal logging, where no royalties are paid on the illegal portion of the harvest, the *ad valorem* royalty may not be non-distortionary across its feasible range under the participation constraint, as high rates may induce illegal logging. Meanwhile, the revenue-based royalty charged will reduce the relative profitability of harvesting the tree, distorting harvest decisions on the margin, creating the possibility of inducing lower harvest levels, which may or may not be a desirable effect, given the government's objectives. The same risk of high rates inducing illegal harvests may also be present with the revenue-based royalty.

The area fee as used in this analysis is also non-distortionary in terms of harvest decisions, although at a larger scale the fee may help determine what lands are profitable for harvest. In practice, the area fee can be identified via a competitive or administrative process. In this study, the area fee required to bind the concessionaire's participation constraint is determined after the optimal harvest is identified. The value in calculating the area fee in this manner is that it can help guide decisions about what the concessionaire might be willing to pay for harvest rights under a given set of royalty and enforcement mechanisms. The area fee amounts generated in this study could serve as estimates of the reservation price for the auction of the concession in a competitive process. Alternatively, the area fees can represent the administratively determined price for harvest rights within non-competitive environments.

In the section that follows, the optimization model of the previous chapters will be modified to meet the objectives of this chapter. Results of several representative scenarios will then be presented. To conclude, these results will be discussed in light of their policy implications. Further data collection and research is also suggested.

The Model

Partial RIL Adoption

To perform the analysis in this chapter, the model requires further development to account for harvesting above the legal limit, the choice of logging technique, a budget-constrained government, and royalty and enforcement mechanisms. Because the model developed here is static as opposed to the dynamic model of earlier chapters, the subscript for time has been removed from previously-defined model components.

As in Boscolo and Vincent (2000), in order to reflect the reality that the logger might imperfectly adopt RIL, the logger is able to choose at harvest a value, $\omega \in [0,1]$, where $\omega = 0$ implies no RIL practices are adopted while $\omega = 1$ implies the full portfolio of RIL practices are adopted. The degree to which RIL is not implemented illegally, $\omega_{illegal}$, is measured by:

$$\omega_{illegal} = 1 - \omega . \tag{4-1}$$

This formulation implies that $\omega_{illegal} \in [0,1]$. Since the rate of RIL adoption will influence harvest damage, the damage vector from previous chapters is now written as the *mn* x 1 vector, $\mathbf{d}_\omega$, which is determined by the following linear interpolation:

$$\mathbf{d}_\omega = \omega \mathbf{d}_1 + (1-\omega)\mathbf{d}_2 \tag{4-2}$$

where $\mathbf{d}_1$ captures the damage under full implementation of RIL and $\mathbf{d}_2$ captures the damage under full implementation of conventional logging (CL).

This formulation assumes the logger will receive the full benefit of reducing damage when RIL is fully implemented, while incremental reductions in the rate of adoption cause linear increases in the damage. When RIL is not adopted at all, the damage vector is equivalent to the vector for the CL logger. Imposing the linear interpolation on the decision is a simplification necessitated by the data and model. Within an actual logging environment, some practices are more costly than others while some are more easily shirked than others. Also, simple oversight or lack of training may cause firms to fail to adopt particular RIL guidelines. For example, in a study of two large certified companies in the Brazilian Amazon, Pokorny et al. (2005) note that about one-third of a set of 61 RIL guidelines were not fully implemented. The lack of sufficient monitoring, training, and equipment explains many of the failures to meet guidelines (Pokorny et al., 2005).

Meanwhile the returns to implementing RIL activities may have different time horizons. Given the evidence that the short-term operational improvements from implementing RIL can offset the costs, the firm may adopt practices that emphasize short run benefits over the long run benefit of protecting future harvests. For example, firms are unlikely to shirk developing relatively low cost but high quality inventories and maps because of the significant reduction in losses attributable to the improved ability to find felled trees. Directional felling is a counter-example of an RIL activity that incurs costs for little immediate operational benefit while significantly reducing damage to future harvest trees.

It is important to note that the static formulation of the problem implies that the concessionaire will not perform a second harvest. The concessionaire, then, has no financial interest in implementing RIL to improve the future productivity of the forest. However, given many of the gains of implementing RIL occur in the first harvest through planning and operational improvements, implementing RIL in the single harvest problem can be significantly beneficial, depending on the costs. That said, by the definition of the static problem, RIL becomes relatively more costly and less likely to be implemented.

Recalling that both types of logger will reject stems with poor form, but the RIL loggers will test all trees targeted for harvest for hollowness and reject harvesting the tree if it is found to be hollow, it is necessary to adjust the merchantability matrix from earlier chapters. Let $\mathbf{M}_{\omega}$ be a *mn* x *mn* diagonal matrix where the diagonal contains the *perceived* (as a function of logging system adopted) merchantable proportion of stems in each species group *i* and size *j*. Then $\mathbf{y}_{\omega}^{m}$ is a *mn* x 1 vector representing the standing stock of merchantable timber, which is calculated by:

$$\mathbf{y}_{\omega}^{m} = \mathbf{M}_{\omega}\mathbf{y} \tag{4-3}$$

where:

$$\mathbf{M}_{\omega} = \omega\mathbf{M}_{1} + (1-\omega)\mathbf{M}_{2} \tag{4-4}$$

and $\mathbf{M}_{1}$ captures the perceived merchantability under full implementation of RIL and $\mathbf{M}_{2}$ captures the perceived merchantability under full implementation of CL. Where $\mathbf{d}_{\omega}^{m}$ is a *mn* x 1 vector capturing the number of merchantable stems in species group *i* and size *j* killed accidentally during harvest as a function of RIL adoption, ω, the logger will not harvest and kill by damage more than the logger perceives is merchantable:

$$\mathbf{h} + \mathbf{d}_{\omega}^{m} \leq \mathbf{y}_{\omega}^{m}. \tag{4-5}$$

The benefits of implementing RIL, in particular from operational planning improvements, extend beyond the reduction of damage to the residual stand and minimizing the felling of hollow trees to a general reduction of waste during the forest operation (Barreto et al., 1998; Boltz et al., 2003; Holmes et al., 2002). Again, in order to capture the logger's choice of harvest system, a linear interpolation between the CL and RIL choice is applied:

$$waste_{\omega} = \omega waste_{1} + (1-\omega)\, waste_{2} \tag{4-6}$$

where $waste_1$ is the percentage of harvested volume wasted under full implementation of RIL and $waste_2$ is the percentage of harvested volume wasted under full implementation of CL.

Harvesting Above the Legal Volume Limit

As in previous chapters, the regulatory agency has available a set of simple rules that it can use to try to induce desired logging behavior. The regulatory agency may apply diameter cutting limits, harvest volume intensity limits at the overall stand-level, and provisions for leaving seed and rare trees standing. The regulations are assumed to remain fixed throughout the horizon of the scenario. Whereas in the previous chapter the rules were assumed to be either perfectly enforced or perfectly un-enforced, this chapter loosens this assumption to allow the logger the possibility of breaking the harvest volume regulation. The harvest above the legal volume limit, $h_{illegal}$, is measured as harvest above the permitted limit of 30m^3/ha:

$$h_{illegal} = \begin{cases} \boldsymbol{\psi}'\mathbf{h} - 30 & \text{if } \boldsymbol{\psi}'\mathbf{h} > 30 \text{ m}^3/\text{ha} \\ 0 & \text{otherwise.} \end{cases} \tag{4-7}$$

The standing stock of merchantable timber in the initial stand is 41.0 m^3/ha, implying that $h_{illegal} \in [0,11]$.

It is important to note that the harvest of trees and the implementation of RIL are treated as independent choice variables in this study in order to permit stronger comparisons between the choices under different regulatory regimes. Treating the choices as independent, for example, permits firms to fully implement RIL while completely ignoring harvest volume regulations. The converse, fully legal harvests with no implementation of RIL, is also possible. In a real forest environment, the firms may often see these decisions as interconnected. For example, road infrastructure may be designed and constructed out of compliance with RIL principles in order to facilitate harvests above the legal volume limit.

Enforcement Mechanisms

Audit pressure

Enforcement responsibilities on the Brazilian concessions will be divided between the government and independent auditors. The law requires that the new forest agency, the Serviço Florestal Brasileiro (SFB), oversee the concession contracts, while the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) and state environmental agencies will maintain their traditional roles in regulating management plans and operations on national and state lands, respectively. Meanwhile, under a certification-like model, the law requires that concessions are independently audited at least once every three years. While on paper this system establishes checks and balances and several redundancies, the current enforcement capacity within SFB and IBAMA and within the judiciary more generally is low (Brito and Barreto, 2004; Brito and Barreto, 2006; Hirakuri, 2003; Schulze et al., 2007b), and the promises of high enforcement expressed in the PFML might not be enacted in the short term.

In a study of a sample of forest environmental crimes in the state of Pará between 1999 and 2002, Brito and Barreto (2006) find that a large majority of citations (72%) are issued for storage and transport violations, while relatively few are issued for violations in the forest (6%). Of the citations issued in the sample, very few of the accused ultimately paid a fine. Brito and Barreto (2006) find that over 60% of accused individuals or firms are never served process, meaning the alleged violators were not found in order to initiate legal proceedings. Negotiated settlements requiring payments for social services or environmental reparations are a large component of the environmental judicial process in Brazil. Settlements offered to individuals cited for environmental crime in Pará ranged from \$5.50 - \$54.10/m^3 roundwood with the offers to firms ranging from \$7.20 - \$217.20/m^3, although the actual settled values varied greatly from these ranges, from \$0.77 - \$480.50/m^3 (Brito et al., 2005). Ultimately, fewer than half of the fines levies were paid (Brito and Barreto, 2006; Hirakuri, 2003).

To reflect the relative weakness of enforcement in the model, the probability of being caught and punished for breaking a rule is considered an increasing function in the level of rule-breaking behavior, operationalized in this study by the weighted sum of illegal harvest volume and the degree to which RIL is not implemented, a variable which will be defined later in the text. While there are no empirically-based estimates of the penalty function for concession logging in Brazil, it is reasonable to assume that, similar to the penalty function presented in Sun (1997), the function would take a logistic form. Where x represents an illegality factor and $\theta\left(x\right)$ represents the probability of being caught and ultimately paying a fine as a function of the illegality factor, the logistic form of the penalty function follows:

$$\theta\left(x\right)=\frac{1}{1+e^{-x}}. \tag{4-8}$$

Recalling that $\omega_{illegal}\in\left[0,1\right]$ and $h_{illegal}\in\left[0,11\right]$, it is necessary to introduce a variable that weighs the relative contribution of each activity to the penalty function. In this case, failure to adopt RIL and illegally harvested volume are assumed to have equal weight in the penalty function. In order to weight these factors equally, $\omega_{illegal}$ is multiplied against η, where $\eta=11$. This allows $\eta\omega_{illegal}$ to have the equivalent range as $h_{illegal}$. Now, the illegality variable, x, can be fully defined:

$$x=h_{illegal}+\eta\omega_{illegal}-\tau \tag{4-9}$$

where the constant $\tau = 11$. The constant serves the purpose of re-centering the distribution of $\theta(x)$ such that if $h_{illegal}$ and $\omega_{illegal}$ are equal to zero, then $\theta(x) = 0$. Also, when $h_{illegal}$ and $\omega_{illegal}$ are at their maximum values, $\theta(x) = 1$. The probability of being caught breaking the rules and paying a fine as a function of x is graphed in Figure 4-1.

The probability of capture increases slowly within the lower range of x as the concessionaire harvests slightly over the legal limit and/or shirks few RIL-required activities. As the over-harvests or shirking of RIL-required activities increases into the middle range, the likelihood of capture increases rapidly, quickly peaking as harvest damage becomes more obvious to the enforcement agent or auditor. The shape of the enforcement function is consistent with the observation that low levels of rule-breaking behavior may not be easily observable in complex and remote forest environments, while increasing harvest intensity or poor logging technique is more readily observable, particularly by the real-time forest management remote sensing techniques expected to form an important component of enforcement capacity in the concession system (Monteiro and Souza Jr., 2006; Souza Jr. et al., 2006). It is important to note that the probabilities here reflect the likelihood that the rule-breaking concessionaire will be successfully prosecuted throughout the enforcement chain and pay a fine. Hence, the low probabilities of capture at lower levels of rule-breaking behavior is consistent with empirical observations with respect to the low likelihood of a rule-breaker actually paying a fine (Brito and Barreto, 2004; Brito and Barreto, 2006). So, while it is unfortunate that an empirical estimated enforcement model is unavailable, the model presented here is a reasonable approximation.

Performance bonds

The use of performance bond mechanisms (also referred to as a forest guarantee bond) is often proposed as a royalty instrument and has been the subject of several studies (Boltz, 2003;

Boscolo and Vincent, 2000; Leruth et al., 2001; Paris et al., 1991; Sun, 1997), yet there is very little practical experience with performance bonds in tropical country concessions. In this study, concessionaires deposit a payment, denoted by the variable *bond* in this chapter, with the government before harvest. Upon execution of the harvest, concessionaires are refunded a quantity proportional to the satisfaction of required performance measurements. When ρ represents the proportion of the rules that have been followed, as measured by the illegality factor, x, the concessionaire will be reimbursed $\rho \times bond$. If rules have been found to be broken, the government will keep the residual to compensate for losses.

Economic Variables

As in the previous chapter, a constant real discount rate, r, of 9.75% was applied throughout the analysis within the discount function, $\delta = \frac{1}{1+r}$. For this analysis, the unit values of prices and costs are assumed to be fixed in real terms throughout the time horizon and are expressed throughout the study in US$2004. The price of a tree, p_{ij}, from species group i and size j is presented in Table 3-3. These values were calculated based upon the mill gate Free On Board prices in the Paragominas region, according to economic surveys of mill owners and operators (Lentini et al., 2005).

Management costs for Free On Board forest mill are classified as either variable or fixed costs and are drawn from Barreto et al. (1998) and Lentini et al. (2005). Variable costs of harvesting a tree in species group i and size j under harvest system s is represented by vc_{ijs} and includes the costs associated with felling, skidding and log deck operations, and transportation costs incurred relative to the level of harvest intensity and harvest system choice s. The costs are estimated based upon \$15.64/m^3 for the RIL logger and \$13.48/m^3 for the CL logger, and the per-tree costs are shown in Table 3-4. Fixed costs in \$/ha, represented by fc_s, are incurred regardless of harvest intensity at each cutting cycle entry for planning and capital costs as well as transaction costs and are estimated at \$50.56/ha for the RIL logger and \$13.91/ha for the CL logger. Because the terrain at the experimental forest of this study is relatively flat and did not include any slopes or stream buffer areas that firms are required to set aside as reserves, there is a risk that benefits of RIL will be over-stated because the estimated costs do not account for these factors (Putz et al., 2000). To reflect this possibility, additional scenarios are simulated reflecting a 50% increase in variable and fixed costs of implementing RIL. Additionally, the costs must be adjusted to account for partial RIL implementation using the interpolation technique:

$$vc_{ij\omega} = \omega vc_{ij1} + (1-\omega)\, vc_{ij2} \quad \forall i, j \tag{4-10}$$

$$fc_{\omega} = \omega fc_1 + (1-\omega)\, fc_2 \tag{4-11}$$

where costs indexed by 1 indicate costs of RIL operations and costs indexed by 2 indicate costs of CL operations.

In addition to fixed harvest and management plan costs, concessionaires will be expected to pay for the required independent audits. These audits will be performed by the Brazilian Program of Forest Certification (CERFLOR) under a set of technical standards developed by the Brazilian National Institute of Meteorology, Standardization, and Industrial Quality. While this system is endorsed by the Programme for the Endorsement of Forest Certification, Brazilian firms have significantly more experience under the Forest Stewardship Council certification system, so estimates of the costs concessionaires will bear for certification are drawn from FSC-certified operations which were certified by the Brazilian certifying organization, Instituto de

Manejo e Certificação Florestal e Agrícola (IMAFLORA). Certification costs, *cc*, for a large concession with more than 100,000 ha include \$0.46/ha upfront costs for the required preliminary evaluation and certifying evaluation (Mauricio de Almeida Voivodic, IMAFLORA, *personal communication*). These costs are charged at $t = 0$, then recur every five years. During the years between the larger-scale evaluations, the firm must pay \$0.30/ha for annual audits (Mauricio de Almeida Voivodic, IMAFLORA, *personal communication*). The net present value (NPV) of the certification costs over a 40-year concession agreement is estimated as \$2.10/ha.

In this model, the concessionaire will face a participation constraint in which the concessionaire will only bid a concession if the expected return is greater than or equal to alternative possibilities. It is assumed that the concessionaire's alternative opportunity is to perform forest exploitation on private lands. The average gross profitability of logging in private lands in the state of Pará has been estimated to range from 10 to 26% (Veríssimo et al., 2002b). In this analysis, a minimum acceptable gross profit level of 20% is assumed. When $E(\pi)$ represents expected profit and π^* represents the minimum acceptable gross profit, the participation constraint is expressed by:

$$E(\pi) \geq \pi^* \tag{4-12}$$

While this constraint will not affect the profit-maximizing concessionaire's marginal harvest decisions, identifying under what policies and royalty rates the constraint binds will help identify feasible policies.

Government Payments and Costs

Parallel to the concessionaire facing a participation constraint, the government will face a revenue constraint, in which expected revenues must meet the costs in establishing, administering, and enforcing the concession system. Expected government revenue, $E(R)$, is the sum of royalty payments, area fees, fines, and unreturned performance bonds. The fine is denominated by f, where $f = \$700/\text{ha}$ to reflect the maximum fine for deforestation and illegal logging under the Brazilian Environmental Crimes Law (Lei 9605/98).

The area fee is denoted by β. When α represents the percentage charge against marginal profit per legally harvested tree, the government revenue collected under the *ad valorem* royalty system is calculated by:

$$E(R) = \sum_{ij} \alpha\left(p_{ij}\overline{h}_{ij} - vc_{ij}\overline{h}_{ij}\right) + \beta + f\theta(x) + (1-\rho)bond \qquad (4\text{-}13)$$

When α represents the percentage charge against the price of a tree, government revenue collected under the revenue-based royalty rate is calculated by:

$$E(R) = \sum_{ij} \alpha p_{ij}\overline{h}_{ij} + \beta + f\theta(x) + (1-\rho)bond \qquad (4\text{-}14)$$

The government's establishment costs may include costs associate with the government performing forest inventories, preliminary studies, granting licenses, and conducting the proposal and auction processes. These types of costs will be location-specific and are likely to vary greatly. However, sufficient information exists to generate an approximation of the establishment costs. Inventories for private timber firms in the Brazilian Amazon cost \$13-\$17/ha (Sabogal et al., 2006). Making rough extrapolations for the other likely establishment costs components leads to an estimate of \$15-40/ha. In order to be conservative, the high end of this range (\$40/ha) was chosen for this study.

As is the case with establishment costs, very few data exist concerning the costs of concession administration and forest law enforcement in Brazil. For lack of an alternative figure, this study assumes that administrative costs from the government's perspective are equivalent to certification costs borne by the concessionaire, or \$2.10/ha. The costs associated with enforcing public forests management plans is assumed to be similar to the costs associated with enforcement in private lands. After modifying calculations in Hirakuri (2003), IBAMA's annual costs for post-harvest inspections and pre-harvest permitting and inspection for the subsequent harvest unit estimated at \$2.80/ha for a relatively large harvest unit of 1500 ha. Extrapolations based upon annual enforcement budgets reported in IBAMA technical reports (IBAMA, 2002) reveal similar figures.

The sum of establishment and enforcement costs forms the government budget constraint, $R^* = \$44.90/\text{ha}$. In the simulations where the constraint is applied, the sum of expected royalties, fines, and unreturned performance bonds must exceed R^*:

$$E(R) \geq R^* \tag{4-15}$$

In reality, the government costs might predominantly be incurred during earlier years of the concession's time horizon. In order to simplify the accounting within the model, however, the revenue constraint is applied each year equally.

Objective Functions under Imperfect Enforcement and Performance Bonds

When h_{ij} equals the entire harvest and $\overline{h}_{ij}$ equals the legal harvest from each species group i and size j, respectively, the expected profit, $E(\pi)$, from a single harvest of a representative hectare stand under the *ad valorem* royalty is written as:

$$\begin{aligned} E(\pi) = \sum_{ij} \Big((1 - waste_{\omega})\, p_{ij} h_{ij0} - \alpha \left(p_{ij}\overline{h}_{ij} - vc_{ij}\overline{h}_{ij} \right) - vc_{\omega} h_{ij} \Big) \\ - fc_{\omega} - cc - \beta - f\theta(x) - bond + \rho \times bond \end{aligned} \tag{4-16}$$

Expected profit under the revenue-based royalty is written as:

$$E(\pi)=\sum_{ij}\left(\left(1-waste_{\omega}\right)p_{ij}h_{ij0}-\alpha p_{ij}\bar{h}_{ij}-vc_{\omega}h_{ij}\right) \\ -fc_{\omega}-cc-\beta-f\theta(x)-bond+\rho\times bond \tag{4-17}$$

As in Boscolo and Vincent (2000), the sequential harvest problem assumes that the concession's cutting blocks are homogenous in space and economic factors are homogenous in time, implying that the concessionaire makes identical choices in each cutting block at each point in time. The expected net present value (NPV) over the time horizon, *T*, of the concession is equal to:

$$E(NPV)=E(\pi)+\delta E(\pi)+...+\delta^{T-1}E(\pi) \\ =E(\pi)\sum_{t=0}^{T-1}\delta^{t} \tag{4-18}$$

Because each cutting block is standardized to a single hectare, this formulation implies one representative hectare is logged each year. The size of the concession, then, is *T* hectares.

As discussed earlier, concessions are expected to undergo periodic independent audits (at least once every three years according to the PFML) as well as annual post-harvest inspections by IBAMA or the relevant state-level agency. In this study, if the concessionaire is caught violating the rules during an independent audit, the concessionaire will risk losing the concession. If the concessionaire fails an audit, the concessionaire will not be able to operate on the concession for the remainder of the time horizon of the contract. If the concessionaire is caught during an annual IBAMA inspection, the concessionaire simply risks paying a fine. Periodic audits and annual harvest inspections are assumed to share the same penalty function.

When enforcement pressure of this nature is introduced, it is necessary to consider the cumulative effects of the periodic audits. By assumption, the audits are performed independently, and the concessionaire does not know when the auditors will appear but has an expectation of the number of visits they will receive. Let Q equal the expected number of randomly-timed independent audits. Upon the first audit, given a harvest decision that the leads to the level of illegal behavior, x, the probability the concessionaire is caught-breaking the rules and losing the concession is given by $\theta(x)$. Because being caught breaking the rules during the second audit is dependent upon not getting caught during the first audit, the probability the concessionaire being caught breaking the rules during the second audit is given by $\theta(x)(1-\theta(x))$. The probability of being caught in the third audit is contingent upon not getting caught during the first two audits, $\theta(x)(1-\theta(x))^2$, and so on. Letting q index the individual audits, the probability of being caught breaking the rules across the time horizon of the contract given Q audits assumes the following negative binomial recursive structure:

$$\sum_{q=1}^{Q}\left(\theta(x)(1-\theta(x))^{q-1}\right) \tag{4-19}$$

Fully stated, the concessionaire's private sequential harvest problem under imperfect enforcement can be written as a function of not getting caught during a periodic audit:

$$\max_{\mathbf{h},\omega} E(NPV) = \left(1-\sum_{q=1}^{Q}\left(\theta(x)(1-\theta(x))^{q-1}\right)\right)\left(E(\pi)\sum_{t=0}^{T-1}\delta^{t}\right) \tag{4-20}$$

subject to:

$$\sum_{j=1}^{4} h_{ij} = 0 \tag{4-21}$$

$$\mathbf{h}-\mathbf{d}_{\omega}^{m} \leq \mathbf{y}_{\omega}^{m} \tag{4-22}$$

$$\mathbf{h} \geq 0 \tag{4-23}$$

$$\mathbf{y} = \mathbf{y}_{actual} \tag{4-24}$$

$$E(\pi) \geq \pi^* \tag{4-25}$$

$$E(R) \geq R^* \tag{4-26}$$

where Equation 4-21 is a merchantable size constraint, Equation 4-22 is a merchantable harvest constraint, Equation 4-23 is a non-negativity constraint, Equation 4-24 defines the initial condition of the stand, based upon the average condition of the study site, Equation 4-25 represents the concessionaire's participation constraint, and Equation 4-26 represents the government's budget constraint.

Under performance bonds, the concessionaire seeks to maximize the expected NPV but without the term accounting for periodic audit pressure:

$$\max_{\mathbf{h},\omega} E(NPV) = \left(E(\pi) \sum_{t=0}^{T-1} \delta^t \right) \tag{4-27}$$

The concessionaire under performance bonds also faces the same set of constraints, Equations 4-21 through 4-26.

Results and Discussion

Renewability Audits and Annual Harvest Inspections

Figure 4-2 shows how concessionaire behavior shifts as the number of audits per concession time horizon increases. In the results depicted in this figure, annual harvest inspections are performed under the threat of a \$700/ha fine. Additionally, a 20% *ad valorem* rate is charged against legally harvested trees in order to simulate the general case of value-added taxation in Brazil. As expected, for the given audit function, increasing the frequency of audits in addition to the performing annual harvest inspections decreases illegal activities, but high audit frequencies do not induce full compliance with the law. As audit pressure increases, illegal behavior decreases but gradually decreases into the region of the penalty function where the likelihood of being caught and punish is very low.

Concessionaire behavior with respect to audit pressure varies greatly when different RIL costs are considered. When the costs estimated from the study site are used within the simulations, the logger will fully implement RIL. This result is consistent with the findings earlier in this study and in Barreto et al. (1998) and Holmes et al. (2002). Meanwhile, the logger will illegally harvest timber, regardless of audit pressure. Increasing audit pressure has the strongest deterrent effect when the number of audits across the concession's time horizon increases from zero to one, dropping the illegal harvest from about 10 m^3/ha to about 6 m^3/ha. Meanwhile, increasing the number of audits above one has a more gradual effect on reducing illegal harvest. The PFML, for example, requires at least one independent audit every three years, which translates to about 14 audits over a typical 40-year concession contract. Given the parameters of this simulation, the logger under the legally required pressure would harvest 34.5 m^3/ha, which is 4.5 m^3/ha over the legal limit.

When the variable and fixed costs of RIL are increased by 50% in order to reflect the potential situation where RIL is more expensive than at the study site, the logger exhibits a very different behavior. At zero audit levels under the threat of the fine that arises from the annual harvest inspection, the logger chooses to harvest at the legal limit while shirking all RIL obligations. As audits increase, RIL adoption increases but full adoption is unlikely. Under the legally mandated 14 audits, RIL adoption would be just over 50% when RIL costs are high. At all audit frequencies, harvest volumes are within the legal limit.

In either case, the logger chooses to obey one set of rules, while breaking the rule that is most advantageous in that the rule-breaking provides the most benefit at the least risk of getting caught and losing the concession. While the results presented here are parameter-dependent simulations, the fact that concessionaire behavior varies dramatically as a function of RIL costs is indicative of policy complexity. Varying the costs of operating within the same forest can have very different outcomes. While the scenarios modeled show the concessionaire's shirking ignoring the harvest limit or shirking the RIL requirement exclusively, it is possible under different costs that both rules are broken simultaneously.

Performance Bonds

While increasing audit pressure incrementally reduces illegal activities, increasing the amount of performance bonds has threshold effects; the use of bonds has no effect until a critical value is achieved that causes rapid declines in illegal behavior. Figure 4-3 depicts the effects of increasing performance bonds on illegal harvest and RIL adoption. In this case, the annual harvest inspections and periodic audits are not in place in order to better compare the instruments. Absent inspections, audits, or a performance bond, the logger with RIL costs from the study site harvests all merchantable stock, while implementing RIL, the same result found in Chapter 3. As performance bonds increase from about $200/ha to $250/ha, the illegal harvest is eliminated. Bond amounts above $250/ha are, in this case, redundant.

When RIL costs are high and there is no enforcement or performance bond, the logger harvests the entire merchantable stock and fully implements conventional logging techniques. Bonds of about $150 to $190/ha are effective in inducing legal harvest volumes. Meanwhile, bonds up to about $230/ha are required to induce full RIL implementation. As in the case of the lower RIL costs, bonds above $240/ha are redundant.

Royalty Instruments

While the simulations were performed for the 40-year sequential harvest problem in order to evaluate the response to increasing periodic enforcement pressure, the general results will be presented based upon the per-hectare values associated with the optimal solution of the sequential harvest problem. The *ad valorem* and revenue-based royalty charges will be compared under imperfect enforcement and the performance bond scenarios. For the imperfect enforcement scenario, the total number of audits is set at 14 and the fine at $700/ha to approximate the general Brazilian enforcement and taxation context. The performance bond is set at $250/ha, which is the amount shown in Figure 4-3 to induce full compliance to harvest and RIL regulations.

***Ad valorem* royalty under audit pressure**

When the actual RIL costs are used under audit pressure, the government needs to apply a 5% *ad valorem* rate in order to satisfy the budget constraint, while a maximum rate of 66% feasibly satisfies the concessionaire's participation constraint (Table 4-1). As discussed earlier, the *ad valorem* royalty is typically non-distortionary. But, in the presence of illegal logging, increasing the rate induces slightly higher levels of illegal logging, as the incentive to log low-value timber illegally increases slightly as profits are reduced through the royalty policy. The effect is relatively mild, as illegal harvests increase 1.6 m^3/ha as the rate increases from its minimum to its maximum. Increasing the *ad valorem* rate additionally has no effect on the adoption of RIL; adoption is cost-effective across the feasible range of the rate.

The per-hectare profit decreases from $518/ha to $200/ha as the rate increases from 5 to 66% (Table 4-1). Revenues from illegal logging increases as illegal harvests increase, and this revenue at the high-end of the *ad valorem* rate is used to satisfy the participation constraint. This dynamic raises the issue that illegal logging is not simply induced by higher *ad valorem* rates, but is required, as the heavy royalty burden provides incentives for the logger to seek royalty-free income. Absent this ability, the logger will not participate in the concession.

Similar to the results shown in Figure 4-2, when variable and fixed RIL costs are increased 50%, the form of illegal behavior shifts from illegal harvest to shirking RIL requirements (Table 4-2). Increasing *ad valorem* rates slightly increases RIL adoption, a critical difference from the actual RIL cost case when increasing the rate induces higher illegal harvests. This effect reaffirms the earlier highlight that the royalty instruments might induce different behaviors from firms with different costs, even if the forest resource itself is the same across firms.

When RIL costs are high and the *ad valorem* rate nears the maximum feasible of 40% under the participation constraint, the concessionaire reduces harvests by over 50% (Table 4-2). Under the participation constraint and heavy royalty burden, the high cost logger is forced to harvest from only the most valuable species groups, as lower value species are no longer cost-effective to harvest, even illegally. Absent the participation constraint, the logger would likely maintain the harvest at the legal limit throughout the range of the *ad valorem* instrument.

The trade-off between increasing *ad valorem* rates and decreasing potential area fees is clear. At the high end of the feasible *ad valorem* rates, the potential to collect area fees reduces to zero (Tables 4-1 and 4-2). The optimal choice between applying a royalty-based strategy and a strategy based upon an area fee determined through a competitive or administrative process is crucial and is likely dependent upon the qualities and quantities of the forest resource, the characteristics of the logging firms, and regional institutional strength. This study of course assumes the harvest royalties applied to the legal harvest and the potential area fee are actually collected, which is another important factor to consider.

Revenue-based royalty under audit pressure

When actual RIL costs are used under audit pressure and increasing revenue-based royalty rates, illegal harvest rates rise slowly, as in the *ad valorem* (Table 4-3). The royalty instruments theoretical ability to reduce harvest rates as the rate increases is shown to be eliminated when the concessionaire who faces actual RIL costs can hide illegally harvested volumes. Meanwhile, when the concessionaire faces high RIL costs, the increasing royalty rate decreases harvest volumes as expected (Table 4-4). The results show the ability for the revenue-based instrument to influence marginal harvest rates is highly dependent upon RIL costs, a result again pointing at the contingent effectiveness of the royalty instruments to influence behavior.

The feasible range for the revenue-based instrument under audit pressure is smaller than the range for the *ad valorem* instrument. Under actual RIL costs, the feasible range is from 5 to 36%, while under high RIL costs, the feasible range is 5 to 26%.

As in the *ad valorem* instrument under actual RIL costs, RIL is fully adopted under the revenue-based instrument when the concessionaire faces actual costs (Table 4-3). However, under high RIL costs, RIL adoption decreases slightly as the revenue-based royalty rate rises.

***Ad valorem* royalty under performance bonds**

The behavior of the concessionaire under performance bonds and *ad valorem* royalties is very different than the behavior of the concessionaire under audit pressure. While Figure 4-3 showed the effectiveness of high performance bonds in inducing regulatory compliance, a background *ad valorem* rate of 20% was applied to reflect the general case of forest taxation in Brazil. In Table 4-5, it is evident that increasing the *ad valorem* rate above 20% has no effect on harvest behavior until the rate binds the participation constraint. At that point, as the concessionaire loses income to royalties, it becomes increasingly attractive to log illegally and shirk royalties. Meanwhile, RIL adoption for the logger facing actual RIL costs remains full across the feasible range of the *ad valorem* instrument, 8 to 54%.

Meanwhile, when RIL costs are high, the performance bond is sufficient to induce legal harvests throughout full adoption the feasible range of the *ad valorem* instrument, 8 to 30% (Table 4-6). However, while rates of up to 20% induce harvests at the legal limit, RIL implementation is about 90%. Increasing the *ad valorem* rates beyond 20% reduces harvests to about 24 m^3/ha, while inducing full implementation of RIL. Again, the effectiveness of any given instrument is dependent upon costs and the rate at which the instrument is set.

Revenue-based royalty under performance bonds

The combined use of performance bonds and the revenue-based instrument appears relatively robust. Under actual RIL costs, rates across the feasible range of 5 to 35% induce full RIL adoption. However, as the rate is increased to the point of binding the participation constraint, harvest falls below the legal minimum, again highlighting the sensitivity of logging to the rate of the royalty instrument. When RIL costs are high, the revenue-based royalty has a relatively small feasible range, from 9 to 19% (Table 4-8). Harvest volumes are low under this instrument and high costs. At the low to middle-range of the rate, harvest volumes stand at 23 m^3/ha. At very high royalty rates, harvests fall to 12 m^3/ha.

Issues with differentiated royalties

In principle, a royalty system such as the revenue-based scheme discussed can be designed such that the rate charged is differentiated by species, size, quality, or site. This much discussed advantage changes the relative price of each tree, which can modify harvest behavior at the margin. In practice in tropical forests, however, because of the large number of timber species and administrative inadequacies and corruption, these royalties have proven difficult to administer and collect.

An added complexity little discussed in the literature is the fact that timber prices and harvest costs are very heterogeneous. The relative profit margin for any given tree species is likely to differ across regions or even firms. A set of royalty rates which is well-calibrated to induce a desirable harvest distribution from a firm with a particular cost function may not function well if applied to another firm operating in the same forest or the same firm operating in another region.

For example, one possible desirable and relatively simple harvest distribution might be that all harvested trees are drawn from each species group in equal proportion, rather than extracting trees in descending order of their value until relevant constraints bind. Experimentation with a range of revenue-based royalty rates under imperfect enforcement and performance bonds with actual and high RIL costs showed that it is unlikely to find a set of differentiated royalty rates that could induce this desired distribution of the harvest across species groups while satisfying the revenue and participation constraints.

Performance Bonds and Firm Size

In an effort to improve the distribution of forest concessions across firm size and prevent domination by larger-scale industrial forest products firms, the PFML imposes requirements to allocate forest concessions across small (< 10,000 ha), medium (10-40,000 ha), and large concessions (40-200,000 ha). It can be expected that firms along the continuum of firm size will have differing capacities to pay performance bonds. For example, the larger, well-capitalized timber firms operating in the Brazilian Amazon, which are typically certified and export a large proportion of their production, are likely to have the upfront capacity to pay performance bonds. Meanwhile, smaller firm and community forestry operations that are expected to bid for the smaller concessions are likely to perform relatively low intensity and impact harvests, often in collaboration with a nongovernmental organization. These operations are likely to pursue socio-environmental goals rather than maximize harvests. As such, the smaller operation may not need to provide strong environmental performance assurances.

Meanwhile, mid-sized firms on the economic margin supply a large quantity of the timber in the Brazilian Amazon (Merry and Amacher 2005). In addition to competing with timber from large firms operating on private lands and forest concessions, these firms compete intensely against the large supply of low-cost timber from legal deforestation headed for the domestic market (Merry and Amacher 2005). For this group, requiring the payment of performance bonds and the performance of what might be relatively high cost management activities may create a crippling entry barrier to participation in the concession system. While the performance bonds may be an effective instrument to guarantee the performance of these firms, the Brazilian government should consider a phased or firm-by-firm bond system in order to maximize the equitable access to concessions across firm size.

A Note on Market-based Enforcement Efforts

This study focuses on a small set of state-centered mechanisms to induce regulatory compliance to the exclusion of non-state mechanisms such as forest certification. The enforcement within this study also emphasizes the state's role in monitoring operations within the forest, rather than at mills, along roads, or at the ultimate destination of the timber, predominantly large domestic and international cities. Driven by the increasing leverage of consumer interest groups, nongovernmental environmental organizations, and improvements in monitoring technology such as publicly accessible remote sensing imagery, a broader portfolio of enforcement measures is emerging in the Brazilian Amazon and, indeed, most forested countries of the world (Kramme and Price, 2005). A state seeking to optimize the allocation of enforcement resources will consider a range of instruments including partnerships with nongovernmental sectors. Future research in this area should incorporate these potentially more effective mechanisms.

Conclusion

In this chapter, a sequential harvest model was developed to evaluate the response of a representative concessionaire to royalty instruments under imperfect enforcement and performance bonds when there are incentives to harvest timber volumes over the legal limit and shirk RIL requirements. The model was developed in the form of a classic principal agent problem in which the government is revenue-constrained and the concessionaire faces a participation constraint. The results show that each instrument has strengths and weaknesses that are contingent upon the costs firms face to implement RIL.

In a weak enforcement environment, the results show that audit pressure is unlikely to induce full compliance with harvest regulations. Under clear incentives for harvesting over the legal limit, it is possible to maintain low-levels of illegal behavior hidden from regulators. It is critical to develop human technical capacity to register and punish low-level illegal activities. In Brazil, the combined pressure of independent audits and remote sensing of harvest-related forest damage should help ameliorate this problem, assuming the performance of the judicial system improves along with audit capacity.

As found in Boltz (2003), Boscolo and Vincent (2000), Leruth et al. (2001), and Paris et al. (1991), the effectiveness of performance bonds is attractive. In an environment with corruption and an inefficient or ineffective legal environment, the payment sequence affords a strong information advantage. In the enforcement case, a citation may take years to process and fines may never be paid. In the bond case, the preventive fine is paid at the outset. The relative efficiency of the bond instrument over traditional enforcement will arise from the efficiency of the government to evaluate logger performance and return the appropriate proportion of the bond. In Brazil, where loggers' trust in government officials is low (Merry and Amacher, 2005), the logger may be reluctant to contract under performance bonds fearing that the same inefficiencies and corruption might pervade the system as in the traditional enforcement system.

With respect to the potential advantage of performance bonds, as with all things in political economy, the development of credible institutions matter.

The use of traditional royalty instruments such as the *ad valorem* and revenue-based royalty can effectively generate revenues and, in the case of revenue-based instruments, modify harvest behavior, but only under very limited circumstances. When simple but critical variables change, such as the costs to implement RIL, the outcomes under the same instrument can vary dramatically. In this model, the concessionaire is able to shift to harvest volumes over the legal limit when the royalty rate becomes too high.

Meanwhile, if enforcement or bonds are effectively inducing overall compliance with rules, the concessionaire's participation constraint can hinder the effectiveness of the instruments to modify harvest behavior in ways that might better protect future resource and reduce externalities. Recalling the harvests determined under the sustainability constraints in Chapter 3, the royalty instruments applied here are unlikely to induce the harvests required for sustaining timber inventories at the stand and species-group level. In terms of capturing forest rent, these results appear to favor market-determined payments for harvest rights combined with more effective enforcement to induce desired harvest volumes.

As the Brazilian experience with forest concessions is only beginning, there are ample opportunities to extend this research as data from new concessions accumulates. A primary need is to develop an empirically-based penalty function that more effectively models enforcement success as a function of enforcement effort and concessionaire behavior. Also, as more concessions are implemented, it is important to continuously collect quality data on government costs. A recurrent problem identified in the concession economics literature is that the government can become rent-seeking, attempting to increase government receipts by lowering royalty rates and expanding the land base under logging concessions. More empirical evidence is required to evaluate and mitigate this risk. Finally, inasmuch as this model can be used to provide guidance for revenue and regulatory decisions, it is important to calibrate the model using a range of forest sites under different economic conditions.

Table 4-1. Results under imperfect enforcement (audits = 14 and fine = $700/ha) and *ad valorem* royalties (actual RIL costs)

Ad valorem rate (%)	Harvest (m^3/ha)	RIL adoption (%)	Profit ($/ha)	Illegal revenues ($/ha)	Royalties ($/ha)	Excess profits ($/ha)
5*	34.2	100.0	518.4	143.1	53.1	390.1
10	34.3	100.0	512.7	145.0	59.2	383.0
20	34.5	100.0	455.4	151.3	118.0	313.2
30	34.7	100.0	398.4	157.8	176.5	243.9
40	34.9	100.0	341.7	164.5	234.6	174.9
50	35.1	100.0	285.5	171.6	292.3	106.4
60	35.3	100.0	229.8	179.3	349.6	38.4
66**	35.8	100.0	199.6	193.0	382.2	0.0

Notes: * Minimum rate feasible under revenue constraint. **Maximum rate feasible under participation constraint.

Table 4-2. Results under imperfect enforcement (audits = 14 and fine = $700/ha) and *ad valorem* royalties (high RIL costs)

Ad valorem rate (%)	Harvest (m^3/ha)	RIL adoption (%)	Profit ($/ha)	Illegal revenues ($/ha)	Royalties ($/ha)	Excess profits ($/ha)
9*	30.0	56.5	276.5	0.0	46.8	142.0
10	30.0	56.5	271.3	0.0	52.0	135.7
20	30.0	56.5	219.3	0.0	103.9	73.4
30	30.0	56.5	167.4	0.0	155.9	11.0
40**	14.4	58.7	98.0	0.0	158.1	0.0

Notes: * Minimum rate feasible under revenue constraint. **Maximum rate feasible under participation constraint.

Table 4-3. Results under imperfect enforcement (audits = 14 and fine = $700/ha) and revenue-based royalties (actual RIL costs)

Revenue-based rate (%)	Harvest (m^3/ha)	RIL adoption (%)	Profit ($/ha)	Illegal revenues ($/ha)	Royalties ($/ha)	Excess profits ($/ha)
5*	34.2	100.0	518.4	143.1	53.1	390.1
10	34.4	100.0	466.5	147.8	106.0	327.2
20	34.7	100.0	363.4	157.8	211.5	201.9
30	35.0	100.0	261.1	169.5	316.3	77.4
36**	35.3	100.0	200.4	177.8	378.8	3.2

Notes: * Minimum rate feasible under revenue constraint. **Maximum rate feasible under participation constraint.

Table 4-4. Results under imperfect enforcement (audits = 14 and fine = $700/ha) and revenue-based royalties (high RIL costs)

Revenue-based rate (%)	Harvest (m^3/ha)	RIL adoption (%)	Profit ($/ha)	Illegal revenues ($/ha)	Royalties ($/ha)	Excess profits ($/ha)
5*	30.0	53.8	272.2	0.0	54.7	137.9
10	30.0	53.8	217.5	0.0	109.3	72.3
20	19.7	51.6	127.2	0.0	165.4	10.7
26**	11.0	44.9	78.3	0.0	144.6	0.0

Notes: * Minimum rate feasible under revenue constraint. **Maximum rate feasible under participation constraint.

Table 4-5. Results under performance bonds (*bond* = $250/ha) and *ad valorem* royalties (actual RIL costs)

Ad valorem rate (%)	Harvest (m^3/ha)	RIL adoption (%)	Profit ($/ha)	Illegal revenues ($/ha)	Royalties ($/ha)	Excess profits ($/ha)
8*	30.0	100.0	473.6	0.0	49.7	359.3
10	30.0	100.0	461.2	0.0	62.2	344.4
20	30.0	100.0	399.0	0.0	124.3	269.8
30	30.0	100.0	336.9	0.0	186.5	195.2
40	30.0	100.0	274.7	0.0	248.7	120.6
50	30.0	100.0	212.6	0.0	310.8	46.0
54*	36.5	100.0	202.7	0.0	315.1	0.0

Notes: * Minimum rate feasible under revenue constraint. **Maximum rate feasible under participation constraint.

Table 4-6. Results under performance bonds (*bond* = $250/ha) and *ad valorem* royalties (high RIL costs)

Ad valorem rate (%)	Harvest (m^3/ha)	RIL adoption (%)	Profit ($/ha)	Illegal revenues ($/ha)	Royalties ($/ha)	Excess profits ($/ha)
8*	30.0	89.8	232.3	0.0	33.5	74.0
10	30.0	89.8	223.9	0.0	41.9	64.0
20	30.0	89.8	181.9	0.0	83.9	13.7
30**	23.7	100.0	149.7	0.0	114.4	0.0

Notes: * Minimum rate feasible under revenue constraint. **Maximum rate feasible under participation constraint.

Table 4-7. Results under performance bonds (*bond* = $250/ha) and revenue-based royalties (actual RIL costs)

Revenue-based rate (%)	Harvest (m^3/ha)	RIL adoption (%)	Profit ($/ha)	Illegal revenues ($/ha)	Royalties ($/ha)	Excess profits ($/ha)
5*	30.0	100.0	474.5	0.0	54.9	359.2
10	30.0	100.0	419.6	0.0	109.7	293.4
20	30.0	100.0	309.9	0.0	219.4	161.7
30	30.0	100.0	200.2	0.0	329.1	30.1
35**	22.8	100.0	145.9	0.0	319.9	0.0

Notes: * Minimum rate feasible under revenue constraint. **Maximum rate feasible under participation constraint.

Table 4-8. Results under performance bonds (*bond* = $250/ha) and revenue-based royalties (high RIL costs)

Revenue-based rate (%)	Harvest (m^3/ha)	RIL adoption (%)	Profit ($/ha)	Illegal revenues ($/ha)	Royalties ($/ha)	Excess profits ($/ha)
9*	23.4	100.0	179.9	0.0	83.6	37.9
10	23.4	100.0	170.6	0.0	92.8	26.8
19*	12.2	100.0	95.5	0.0	113.6	0.0

Notes: * Minimum rate feasible under revenue constraint. **Maximum rate feasible under participation constraint.

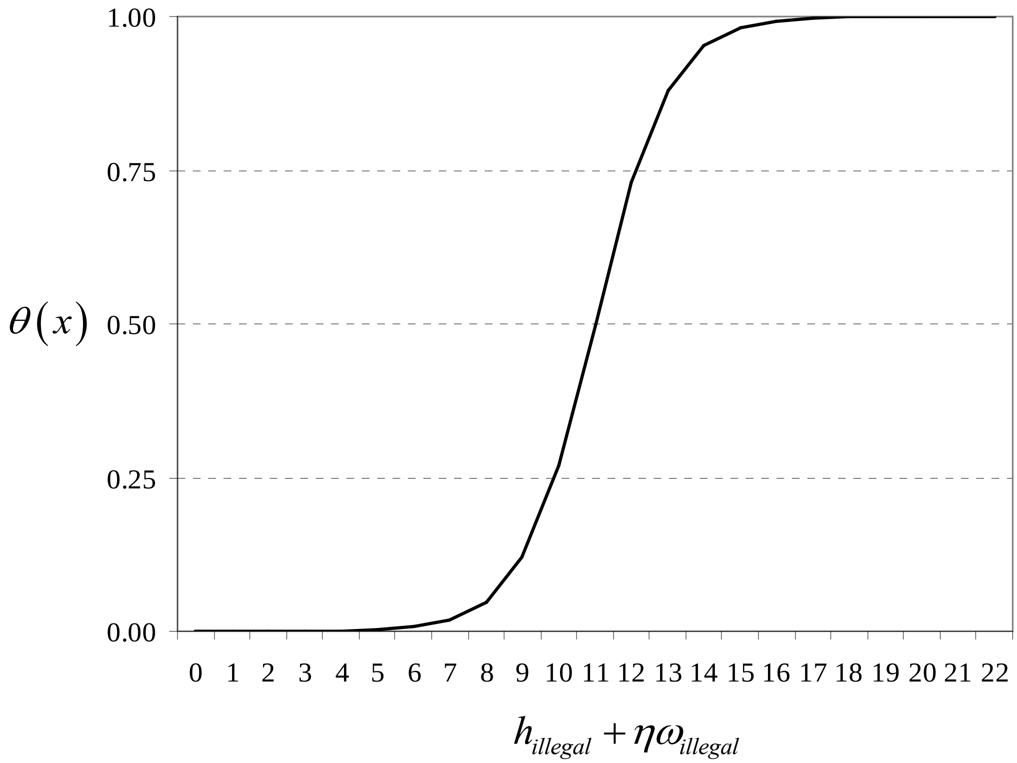
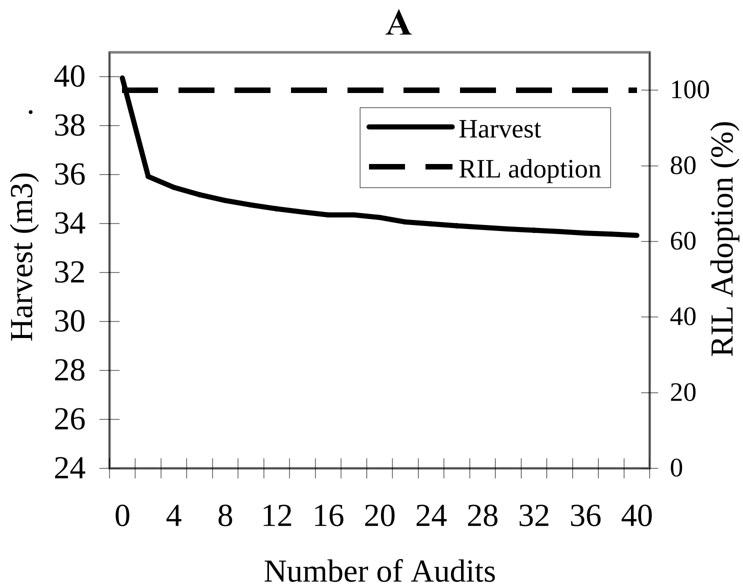


Figure 4-1. Probability of being caught breaking laws and paying fine as an increasing function of illegal behavior



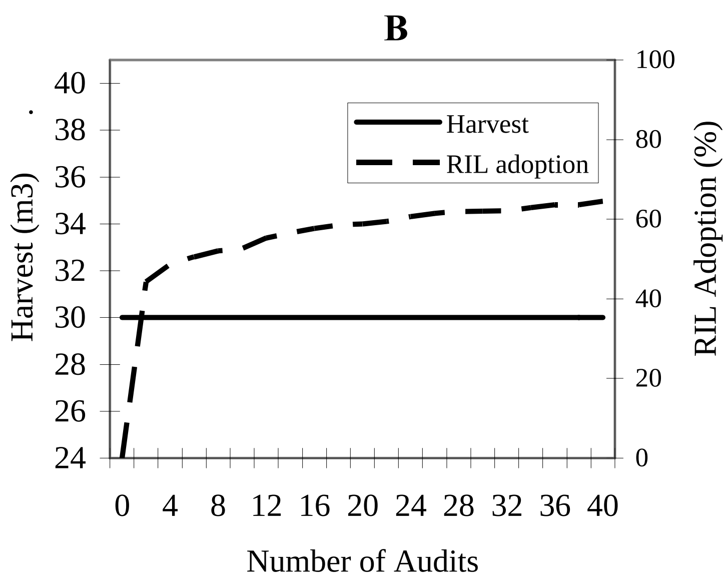
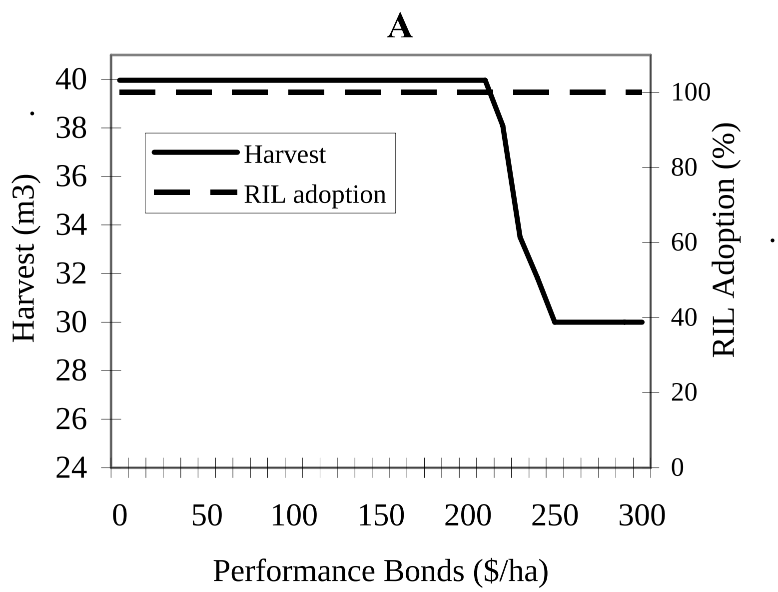


Figure 4-2. Effect of increasing number of periodic audits. A) Actual RIL costs. B). High RIL costs.



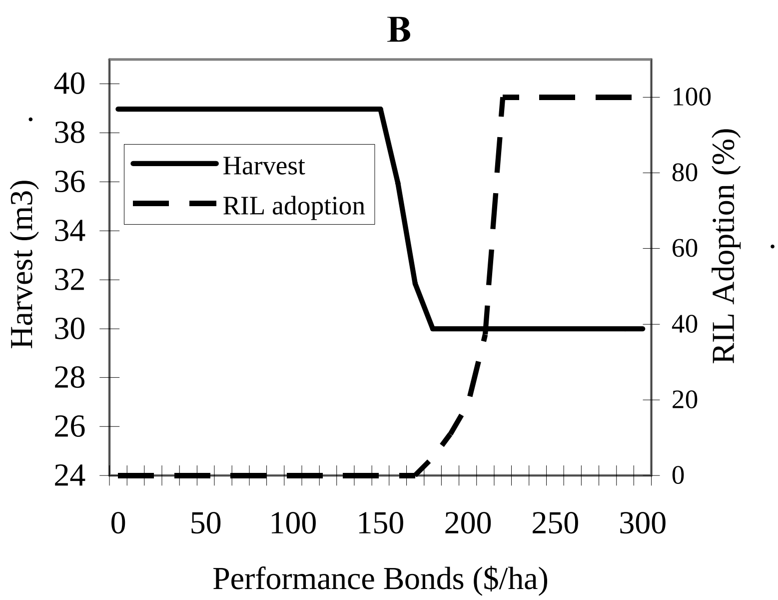


Figure 4-3. Effect of increasing performance bonds. A) Actual RIL costs. B). High RIL costs.

CHAPTER 5
CONCLUSIONS

Findings and Methodological Advances

This study used data from one of the longer running tropical forest experiments in the Eastern Brazilian Amazon region to develop a growth and yield matrix model based upon transition parameters estimated using a multinomial logit discrete choice model. This model is intended to advance the use of matrix models to study tropical forest management by, first, improving the capacity of the model to capture the dynamic effects of harvest on forest structure and composition; and, second, by endogenizing the choice of harvest system that allows the manager to best meet objectives.

The growth and yield model was embedded within a dynamic forest management model in order to quantitatively analyze the dynamic cost-effectiveness of reduced impact logging (RIL) and sustainable yield constraints. Two new operational mathematical definitions for total volume and species-level sustainability were proposed. These definitions of sustainability focus on sustaining standing timber inventories across cutting cycle entries, rather than on sustaining harvest yields, as is typically the case. The results of this study were mixed. While it is shown that RIL is cost-effective to implement, the bulk of the financial gains are due to harvest planning improvements over conventional techniques, rather than through protection of the forest resource. RIL is shown to marginally increase the volumes of merchantable timber available in future harvests, but does not significantly change what is now well-known about logged forests; the structure and composition of the managed forests will be different than that of the primary forest. Perhaps silvicultural techniques in addition to continued development of improved logging techniques will mitigate this effect in the future. However, given the likelihood that certain RIL practices may be more financially beneficial than others, such as testing hollows or reducing wood waste and skidder-time in the forest, there is the possibility that RIL may more often be partially implemented, as managers determine the relative costs and benefits of shirking certain cost-ineffective activities.

While volumes of merchantable timber predicted to be available for the second and third harvests are significantly lower than the available timber in the primary forests, the second and third harvests are projected to be profitable and appear to have the potential for sustainability at the stand-level. The Weakly Sustainable Inventory (WSI) scenario showed that stand-level sustainability is likely to be possible at lower volumes and lower economic value, but that sustainable management by the criteria driving that scenario is viable. The harvests under the Strongly Sustainable Inventory (SSI) scenario were profitable, but at the expense of harvesting very little of the most valuable timber. While profitable, the WSI and SSI scenarios leave valuable timber standing, creating strong incentives for timber trespass.

The fourth chapter developed a sequential harvest model in order to evaluate the response of a representative concessionaire to royalty instruments under imperfect enforcement and performance bonds when there are incentives to harvest illegal volumes of timber and shirk RIL requirements. The model was developed in the form of a classic principal agent problem, in which the government is revenue-constrained and the concessionaire faces a participation constraint. The results show that each instrument has strengths and weakness that are contingent upon the costs firms face to implement RIL.

In a weak enforcement environment, the results show that audit pressure is unlikely to induce full compliance with harvest regulations. Under clear incentives for illegal logging, it is possible to maintain low-levels of illegal behavior hidden from regulators. Meanwhile, the effectiveness of performance bonds is attractive. However, as with all policy instruments, the development of credible institutions matters.

The use of traditional royalty instruments such as the *ad valorem* and revenue-based royalty can effectively generate revenues and, in the case of revenue-based instruments, modify harvest behavior, but only under very limited circumstances. When simple but critical variables change, such as the costs to implement RIL in this study, the outcomes under the same instrument can vary dramatically. In this model, the concessionaire is able to shift to illegal harvests when the royalty rate reduces profit rates to near the participation constraint.

Meanwhile, if enforcement or bonds are effectively inducing overall compliance with rules, the concessionaire's participation constraint can hinder the effectiveness of the instruments to modify harvest behavior in ways that might better protect future resource values and reduce externalities. Recalling the sustainability-constrained harvests of Chapter 3, the royalty instruments applied here are unlikely to induce the harvest required for sustainability. In terms of capturing forest rent, these results appear to favor market-determined payments for harvest rights combined with more effective enforcement to induce desired harvest volumes and distributions across species and sizes.

While this study is performed with the intent to provide analytical support to public forest planning, there is no reason that the results should apply exclusively to public lands. Many results may apply to private lands equally, although the policy implications may differ across tenures, depending on over-arching management objectives for the different lands and public preferences for goods and services delivered from public lands. That said, perhaps one the most important implication of the results, which is not original to this study (see e.g. Karsenty and Gourlet-Floury, 2006, and Van Gardingen 2006), is that the public, forest sector, decisionmakers, and other stakeholders such as non-governmental organizations and certifying bodies should reflect and revise their visions for the likely financial and ecological outcomes of multi-cyclic management of natural forests in the Eastern Amazon region.

The analysis in this study has shown that the restricted harvests which are required to sustain timber volumes or to simply follow current rules present opportunity costs. These assertions beg the questions, however, of who bears these costs, and what are the available mechanisms to compensate for these costs? In a simple analysis, the concessionaire will face significantly lower profit margins if they follow sustainability guidelines. However, as the results under imperfect command and control enforcement show, the concessionaire may break the rules to satisfy the participation constraint. Subsidies through environmental management incentives or low cost harvest rights might be directed toward private firms to compensate for the opportunity costs, but this raises the possibility of perhaps unfairly shifting the burden of from the private agent to the public, which may not be welfare enhancing. Under the current language of the Public Forests Management Law (PFML), should markets for environmental services arise in the future, concessionaires have no right to receive compensation for these services in the same manner concessionaires have no claim to mineral rights that may underlie the forest concession. Even if the law is rewritten to allow such transfers, the specter of private appropriation of public resources is still present, as concessionaires are simply leaseholders of harvest and management rights on public lands.

The potential solutions to these issues are probably not found at the level of individual concessions, but, rather, at the regional-level, where harvests of public forestlands should be a component of larger economic development policies that include interactions with private sector logging, particularly logging on smallholder properties. Much will depend upon how nature's immense natural capital is converted into regional development through direct and indirect employment and the redistribution of royalties and fees. For example, how would forest sector employment and the regional economy through the multiplier effect be changed if the Brazilian government committed to the reduced but sustainable RIL harvests discussed in Chapter 3? Incentives and control measures should be developed that facilitate the sustainable multiple use of public forests, while contributing effectively to regional development, without crowding out smallholder activities which may be more welfare enhancing and less destructive of natural resources. Further research in this area would help elucidate the costs and benefits of a wide range of policy choices.

Data Limitations

As with any study, there are limitations to the model that future efforts may address. The linear treatment of harvest costs in this model can be improved significantly. For example, Bauch et al. (2007) present a Cobb-Douglas harvest costs model based upon data collected from a large survey within the Brazilian Amazon that potentially could be used to more accurately reflect nonlinear variable harvest costs, but the sample from which the model was estimated included few RIL operators, making it difficult to implement well within this study.

Another crucial need is to develop an empirically-based penalty function that more effectively models enforcement success as a function of enforcement effort and concessionaire behavior. This requires audit by audit data collection, including information on enforcement inputs, such as expenditures and personnel required per audit, as well as outcomes, such as audit findings and results of any proceedings against the concessionaire should rule-breaking be identified.

Also, as more concessions are implemented, it is important to continuously collect quality data on government costs. A recurrent problem identified in the concession economics literature is that the government can become rent-seeking, attempting to increase government receipts by lowering royalty rates and expanding the land base under logging concessions. More empirical evidence is required to evaluate and mitigate this risk on an ongoing basis.

As the Brazilian experience with forest concessions is only beginning, there are ample opportunities to extend this research as data from new concessions accumulates. This data need highlights an important policy recommendation that the Brazilian government rapidly establish a forest sector social science data collection and research capacity within the new Serviço Florestal Brasileiro. Because a large portion of current Amazon region research capacity resides within nongovernmental research institutes, strategic partnerships should be further strengthened in order to start building long-term datasets on fundamental economic variables, such as harvest volumes, prices, costs, and enforcement effectiveness, from both the private and government perspectives.

Future Extensions of the Model

The models developed within this study can be extended to address many issues. Several possible extensions are highly relevant to current policy debates. First, the model can be extended to the landscape-scale for regional planning purposes. Under PFML, the Brazilian government, with assistance from nongovernmental research institutes, is actively planning the expansion of the state and national forest systems. Each forest will contain a mosaic of land uses, designed to meet multiple social, economic, and ecological objectives. Some objectives will be complementary; other objectives will conflict. Given this complexity, it is important to develop tools to aid decision-makers and stakeholders to envision alternative landscape visions. One tool being developed is a forest-level optimization model that integrates geographic information systems and mathematical programming techniques to design “optimal” landscapes according to the objectives being sought (Lentini, 2007). For example, a landscape that meets goals for timber harvesting, community reserves, and biodiversity areas can be designed. The model developed in this study can introduce a dynamic element to this planning tool. Simple dynamic rules can be generated that connect present and future harvests in order to better plan timber production on public forests over long time horizons. Given the evidence in this study and other similar studies that timber harvests under current rules and best logging practices are unlikely to be sustainable, it is important to incorporate these dynamic decision rules to help decisionmakers avoid the unintended consequence of planning a status quo, boom-bust timber economy in and around public forests.

In a second extension, the model can be adapted to incorporate non-timber forest products and services, such as carbon sequestration. Recent Kyoto Protocol negotiations have looked more favorably upon forested developing countries to include averted deforestation, or compensated reduction, into the Protocol (Gullison et al., 2007). The central idea of compensated reduction is that countries can chose to reduce national deforestation levels below historical levels and receive payments upon accomplishing targeted reductions, which would create significant incentives to reduce deforestation (Santilli et al., 2005). Under particular proposals, the incentives are directed toward decreases in overall deforestation rates, not toward particular projects, freeing governments to seek the gains with the lowest marginal costs. Given that the establishment of state and national forests is a significant component of the Brazilian national strategy, and that the carbon sequestration benefits of reduced impact logging have been demonstrated (Boscolo et al., 1997; Boscolo and Buongiorno, 1997; Pinard and Putz, 1996; Putz and Pinard, 1993; Smith and Applegate, 2004) resources could be directed at securing and improving long-term management of public production forests. Given this discussion, the market value of carbon under a range of price scenarios can be introduced to the model to represent society’s interest capturing global resources in order to sustain flows of critical ecosystem services from managed forests. A social planner’s solution, which values carbon sequestration, can be compared to the private solutions found in this study to estimate the benefits and costs of different policies under Kyoto.

Third, the model can be used to evaluate additional critical issues in tropical forest management. For example, the model can be used to better understand how exploiting lesser-known timber species can affect the viability of forest management in the future, an issue of critical importance but virtually unstudied using empirical data. As discussed earlier, the Paragominas region of this study was central to the Eastern Amazon logging boom during the 1970s and 1980s. The commercial species list in this region is extensive as mill operators have had sufficient time to develop markets and learn the milling requirements of various species, particular as many of the forests of the region have been reentered and logged haphazardly for smaller-diameter trees and trees of lesser-known species before land conversion. A good exercise would be to, in a sense, step back in time in an effort to mimic the economic conditions within areas along current logging frontiers where only the species of highest value are currently profitable. Within this context, the benefits of implementing RIL practices to protect future harvests is likely to be more pronounced than in this study.

Another possibility is that the model can be used to examine the specific costs and benefits of RIL practices in order to identify specific practices which are likely to be ignored or practiced incompletely. This study could be of benefit to regulators and certifiers who are responsible for ensuring private agents are implementing best practice logging and forest management.

Experimentation and Adaptiveness

In the Brazilian Amazon, deforestation and forest degradation continues at a strong pace. The forces that drive deforestation and degradation will remain in place for the foreseeable future. In many ways, Brazil is in the midst of an historical moment in the history of its forests. The Atlantic Forest, once close to disappearing is beginning to rebound, and much of the Brazilian Amazon still remains. The ratification of the PFML is just one of Brazilian society's many efforts to sustain the country's great forests for future generations.

While events move rapidly and there seems to be little time to save the forests, there is ample space for policy experimentation under the new law. Rather than muddle through with incremental changes to one-size-fits-all policy, policy experimentation can be performed. The experiments (or quasi-experiments) can be formally designed to elicit scientific information about the impacts of certain policies, programs, or procedures. Ferraro and Pattanayak (2006) write that it is important to test hypothesis about programs intended to protect biodiversity in the same way that hypotheses are tested in the ecological sciences. Formal program evaluation enables the estimation of the causal effect of interventions on outcomes (Ferraro and Pattanayak, 2006).

Concessions will be allocated on a case-by-case basis. Additionally, in any given state or national forest, multiple concessions are likely to be allocated. This raises the possibility of structuring learning experiments by varying the "treatments" received by the concessionaires. For example, the performance bond mechanism could be varied across pairs of logging firms in operating in sufficiently similar environments. Another possibility would be to vary the auction process itself, comparing behavior around bid systems or reservation prices. Concessionaire response to varying logging rules could be also be examined. In short, many possibilities exist for strengthening the learning process.

Beyond formal experiments, policy and critical administrative rulings need to be adaptive to the wide range of conditions that exist in the region. The policies and rules should also be adaptive to emergent influences and new information within the forest sector across sectors of the Brazilian and international economies. The National Forestry Development Fund (Fundo Nacional de Desenvolvimento Florestal) established by the PMFL can play a critical role in funding applied research that informs the dynamic course of concession policy and administration.

APPENDIX A
FAZENDA SETE SPECIES LIST, GROUPS, AND PRICES

Table A-1. Species groups, scientific names, common names, and economic value class (stems/ha)

			Price-class				
Species Group	Scientific name	Common name	No value	Low value	Med. Value	High value	Total
Pioneer							
	Apeiba burchelli	Pente de macaco sulcado	2.0	0.0	0.0	0.0	2.0
	Apeiba echinata	Pente de macaco serrado	1.5	0.0	0.0	0.0	1.5
	Apeiba sp	Pente de macaco	0.3	0.0	0.0	0.0	0.3
	Bagassa guianensis	Tatajuba	0.0	0.0	0.3	0.0	0.3
	Bellucia grossularioides	Goiaba de anta	0.3	0.0	0.0	0.0	0.3
	Bixa arborea	Urucum da mata	0.1	0.0	0.0	0.0	0.1
	Cecropia obtusa	Imbaúba branca	0.7	0.0	0.0	0.0	0.7
	Cecropia sciadophylla	Embaúba	6.7	0.0	0.0	0.0	6.7
	Eugenia heterochroma	Goiabinha	0.9	0.0	0.0	0.0	0.9
	Jacaranda copaia	Para-para	0.0	1.4	0.0	0.0	1.4
	Jacaratia espinosa	Mamuí	0.3	0.0	0.0	0.0	0.3
	Laetia procera	Pau jacare	0.0	5.0	0.0	0.0	5.0
	Pouroma guianensis	Mapatirana	3.3	0.0	0.0	0.0	3.3
	Pourouma minor	Embaúba torém	0.1	0.0	0.0	0.0	0.1
	Scheffera morototoni	Morototó	0.0	1.0	0.0	0.0	1.0
	Shichozolobium amazonicum	Paricá	0.0	0.1	0.0	0.0	0.1
	Sloanea obtusa	Urucurana	0.6	0.0	0.0	0.0	0.6
	Vismia guianensis	Lacre	1.0	0.0	0.0	0.0	1.0
	Zanthoxylum rhoifolia	Limãozinho/ Tamanqueira	2.7	0.0	0.0	0.0	2.7
	Not identified	Imbaúba vermelha	0.1	0.0	0.0	0.0	0.1
	Not identified	Pau de gafanhoto	1.2	0.0	0.0	0.0	1.2
Pioneer total			21.8	7.5	0.3	0.0	29.6

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class No value	Low value	Med. Value	High value	Total
Light-demanding							
	Allophylus robustus	Espeturana trifoliar	0.1	0.0	0.0	0.0	0.1
	Balizia pedicellaris	Mapucuxi vermelho	0.1	0.0	0.0	0.0	0.1
	Bombax paraensis	Mamorana terra firme	0.1	0.0	0.0	0.0	0.1
	Byrsonima aerugo	Murucí	0.3	0.0	0.0	0.0	0.3
	Caraipa grandifolia	Louro tamaquaré	0.0	1.4	0.0	0.0	1.4
	Casearia arborea	Casiaria arboria	0.1	0.0	0.0	0.0	0.1
	Cordia bicolor	Freijo branco	0.0	9.2	0.0	0.0	9.2
	Cordia scabrida	Freijozinho	1.3	0.0	0.0	0.0	1.3
	Enterolobium maximum	Orelha de macaco	0.0	0.1	0.0	0.0	0.1
	Eriotheca globosa	Mamorana	0.6	0.0	0.0	0.0	0.6
	Inga alba	Inga vermelha	0.0	0.2	0.0	0.0	0.2
	Inga capitata	Inga	0.5	0.0	0.0	0.0	0.5
	Inga cylindrica	Ingá branca	36.5	0.0	0.0	0.0	36.5
	Inga pezizifera	Ingá cilíndrica	0.1	0.0	0.0	0.0	0.1
	Inga dumosa	Ingá maguinata	0.1	0.0	0.0	0.0	0.1
	Inga edulis	Inga cipo	1.4	0.0	0.0	0.0	1.4
	Inga eplendens	Ingá facãozinho	0.1	0.0	0.0	0.0	0.1
	Inga falcistipula	Ingá estípula pequena	0.2	0.0	0.0	0.0	0.2
	Inga gracilifolia	Ingá coração de preguiça	0.1	0.0	0.0	0.0	0.1
	Inga ingoides	Ingá folha peluda	1.4	0.0	0.0	0.0	1.4
	Inga macrophylla	Ingá folha grande	0.1	0.0	0.0	0.0	0.1
	Inga melinones	Inga sulcado	0.5	0.0	0.0	0.0	0.5
	Inga microcalix	Ingá de sangue	0.1	0.0	0.0	0.0	0.1

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class: No value	Low value	Med. Value	High value	Total
Light-demanding (continued)							
	Not identified	Tento folha miuda	0.1	0.0	0.0	0.0	0.1
Light-demanding total			61.2	23.6	0.3	0.0	85.2
Intermediate							
	Aioea att. Densiflora	Louro preto folha brilhante	0.1	0.0	0.0	0.0	0.1
	Aiouea sp	Louro folha verticilada	0.1	0.0	0.0	0.0	0.1
	Annona sp	Envira sombrera	2.1	0.0	0.0	0.0	2.1
	Astronium lecointei	Muiracatiara	0.0	0.0	0.7	0.0	0.7
	Auxemma oncocalyx	Pau branco	15.9	0.0	0.0	0.0	15.9
	Brosimum obovata	Murure	0.0	0.7	0.0	0.0	0.7
	Calophyllum brasiliense	Jacareúba	0.0	0.1	0.0	0.0	0.1
	Carapa guianensis	Andiroba	0.0	0.0	0.8	0.0	0.8
	Clarisa racemosa	Guariúba	0.0	2.3	0.0	0.0	2.3
	Clarisia ilicifolia	Janitá	0.1	0.0	0.0	0.0	0.1
	Copaifera duckei	Copaíba	0.0	0.5	0.0	0.0	0.5
	Dialium guianesis	Jutaí pororoca	0.0	0.1	0.0	0.0	0.1
	Franchetella sangotiana	Guajararana	0.2	0.0	0.0	0.0	0.2
	Himatanthus sucuuba	Sucuuba	1.0	0.0	0.0	0.0	1.0
	Licaria rigida	Louro amarelo	0.0	0.5	0.0	0.0	0.5
	Luehea speciosa	Açoita cavalo	0.1	0.0	0.0	0.0	0.1
	Moronobea coccinea	Ananin	0.0	0.4	0.0	0.0	0.4
	Nectandra cuspidata	Louro tamanco	0.0	0.1	0.0	0.0	0.1
	Nectandra grandis	Louro puxurí bravo	0.1	0.0	0.0	0.0	0.1
	Nectandra pichurim	Louro	0.0	0.1	0.0	0.0	0.1

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class No value	Low value	Med. Value	High value	Total
Intermediate (continued)							
	Neoxythece robusta	Guajará	0.1	0.0	0.0	0.0	0.1
	Ocotea caudata	Louro preto	0.0	1.0	0.0	0.0	1.0
	Ocotea cernu	Louro da folhona	0.1	0.0	0.0	0.0	0.1
	Ocotea fragantissima	Louro canela	0.0	0.1	0.0	0.0	0.1
	Ocotea glomerata	Louro abacate	0.0	1.2	0.0	0.0	1.2
	Ocotea guianensis	Louro branco	0.0	0.1	0.0	0.0	0.1
	Ocotea longifolia	Louro vermelho vincado	0.2	0.0	0.0	0.0	0.2
	Ocotea rubra	Louro vermelho	0.0	0.0	4.5	0.0	4.5
	Ormosia coutinhoi	Buiuçu	0.0	0.7	0.0	0.0	0.7
	Parahancornia amapa	Amapá	0.0	0.0	0.2	0.0	0.2
	Platymiscium filipes	Macacaúba	0.0	0.0	0.3	0.0	0.3
	Poecilanthe effusa	Gema de ovo	5.2	0.0	0.0	0.0	5.2
	Pseudopiptadenia suaveolens	Timborana	0.0	3.0	0.0	0.0	3.0
	Pterocarpus rohrii	Mututi	1.4	0.0	0.0	0.0	1.4
	Sacoglottis amazonica	Uxirana	0.0	1.2	0.0	0.0	1.2
	Sagotia racemosa	Uxirana	0.0	0.1	0.0	0.0	0.1
	Sclerobium melanocaroum	Tachi vermelho	0.0	1.3	0.0	0.0	1.3
	Tachigalia paniculata	Tachi preto	0.0	8.9	0.0	0.0	8.9
	Tetragastris altissima	Breu manga	0.0	11.3	0.0	0.0	11.3
	Tetragastris panamensis	Barrote	0.3	0.0	0.0	0.0	0.3
	Xylopia nitida	Envira branca/ Envira cana	6.8	0.0	0.0	0.0	6.8
	Not identified	Breu amesclão	0.1	0.0	0.0	0.0	0.1
	Not identified	Envira sombreira	0.8	0.0	0.0	0.0	0.8
	Not identified	Louro cheiroso	0.1	0.0	0.0	0.0	0.1

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class: No value	Low value	Med. Value	High value	Total
Intermediate (continued)							
	Not identified	Louro jandauba	0.1	0.0	0.0	0.0	0.1
	Not identified	Pau de colher	1.3	0.0	0.0	0.0	1.3
	Not identified	Pitaíca	0.1	0.0	0.0	0.0	0.1
	Not identified	Tinteiro	4.7	0.0	0.0	0.0	4.7
	Not identified	Ucuuba preta	3.0	0.0	0.0	0.0	3.0
Intermediate total			43.7	33.7	6.4	0.0	83.8
Shade-tolerant							
	Aspidosperma album	Araracanga	0.0	4.5	0.0	0.0	4.5
	Aspidosperma nitidum	Carapanaúba	0.1	0.0	0.0	0.0	0.1
	Bowdichia nitida	Sucupira amarela	0.0	0.0	0.3	0.0	0.3
	Chaunochiton kappleri	Pau vermelho	0.1	0.0	0.0	0.0	0.1
	Chrysophyllum lucentifollium	Abiu casca grossa	0.0	7.6	0.0	0.0	7.6
	Cupania hirsuta	Espeturana peluda	0.1	0.0	0.0	0.0	0.1
	Cupania scrobiculata	Espeturana	1.8	0.0	0.0	0.0	1.8
	Dendrobangia boliviana	Caferana	0.1	0.0	0.0	0.0	0.1
	Diospyros dukei	Caqui preto	18.8	0.0	0.0	0.0	18.8
	Diospyros melinoni	Caqui branco	0.1	0.0	0.0	0.0	0.1
	Diospyros praetermissa	Caqui	0.5	0.0	0.0	0.0	0.5
	Diospyros sp	Caqui casca grossa	0.1	0.0	0.0	0.0	0.1
	Diospyros tectranda	Caqui casca dura	0.1	0.0	0.0	0.0	0.1
	Diploon venezuelana	Seringarana/ Mangabarana folha pequena	0.0	0.1	0.0	0.0	0.1
	Drypetes variabilis	Maparanã	0.6	0.0	0.0	0.0	0.6

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class No value	Low value	Med. Value	High value	Total
Shade-tolerant (continued)							
	Ecclinusa abbreviata	Abiu folha peluda	0.1	0.0	0.0	0.0	0.1
	Eperua schonburgkiana	Muirapiranga	0.0	0.1	0.0	0.0	0.1
	Eschweilera apiculata	Ripeiro	0.2	0.0	0.0	0.0	0.2
	Eschweilera blanchetiana	Mata mata preto	17.8	0.0	0.0	0.0	17.8
	Eschweilera coriaceae	Matá matá branco	4.8	0.0	0.0	0.0	4.8
	Eschweilera grandeflorum	Matá matá grande florum	0.1	0.0	0.0	0.0	0.1
	Eschweilera pedicelata	Matá matá	0.7	0.0	0.0	0.0	0.7
	Guarea kunthiana	Andirobarana folha grande	0.1	0.0	0.0	0.0	0.1
	Guatteria olivacea	Envira preta folha grande	0.0	0.4	0.0	0.0	0.4
	Guatteria poeppigiana	Envira preta casca grossa	0.0	0.1	0.0	0.0	0.1
	Guatteria schomburgkiana	Envira preta	0.0	0.3	0.0	0.0	0.3
	Guatteria schomburgkiana	Envira preta casca sulcada	5.0	0.0	0.0	0.0	5.0
	Guatteria schomburgkiana	Envira preta folha peluda	0.0	0.5	0.0	0.0	0.5
	Guatteria sp	Envira vermelha	13.2	0.0	0.0	0.0	13.2
	Lecythis idatimon	Jatereu	38.4	0.0	0.0	0.0	38.4
	Lecythis lurida	Jarana	0.0	2.5	0.0	0.0	2.5
	Licania heteromorpha	Macucu/ macucu de sangue	0.4	0.0	0.0	0.0	0.4
	Licania kunthiana	Pintadinho	0.3	0.0	0.0	0.0	0.3
	Lindackeria paraensis	Canela de velho/folha seca	0.1	0.0	0.0	0.0	0.1
	Macrolobium campestre	Iperana bifoliar	20.9	0.0	0.0	0.0	20.9
	Manilkara amazonica	Maparajuba	0.0	0.0	0.9	0.0	0.9
	Manilkara huberi	Maçaranduba	0.0	0.0	3.3	0.0	3.3

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class No value	 Low value	 Med. Value	 High value	 Total
Shade-tolerant (continued)							
	Manilkara paraensis	Maçarandubinha	0.0	0.0	0.3	0.0	0.3
	Maquira sclerophylla	Muratinga	0.4	0.0	0.0	0.0	0.4
	Maytenos guianensis	Chichuá/ Xixuá	0.3	0.0	0.0	0.0	0.3
	Micropholis melinoniana	Currupixa	0.0	0.0	0.3	0.0	0.3
	Minquartia guianensis	Acariquara	0.0	0.1	0.0	0.0	0.1
	Mouriria plasschaerti	Muiraúba	0.1	0.0	0.0	0.0	0.1
	Neea sp.	João mole	28.8	0.0	0.0	0.0	28.8
	Perebea guianensis	Moiratinga	0.0	6.1	0.0	0.0	6.1
	Pithecolobium racemosum	Angelim rajado	0.0	0.2	0.0	0.0	0.2
	Pouteria cladantha	Abiurana	6.0	0.0	0.0	0.0	6.0
	Pouteria eugeniifolia	Guajará pedra	0.1	0.0	0.0	0.0	0.1
	Pouteria lasiocarpa	Abiu seco	33.6	0.0	0.0	0.0	33.6
	Pouteria macrophylla	Abiu cutiti/ Abiu cutiti preto	2.2	0.0	0.0	0.0	2.2
	Pouteria manausensis	Guajará preto	3.7	0.0	0.0	0.0	3.7
	Pouteria reticulata	Abiurana amarela	1.2	0.0	0.0	0.0	1.2
	Pouteria sp	Abiu/Abiu sem casca	4.0	0.0	0.0	0.0	4.0
	Protium decandrum	Breu vermelho	0.1	0.0	0.0	0.0	0.1
	Protium tenuifolium	Breu	6.8	0.0	0.0	0.0	6.8
	Rinorea guianensis	Quariquarana	1.4	0.0	0.0	0.0	1.4
	Sagotia racemosa	Arataciu	24.9	0.0	0.0	0.0	24.9
	Sandwithiodoxa egregia	Guajarazinho	0.1	0.0	0.0	0.0	0.1
	Sapium lanciolatum	Murupita	0.5	0.0	0.0	0.0	0.5
	Syzygiopsis oppositifolia	Guajara bolacha	0.0	0.5	0.0	0.0	0.5
	Talisia CF. intermedia	Pitomba da mata	0.1	0.0	0.0	0.0	0.1

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class No value	Low value	Med. Value	High value	Total
Shade-tolerant (continued)							
	Theobroma speciosa	Cacau	2.4	0.0	0.0	0.0	2.4
	Trichilia micrantha	Cachuá	0.2	0.0	0.0	0.0	0.2
	Zizyphus itacaiunensis	Maria preta	0.2	0.0	0.0	0.0	0.2
	Zollernia paraensis	Pau ferro/ pau santo	1.8	0.0	0.0	0.0	1.8
	Not identified	Abiu doce	0.1	0.0	0.0	0.0	0.1
	Not identified	Abiu folha grande	0.1	0.0	0.0	0.0	0.1
	Not identified	Abiu vermelho	0.5	0.0	0.0	0.0	0.5
	Not identified	Abiurana caramuri	0.1	0.0	0.0	0.0	0.1
	Not identified	Abiurana casca fina	0.1	0.0	0.0	0.0	0.1
	Not identified	Abiurana pitomba	0.2	0.0	0.0	0.0	0.2
	Not identified	Abiurana ucuubarana	0.1	0.0	0.0	0.0	0.1
	Not identified	Acariquarana	0.3	0.0	0.0	0.0	0.3
	Not identified	Caqui folha pequena	0.1	0.0	0.0	0.0	0.1
	Not identified	Caraipe	0.1	0.0	0.0	0.0	0.1
	Not identified	Casca grossa	0.1	0.0	0.0	0.0	0.1
	Not identified	Chichua casca grossa	0.2	0.0	0.0	0.0	0.2
	Not identified	Coração de negro	0.6	0.0	0.0	0.0	0.6
	Not identified	Currupixa folha miuda	0.1	0.0	0.0	0.0	0.1
	Not identified	Envira danta	0.7	0.0	0.0	0.0	0.7
	Not identified	Envira folha fina	0.1	0.0	0.0	0.0	0.1
	Not identified	Mata mata	0.1	0.0	0.0	0.0	0.1
	Not identified	Mata mata branco	0.7	0.0	0.0	0.0	0.7
	Not identified	Pau de remo	0.1	0.0	0.0	0.0	0.1
Shade-tolerant total			247.3	22.8	5.0	0.0	275.1

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class No value	Low value	Med. Value	High value	Total
Emergent							
	Caryocar glabum	Piquiarana	0.0	0.0	1.1	0.0	1.1
	Caryocar villosum	Piquiá	0.0	0.0	0.4	0.0	0.4
	Cedrela odorata	Cedro	0.0	0.0	0.0	0.1	0.1
	Couratari guianensis	Tauari/ Estopeiro folha grande	0.0	0.0	0.1	0.0	0.1
	Couratari oblongfolia	Tauari/ Estopeiro folha peque	0.0	0.0	0.3	0.0	0.3
	Dinizia excelsa	Angelim pedra	0.0	0.0	0.2	0.0	0.2
	Dipteryx odorata	Cumaru	0.0	0.0	0.3	0.0	0.3
	Hymenaea courbaril	Jatobá	0.0	0.0	1.2	0.0	1.2
	Hymenaea palustris	Jutaí mirim	0.0	0.0	0.7	0.0	0.7
	Lecythis pisonis	Sapucaia	0.0	0.5	0.0	0.0	0.5
	Qualea cf. lancifolia	Mandioqueiro	0.0	0.1	0.0	0.0	0.1
	Tabebuia impetiginosa	Ipê roxo	0.0	0.0	0.0	0.4	0.4
	Tabebuia serratifolia	Ipê amarelo	0.0	0.0	0.0	0.3	0.3
Emergent total			0.0	0.7	4.3	0.9	5.8
Unknown							
	Brosimum aubletii	Gameleira	0.1	0.0	0.0	0.0	0.1
	Not identified	Caniceiro	1.0	0.0	0.0	0.0	1.0
	Not identified	Galhudinho	0.5	0.0	0.0	0.0	0.5
	Not identified	Guaruta	0.3	0.0	0.0	0.0	0.3

Table A-1. Continued.

Species Group	Scientific name	Common name	Price-class: No value	Low value	Med. Value	High value	Total
Unkown (continued)							
	Not identified	Pau seco	0.1	0.0	0.0	0.0	0.1
	Not identified	Pepino	0.1	0.0	0.0	0.0	0.1
	Not identified	Taquari	0.1	0.0	0.0	0.0	0.1
	Not identified	Not identified	1.0	0.0	0.0	0.0	1.0
	Not identified	Not identified	13.8	0.0	0.0	0.0	13.8
Unknown total			17.0	0.0	0.0	0.0	17.0
Overall total			391.0	87.7	11.9	0.0	490.6

APPENDIX B
LIST OF VARIABLES, VECTORS, AND MATRICES

i index for species group $i = 1,..,m$

j index for size $j = 1,..,n$

s index for harvest system $s = 0,1,2$

t index for time, $t = 0,..,T$

T time horizon of optimization problems

q index for randomly-timed independent audit

Q the expected number of randomly-timed independent audits

θ years between each transition in the growth model

γ transitions in the growth model between harvest entries

ω proportion of reduced impact logging (RIL) implemented

$\omega_{illegal}$ the degree to which RIL is not implemented when required

$\mathbf{y}_0$ $\left[y_{ij0} \right]$ trees/ha in species group i and size j at time 0; the initial condition of the stand

$\mathbf{y}_t$ $\left[y_{ijt} \right]$ trees/ha in species group i and size j at time t

$\mathbf{y}^*$ $\left[y_{ij}^* \right]$ equilibrium trees/ha in species group i and size j

$\mathbf{y}_t^m$ $\left[y_{ijt}^m \right]$ merchantable trees/ha in species group i and size j at time t

$\mathbf{y}^{m*}$ $\left[y_{ij}^* \right]$ equilibrium merchantable trees/ha in species group i and size j

$\mathbf{y}_\omega^m$ $\left[y_{ij\omega}^* \right]$ merchantable trees/ha in species group i and size j when a proportion, ω, of RIL is implemented

$\mathbf{h}_t$ $\left[h_{ijt} \right]$ trees/ha harvested from species group i and size j at time t

$h_{illegal}$ harvest volume over the legal limit (m^3/ha)

$\overline{h}_{ij}$ trees/ha legally harvested from species group i and size j

$\mathbf{D}_s$ diagonal matrix containing logging damage coefficients for trees in species group *i* and size *j* under harvest system type *s*

$\mathbf{d}_{st}$ $\left[d_{ijst}\right]$ trees/ha killed by damage from species group *i* and size *j* under harvest system *s* at time *t*

$\mathbf{d}_{st}^{m}$ $\left[d_{ijst}^{m}\right]$ merchantable trees/ha killed by damage from species group *i* and size *j* under harvest system *s* at time *t*

$\mathbf{d}_{\omega}$ $\left[d_{ij\omega}\right]$ trees/ha killed by damage from species group *i* and size *j* when a proportion, ω, of RIL is implemented

$\mathbf{d}_{\omega}^{m}$ $\left[d_{ij\omega}^{m}\right]$ merchantable trees/ha killed by damage from species group *i* and size *j* when a proportion, ω, of RIL is implemented

$\mathbf{G}_s$ matrix of density-dependent transition probabilities under harvest system *s*

$\mathbf{G}_s^{*}$ repeating cycle of growth matrix applications that arise from the logger's choice of harvest system *s*

$\mathbf{A}_s$ transition matrix for harvest system *s*

R ingrowth matrix that captures the density dependent component of recruitment

$\mathbf{r}_s$ fixed recruitment vector under harvest system *s*

I identity matrix

S diagonal matrix whose elements represent the proportion of the stems from commercial species within each species group *i* and size *j*

Q diagonal matrix who elements represent the proportion of trees in each species group *i* and size *j* with stem form appropriate for milling

H diagonal matrix whose elements represent the proportion of stems in each species group *i* and size *j* thought to be hollow

$\mathbf{M}_s$ diagonal matrix who elements represent the *perceived* merchantable proportion for each species group *i* and size *j* under harvest treatment *s*

$\mathbf{M}_{\omega}$ diagonal matrix who elements represent the *perceived* merchantable proportion for each species group *i* and size *j* when a proportion, ω, of RIL is implemented

$\boldsymbol{\psi}$ $\left[\psi_{ij}\right]$ predicted commercial volume (m^3) per tree in species group *i* and size *j*

vc_{ijs} variable harvest cost per tree ($/tree) in species group *i* and size *j* under harvest system *s*

$vc_{ij\omega}$ variable harvest cost per tree ($/tree) in species group *i* and size *j* when a proportion, ω, of RIL is implemented

fc_s fixed costs ($/ha) under harvest system *s*

fc_ω fixed costs ($/ha) when a proportion, ω, of RIL is implemented

r real discount rate

δ discount function

$waste_s$ proportion of commercial volume harvest wasted under harvest system *s*

$waste_\omega$ proportion of commercial volume harvest wasted when a proportion, ω, of RIL is implemented

π_t profit at time *t*

$E(\pi)$ expected profit

π^* the minimum acceptable gross profit for the concessionaire

ϕ_s the proportion of hollow trees *not* identified by the sawyer as hollow

x weighted sum of potentially illegal activities forms

$\theta(x)$ function that generates the probability of being caught and paying a fine

τ parameter that shifts the distribution of $\theta(x)$

η weighs the relative contribution of under-implementation of RIL to the illegality factor.

f fine ($/ha) paid when caught breaking rules

bond performance bond ($/ha)

ρ % compliance with RIL and harvest regulations to determine how much performance bond will be returned

$E(R)$ Expected government revenue

R^* required level of government revenue

α royalty charge

β area fee

cc certification costs ($/ha)

LIST OF REFERENCES

Amacher, G.S., 2006. Corruption: A challenge for economists interested in forest policy design. Journal of Forest Economics 12, 85-89.

Amacher, G.S., Brazee, R.J., 1997. Designing forest taxes with varying government preferences and budget targets. Journal of Environmental Economics and Management 32, 323-340.

Amacher, G.S., Brazee, R.J., Witvliet, M., 2001. Royalty systems, government revenues, and forest condition: An application from Malaysia. Land Economics 77, 300-313.

Amacher, G.S., Koskela, E., Ollikainen, M., 2007. Royalty reform and illegal reporting of harvest volumes under alternative penalty schemes. In press Environmental & Resource Economics.

Bacha, C.J.C., Rodriguez, L.C.E., 2007. Profitability and social impacts of reduced impact logging in the Tapajós National Forest, Brazil - a case study. Ecological Economics 63, 70-77.

Banco Nacional de Desenvolvimento Econômico e Social - BNDES., 2007. Manual da Taxa de Juros de Longo Prazo (TJLP).

Barany, M., Hammett, A.L., Araman, P., 2003. Lesser used species of Bolivia and their relevance to sustainable forest management. Forest Products Journal 53, 28-33.

Barreto, P., Amaral, P., Vidal, E., Uhl, C., 1998. Costs and benefits of forest management for timber production in eastern Amazonia. Forest Ecology and Management 108, 9-26.

Bauch, S.C., Amacher, G.S., Merry, F.D., 2007. Costs of harvesting, transportation and milling in the Brazilian Amazon: estimation and policy implications. Forest Policy and Economics 9, 903-915.

Becker, G.S., 1968. Crime and punishment: an economic approach. Journal of Political Economy 76, 169-217.

Boltz, F., 2003. Optimal Management of Bolivian Tropical Dry Forests. Ph.D. Dissertation, School of Forest Resources and Conservation, University of Florida. Gainesville, Florida.

Boltz, F., Carter, D.R., 2006. Multinomial logit estimation of a matrix growth model for tropical dry forests of eastern Bolivia. Canadian Journal of Forest Research 36, 2623-2632.

Boltz, F., Holmes, T.P., Carter, D.R., 2003. Economic and environmental impacts of conventional and reduced-impact logging in tropical South America: a comparative review. Forest Policy and Economics 5, 69-81.

Boscolo, M., Buongiorno, J., 1997. Managing a tropical rainforest for timber, carbon storage, and tree diversity. Commonwealth Forestry Review 76, 246-254.

Boscolo, M., Buongiorno, J., Panayatou T., 1997. Simulating options for carbon sequestration through improved management of a lowland tropical rainforest. Environment and Development Economics 2, 239-261.

Boscolo, M., Vincent, J.R., 2000. Promoting better logging practices in tropical forests: A simulation analysis of alternative regulations. Land Economics 76, 1-14.

Boscolo, M., Vincent, J.R., 2003. Nonconvexities in the production of timber, biodiversity, and carbon sequestration. Journal of Environmental Economics and Management 46, 251-268.

Boyland, M., 2006. The economics of using forests to increase carbon storage. Canadian Journal of Forest Research 36, 2223-2234.

Brito, B., Barreto, P., 2004. Aplicação da Lei de Crimes Ambientais pela Justiça Federal no Setor Florestal do Pará. IMAZON, Belém, Brazil.

Brito, B., Barreto, P., 2006. A eficácia da aplicação da lei de crimes ambientais pelo Ibama para proteção de florestas no Pará. Revista de Direito Ambiental 43, 35-65.

Brito, B., Barreto, P., Rothman, J., 2005. Brazil's New Environmental Crimes Law: an Analysis of its Effectiveness in Protecting the Amazonian Forests. IMAZON, Belém, Brazil.

Buongiorno, J., 2001. Quantifying the implications of transformation from even to uneven-aged forest stands. Forest Ecology and Management 151, 121-132.

Buongiorno, J., Michie, B.R., 1980. A matrix model of uneven-aged forest management. Forest Science 26, 609-625.

Buongiorno, J., Peyron, J.L., Houllier, F., Bruciamacchie, M., 1995. Growth and management of mixed-species, uneven-aged forests in the French Jura - implications for economic returns and tree diversity. Forest Science 41, 397-429.

Buschbacher, R., 1990. Natural forest management in the humid tropics: ecological, social, and economic considerations. Ambio 19, 253-258.

Campos, M.T., Nepstad, D.C., 2006. Smallholders, the Amazon's new conservationists. Conservation Biology 20, 1553-1556.

Chomitz, K.M., Buys, P., De Luca, G., Thomas, T.S., Wertz-Kanounnikoff, S., 2007. At Loggerheads: Agricultural Expansion, Poverty Reduction, and Environment in the Tropical Forests. The World Bank, Washington, D.C.

Daly, H., 1996. Beyond Growth. Beacon Press, Boston.

Dauber, E., Fredericksen, T.S., Pena-Claros, M., 2006. Sustainability of timber harvesting in Bolivian tropical forests. Forest Ecology and Management 214, 294-304.

De Graaf, N.R., Poels, R.L.H., Van Rampaey, R.S.A.R., 1999. Effect of silvicultural treatment on growth and mortality of rainforest in Surinam over long periods. Forest Ecology and Management 124, 123-135.

Dekker, M., De Graaf, N.R., 2003. Pioneer and climax tree regeneration following selective logging with silviculture in Suriname. Forest Ecology and Management 172, 183-190.

Delacote, P., 2005a. Forestry sector concentration, corruption, and forest over-exploitation. Manuscript.

Dykstra, D.P., 2002. Reduced Impact Logging: Concepts and Issues. P. 23-39 *in* Applying Reduced Impact Logging to Advance Sustainable Forest Management, Enters, T., P.B. Durst, G.B. Applegate, P.C.S. Kho, and G. Man (eds.), FAO. <ftp://ftp.fao.org/docrep/fao/005/AC805E/Ac805E00.pdf> Last accessed 08/07/2007.

Favrichon, V., 1998. Modeling the dynamics and species composition of a tropical mixed-species uneven-aged natural forest: Effects of alternative cutting regimes. Forest Science 44, 113-124.

Ferraro, P.J., Pattanayak, S.K., 2006. Money for nothing? A call for empirical evaluation of biodiversity conservation investments. Plos Biology 4, 482-488.

Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., DeFries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J., Ramankutty, N., Snyder, P., 2007. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. Frontiers in Ecology and the Environment 5, 25-32.

Fredericksen, T.S., Putz, F.E., 2003. Silvicultural intensification for tropical forest conservation. Biodiversity and Conservation 12, 1445-1453.

Gerwing, J.J., 2002. Degradation of forests through logging and fire in the eastern Brazilian Amazon. Forest Ecology and Management 157, 131-141.

Gerwing, J.J., Vidal, E., 2002. Changes in liana abundance and species diversity eight years after liana cutting and logging in an eastern Amazonian forest. Conservation Biology 16, 544-548.

Gillis, M., 1988. Malaysia: Public Policies and the Tropical Forest. P. 115-164 *in* Public Policies and the Misuse of Forest Resources, Repetto, R. and M. Gillis (eds.), Cambridge University Press, Cambridge.

Gourlet-Fleury, S., Blanc, L., Picard, N., Sist, P., Dick, J., Nasi, R., Swaine, M.D., Forni, E., 2005. Grouping species for predicting mixed tropical forest dynamics: looking for a strategy. Annals of Forest Science 62, 785-796.

Gray, J.A., 2005. Forest Concession Policies and Revenue Systems- Country Experience and Policy Changes for Sustainable Tropical Forestry. World Bank, Washington D.C.

Gullison, R.E., Frumhoff, P.C., Canadell, J.G., Field, C.B., Nepstad, D.C., Hayhoe, K., Avissar, R., Curran, L.M., Friedlingstein, P., Jones, C.D., Nobre, C., 2007. Tropical forests and climate policy. Science 316, 985-986.

Gullison, R.E., Panfil, S.N., Strouse, J.J., Hubbell, S.P., 1996. Ecology and management of mahogany (Swietenia macrophylla King) in the Chimanes Forest, Beni, Bolivia. Botanical Journal of the Linnean Society 122, 9-34.

Hausman, J., McFadden, D., 1984. Specification tests for the multinomial logit model. Econometrica 52, 1219-1240.

Heal, G.M., 1998. Valuing the Future: Economic Theory and Sustainability. Columbia University Press, New York.

Hirakuri, S.R., 2003. Can Law Save the Forest? Lessons from Finland and Brazil. Center for International Forestry Research (CIFOR), Bogor Barat, Indonesia.

Holmes, T.P., Blate, G.M., Zweede, J.C., Pereira, R., Barreto, P., Boltz, F., Bauch, R., 2002. Financial and ecological indicators of reduced impact logging performance in the eastern Amazon. Forest Ecology and Management 163, 93-110.

Hyde, W.F., Sedjo, R.A., 1992. Managing tropical forests - reflections on the rent distribution discussion. Land Economics 68, 343-350.

IBAMA., 2002. Relatório Técnico: Manejo Florestal Sustentável na Amazônia, Ano 2002. Ministério do Meio Ambiente, Brasília, Brazil.

Johns, J.S., Barreto, P., Uhl, C., 1996. Logging damage during planned and unplanned logging operations in the eastern Amazon. Forest Ecology and Management 89, 59-77.

Kaimowitz, D., 2003. Forest law enforcement and rural livelihoods. International Forestry Review 5, 199-210.

Karsenty, A., Gourlet-Fleury, S., 2006. Assessing sustainability of logging practices in the Congo Basin's managed forests: The issue of commercial species recovery. Ecology and Society 11.

Keller, M., Asner, G.P., Blate, G., McGlocklin, J., Merry, F., Peña-Claros, M., Zweede, J., 2007. Timber production in selectively logged tropical forests in South America. Frontiers in Ecology and the Environment 5, 213-216.

Kramme, L.A., Price, S.P., 2005. Practical Actions to Combat Illegal Logging: a Summary of a Multi-stakeholder Dialogue on Best Practices for Business and Civil Society. The Forests Dialogue, New Haven, Connecticut.

Lentini, M., 2007. Land Use Allocation under Multiple Objectives in Amazônia: Creating a Tool to Guide Zoning of Public Production Forests. M.S. Thesis, School of Forest Resources and Conservation, University of Florida. Gainesville, Florida.

Lentini, M., Pereira, D., Celentano, R., Pereira, R., 2005. Fatos Florestais da Amazônia 2005. IMAZON, Belém, Brazil.

Leruth, L., Paris, R., Ruzicka, I., 2001. The compiler pays principle: The limits of fiscal approaches toward sustainable forest management. IMF Staff Papers 48, 397-423.

Lima, E., Merry, F., Nepstad, D., Amacher, G., Azevedo-Ramos, C., Lefebvre, P., Resque, F., 2006. Searching for sustainability: Forest policies, smallholders, and the trans-Amazon highway. Environment 48, 26-38.

Lin, C.R., Buongiorno, J., 1998. Tree diversity, landscape diversity, and economics of maple-birch forests: Implications of Markovian models. Management Science 44, 1351-1366.

Lin, C.R., Buongiorno, J., 1999a. Managing forests for tree and landscape diversity. Part I: Predictions with Markov-chain models. P. 137-157 *in* Multiple Use of Forests and Other Natural Resources: Aspects of Theory and Application, Helles, F., P. Holten-Andersen, and L. Wichmann (eds.), Kluwer Academic Publishers, Boston.

Lin, C.R., Buongiorno, J., 1999b. Managing forests for tree and landscape diversity. Part II: Optimisation with Markov-chain model. P. 158-174 *in* Multiple Use of Forests and Other Natural Resources: Aspects of Theory and Application, Helles, F., P. Holten-Andersen, and L. Wichmann (eds.), Kluwer Academic Publishers, Boston.

Lin, C.R., Buongiorno, J., Vasievich, M., 1996. A multi-species, density-dependent matrix growth model to predict tree diversity and income in northern hardwood stands. Ecological Modelling 91, 193-211.

Lu, H.C., Buongiorno, J., 1993. Long-term and short-term effects of alternative cutting regimes on economic returns and ecological diversity in mixed-species forests. Forest Ecology and Management 58, 173-192.

Luckert, M.K., Williamson, T., 2005. Should sustained yield be part of sustainable forest management? Canadian Journal of Forest Research 35, 356-364.

Mendoza, G.A., Setyarso, A., 1986. A transition matrix forest growth-model for evaluating alternative harvesting schemes in Indonesia. Forest Ecology and Management 15, 219-228.

Merry, F., Amacher, G., Nepstad, D., Lima, E., Lefebvre, P., Bauch, S., 2006. Industrial development on logging frontiers in the Brazilian Amazon. International Journal of Sustainable Development 9, 277-296.

Merry, F.D., Amacher, G.S., 2005. Forest taxes, timber concessions, and policy choices in the Amazon. Journal of Sustainable Forestry **20**, 15-44.

Michie, B.R., Buongiorno, J., 1984. Estimation of a matrix model of forest growth from remeasured permanent plots. Forest Ecology and Management 8, 127-135.

Monteiro, A., Souza Jr., C., 2006. Imagens de Satélite para Avaliar Planos de Manejo Florestal. No. 9. IMAZON, Belém, Brazil.

Nepstad, D., Azevedo-Ramos, C., Lima, E., McGrath, D., Pereira, C., Merry, F., 2004. Managing the Amazon timber industry. Conservation Biology 18, 575-577.

Neumayer, E., 1999. Weak versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms. Edward Elgar, Northampton, MA.

Önal, H., 1997. Trade-off between structural diversity and economic objectives in forest management. American Journal of Agricultural Economics 79, 1001-1012.

Palmer, C.E., 2003b. The nature of corruption in forest management. World Development 6, 1-10.

Paris, R., Ruzicka, I., Speechly, H., 1991. Performance guarantee bonds for commercial management of natural forests: early experience from the Philippines. Commonwealth Forestry Review 73, 106-112.

Pearce, D., Putz, F.E., Vanclay, J.K., 2003. Sustainable forestry in the tropics: panacea or folly? Forest Ecology and Management 172, 229-247.

Pearce, D.W., Markandya, A., Barbier, E., 1989. Blueprint for a Green Economy. Earthscan Publications, London.

Phillips, P.D., de Azevedo, C.P., Degen, B., Thompson, I.S., Silva, J.N.M., Van Gardingen, P.R., 2004. An individual-based spatially explicit simulation model for strategic forest management planning in the eastern Amazon. Ecological Modelling 173, 335-354.

Picard, N., Bar-Hen, A., Franc, A., 2002. Modeling forest dynamics with a combined matrix/individual-based model. Forest Science 48, 643-652.

Pinard, M.A., Putz, F.E., 1996. Retaining forest biomass by reducing logging damage. Biotropica 28, 278-295.

Plumptre, R.A., 1996. Links between utilisation, product marketing, and forest management in tropical moist forests. Commonwealth Forestry Review 75, 316-324.

Pokorny, B., Sabogal, C., Silva, J.N.M., Bernardo, P., Souza, J., Zweede, J., 2005. Compliance with reduced-impact harvesting guidelines by timber enterprises in terra firme forests of the Brazilian Amazon. International Forestry Review 7, 9-20.

Polinsky, A.M., Shavell, S., 1979. Optimal tradeoff between the probability and magnitude of fines. American Economic Review 69, 880-891.

Polinsky, A.M., Shavell, S., 2000. The economic theory of public enforcement of law. Journal of Economic Literature 38, 45-76.

Putz, F.E., Dykstra, D.P., Heinrich, R., 2000. Why poor logging practices persist in the tropics. Conservation Biology 14, 951-956.

Putz, F.E., Pinard, M.A., 1993. Reduced-impact logging as a carbon-offset method. Conservation Biology 7, 755-757.

Repetto, R., Gillis, M., 1988. Public Policies and the Misuse of Forest Resources. Cambridge University Press, Cambridge.

Rhodes, W.M., Allen, E.P., Callahan, M., 2006. Illegal Logging: a Market-based Analysis of Trafficking in Illegal Timber. Abt Associates Inc., Cambridge, Massachusetts.

Rice, R.E., Sugal, C.A., Ratay, S.M., Fonseca, G.A., 2001. Sustainable Forest Management: a Review of Conventional Wisdom. Conservation International, Advances in Applied Biodiversity Science, No. 3. Washington, DC.

Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J.C., Lambin, E., 2005. Forest transitions: towards a global understanding of land use change. Global Environmental Change-Human and Policy Dimensions 15, 23-31.

Sabogal, C., Lentini, M., Pokorny, B., Silva, J.M.C., Zweede, J.C., Veríssimo, A., Boscolo, M., 2006. Manejo Florestal Empresarial na Amazônia Brasileira. CIFOR, Belém, Brazil.

Santilli, M., Moutinho, P., Schwartzman, S., Nepstad, D., Curran, L., Nobre, C., 2005. Tropical deforestation and the Kyoto Protocol. Climatic Change 71, 267-276.

Scholl, J., 2005c. Environmental Fiscal Reform and National Forest Policies: an Overview of Forest Fiscal Systems in 18 Countries. Schemmel, J.P. and D. Drager (eds.). GTZ Environment and Resource Management Unit, Eschborn, Germany.

Schulze, M., 2003. Ecology and Behavior of Nine Timber Tree Species in Pará, Brazil: Links between Species Life History and Forest Management and Conservation. Ph.D. Dissertation, Department of Biology, The Pennsylvania State University. University Park, Pennsylvania.

Schulze, M., Grogan, J., Vidal, E., 2007a. Forest certification in Amazonia: standards matter. Oryx.

Schulze, M., Grogan, J., Vidal, E., 2007b. Technical challenges to sustainable forest management in concessions on public lands in the Brazilian Amazon. in press Journal of Sustainable Forestry.

Schulze, M., Vidal, E., Grogan, J., Zweede, J.C., Zarin, D., 2005. Madeiras nobres em perigo: Práticas e leis atuais de manejo florestal não garantem exploração sustentável. Ciência Hoje 214, 66-69.

Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C.A., Carvalho, M.S.P., 1984. Equaçoes de volume para a Floresta Nacional do Tapajós. Boletim de Pesquisa Florestal, 50-63.

Silva, J.N.M., De Carvalho, J.O.P., Lopes, J.D.A., De Almeida, B.F., Costa, D.H.M., De Oliveira, L.C., Vanclay, J.K., Skovsgaard, J.P., 1995. Growth and yield of a tropical rain-forest in the Brazilian Amazon 13 years after logging. Forest Ecology and Management 71, 267-274.

Sist, P., Ferreira, F.N., 2007. Sustainability of reduced-impact logging in the Eastern Amazon. Forest Ecology and Management 243, 199-209.

Sist, P., Fimbel, R., Sheil, D., Nasi, R., Chevallier, M.H., 2003a. Towards sustainable management of mixed dipterocarp forests of South-east Asia: moving beyond minimum diameter cutting limits. Environmental Conservation 30, 364-374.

Sist, P., Picard, N., Gourlet-Fleury, S., 2003b. Sustainable cutting cycle and yields in a lowland mixed dipterocarp forest of Borneo. Annals of Forest Science 60, 803-814.

Smith, J., Applegate, G., 2004. Could payments for forest carbon contribute to improved tropical forest management? Forest Policy and Economics 6, 153-167.

Smith, J., Colan, V., Sabogal, C., Snook, L., 2006. Why policy reforms fail to improve logging practices: The role of governance and norms in Peru. Forest Policy and Economics 8, 458-469.

Snook, L.K., 1996. Catastrophic disturbance, logging and the ecology of mahogany (Swietenia macrophylla King): Grounds for listing a major tropical timber species in CITES. Botanical Journal of the Linnean Society 122, 35-46.

Souza Jr., C., Veríssimo, A., Micol, L., Guimarães, S., 2006. Boletim Transparência Florestal do Estado de Mato Grosso. Nos. 1-4. IMAZON, Belém, Brazil.

Stone, S.W., 1998a. Evolution of the timber industry along an aging frontier: The case of Paragominas (1990-95). World Development 26, 433-448.

Stone, S.W., 1998b. Using a geographic information system for applied policy analysis: the case of logging in the Eastern Amazon. Ecological Economics 27, 43-61.

Sun, C., 1997. An Economic Analysis of Tropical Timber Concessions. Ph.D. Dissertation, Department of Agricultural Economics, University of Illinois. Urbana-Champaign, Illinois.

Sutinen, J.G., Anderson, P., 1985. The economics of fisheries law-enforcement. Land Economics 61, 387-397.

Uhl, C., Barreto, P., Veríssimo, A., Vidal, E., Amaral, P., Barros, A.C., Souza Jr., C., Johns, Gerwing, J.J., 1997. Natural resource management in the Brazilian Amazon. Bioscience 47, 160-169.

Valle, D., Phillips, P.D., Vidal, E., Schultz, M., Grogan, J., Sales, M., Van Gardingen, P.R., 2007. Adaptation of a spatially explicit tree-based growth and yield model and long term comparison between reduced impact and conventional logging in Eastern Amazônia, Brazil. Forest Ecology and Management 243, 187-198.

Valle, D., Schulze, M., Vidal, E., Grogan, J., Sales, M., 2006. Identifying bias in stand-level growth and yield estimations: A case study in eastern Brazilian Amazonia. Forest Ecology and Management 236, 127-135.

Van Gardingen, P.R., Valle, D., Thompson, I., 2006. Evaluation of yield regulation options for primary forest in Tapajos National Forest, Brazil. Forest Ecology and Management 231, 184-195.

Vanclay, J.K., 2001. Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests. CABI Publishing, Wallingford, UK.

Veríssimo, A., Celentano, D., Souza Jr., C., Salomão, R., 2006. Zoneamento de Áreas para Manejo Florestal no Pará. 8. IMAZON, O Estado da Amazônia.

Veríssimo, A., Souza Jr., C., Amaral, P., 2000. Identificação de Áreas com Potencial para a Criação de Florestas Nacionais na Amazônia Legal. Brazilian Ministry of Environment, Brasília, Brazil.

Veríssimo, A., Souza Jr., C., Stone, S.W., Uhl, C., 1998. Zoning of Timber Extraction in the Brazilian Amazon. Conservation Biology 12, 128-136.

Veríssimo, A., Barreto, P., 2004. National Forests in the Brazilian Amazon: Opportunities and Challenges. P. 31-40 *in* Working Forests in the Tropics: Conservation through Sustainable Management, Zarin, D., J.R.R. Alavalapati, F.E. Putz, and M. Schmink (eds.), Columbia University Press, New York.

Veríssimo, A., Cochrane, M.A., Souza Jr., C., 2002a. National forests in the Amazon. Science 297, 1478.

Veríssimo, A., Lima, E., Lentini, M., 2002b. Pólos Madeireiros do Estado do Pará. IMAZON, Belém, Brazil.

Vidal, E., Johns, J., Gerwing, J.J., Barreto, P., Uhl, C., 1997. Vine management for reduced-impact logging in eastern Amazonia. Forest Ecology and Management 98, 105-114.

Vidal, E.J., 2004. Dinâmica de Florestas Manejadas e sob Exploração Convencional na Amazônia Oriental. Ph.D. Dissertation, São Carlos School of Engineering, University of São Paulo. São Paulo, Brazil.

Vincent, J.R., 1990. Rent capture and the feasibility of tropical forest management. Land Economics 66, 212-223.

Vincent, J.R., 1993. Managing tropical forests - comment. Land Economics 69, 313-318.

Wadsworth, F.H., Zweede, J.C., 2006. Liberation: Acceptable production of tropical forest timber. Forest Ecology and Management 233, 45-51.

Walters, B.B., Sabogal, C., Snook, L.K., de Almeida, E., 2005. Constraints and opportunities for better silvicultural practice in tropical forestry: an interdisciplinary approach. Forest Ecology and Management 209, 3-18.

Winston, W.L., 1991. Operations Research: Applications and Algorithms. PWS-Kent Publishing Company, Boston.

Wunder, S., 2006. Are direct payments for environmental services spelling doom for sustainable forest management in the tropics? Ecology and Society 11.

Wunder, S., 2007. The efficiency of payments for environmental services in tropical conservation. Conservation Biology 21, 48-58.

Youngs, R.L., Hammett, A.L., 2001. Diversity, productivity, profitability, sustainability, and the tao of underutilized species. Forest Products Journal 51, 29-35.

Zarin, D.J., Schulze, M., Vidal, E., Lentini, M., 2007. Beyond reaping the first harvest: Management objectives for timber production in the Brazilian Amazon. In press Conservation Biology.

BIOGRAPHICAL SKETCH

Alexander Macpherson was born in Indianapolis, Indiana, but has lived in a variety of places since growing up and finishing high school in Plymouth, Indiana. He earned a Bachelor of Arts in Political Science and English at North Carolina State University in 1993. After earning a Master of Public and International Affairs in Economic and Social Development at the University of Pittsburgh in 1995, Alexander worked at Carnegie Mellon University for six years as a planning analyst and researcher. After a promotion to senior analyst and, then, assistant director, Alexander returned to school to earn a Master of Science in Agricultural and Applied Economics from the University of Wisconsin in 2004. In 2004, he was awarded a National Science Foundation Integrated Graduate Education and Research Traineeship to pursue his doctoral studies in Forest Resource Economics at the University of Florida.

Alexander has been married to his wife Natalie for 10 years. They have two incredible boys, seven-year-old Ewan and five-year-old Lucas. After Alexander graduates, the Macphersons plan to return to North Carolina to be close to family and friends.