THREE ESSAYS IN NATURAL RESOURCE AND ENVIRONMENTAL ECONOMICS

Olli-Pekka Kuusela

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Forestry

Gregory S. Amacher, Chair

Janaki Alavalapati

Bradley J. Sullivan

Klaus Moeltner

Kwok Ping Tsang

January 18, 2013

Blacksburg, VA

Keywords: Tropical deforestation; Timber concessions; Performance bonds; Permit markets; Macroeconomic uncertainty

THREE ESSAYS IN NATURAL RESOURCE AND ENVIRONMENTAL ECONOMICS

Olli-Pekka Kuusela

ABSTRACT

This dissertation analyses the impact of political and macroeconomic uncertainties on environmental outcomes and design of policy instruments. The first essay examines how the rate of agricultural land expansion in tropical countries depends on the nature and persistence of new political regimes. We use a novel panel data method that extends previous studies. We find that both new autocratic and democratic regimes have accelerated the expansion of agricultural land, thus yielding support to some of the findings in the earlier literature. Interesting differences emerge between regions, with the impact being most pronounced in Latin America. The analysis is developed more formally using a simple competitive land use model with political regime dependent confiscation risk and agricultural subsidy policy. The second essay evaluates the effectiveness of performance bonding for tropical forest concession management in achieving first and second best outcomes concerning reduced impact logging (RIL) standards. As a novel contribution, this essay introduces a simple model of two-stage concession design, and focus on the impact of three complications: harvester participation constraints, government repayment risk, and imperfect enforcement. We find several new and interesting results, in particular, imperfect enforcement and bond risk may deter implementation of bonding schemes as either the bond payment has to be set higher or the penalty mapping has to become more punitive. Policy implications, including potential for mechanisms such as REDD+ in improving the bonding outcomes, and the degree of financial support required to guarantee full implementation of RIL, are also examined. The third essay focuses on the relative performance of fixed versus intensity allowances in the presence of both productivity and energy price uncertainties. Both allowance instruments achieve the same steady-state emissions reduction target of 20%, which is similar to the current policy proposals, and the regulator then chooses the allowance policy that has the lowest expected abatement cost. We use a standard real business cycle (RBC) model to solve for the expected abatement cost under both policies. Unlike previous studies, our results show that under a reasonable model calibration, fixed allowances outperform intensity allowances with as much as 30% cost difference.

To my mother

ACKNOWLEDGEMENTS

I would like to start by expressing my deepest gratitude to my academic advisor and committee chair Dr. Gregory S. Amacher for all the support and help he has provided during the challenging but rewarding years of dissertation work and graduate courses. Anyone who has once embarked on the often solitary journey of Ph.D. studies knows how important it is to have someone who provides guidance, and occasionally, steers off the many dangers lurking along the way. Dr. Amacher's expertise, kind understanding, and dedication made my journey possible, and provided inspiration for my own professional development, and beyond. In retrospect, it was truly a remarkable coincidence that I enrolled to his environmental economics class as an unsuspecting exchange student in 2007. That seemingly minor choice proved to be a momentous decision in regard to my professional career and ambitions.

I would also like to thank each of my committee members for the significant contributions they have made on their part to my intellectual and professional growth. Their dedication and intellectual integrity continues to inspire me. I am also grateful for the great many opportunities I have had to interact with and learn from other professors and researchers during my time as a graduate student. I would like to thank Sue Snow and the rest of the staff at the Department of Forest Resources and Environmental Conservation for all the kindness and assistance they have provided. The department and our great university have both offered a stimulating environment to learn, conduct research, and aspire to excellence.

Finally, I'm forever grateful for the continued support and love of my family and friends. My parents and my sister have always been there for me, whether to share the blessings in my life, or to see through the occasional hardships. Weekly Skype calls, on every Sunday, with my mother and father gave me strength and confidence to push forward. My new life-long friends have made my stay here in Blacksburg, Virginia an unforgettable experience. I am forever indebted for their generosity and unconditional kindness, and without these relationships, my time here would have not been complete and meaningful.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Political and macroeconomic uncertainties are prone to exacerbate both market and policy failures that threaten the quality of our ambient environment and sustainability of our renewable resource base. Macroeconomic instability can be a leading indicator for political and social unrest, and it can also encourage myopic resource extraction. Political risks and institutional unpredictability enforce the vicious cycle of market failures that lead to overexploitation and degradation of natural resource stocks such as tropical forests and ocean fisheries. Institutional failures, such as omnipresent corruption, further feed into this tragedy, but also gain strength from the instability itself. This is evident in the experiences of many tropical countries, and manifested in the alarming rate of tropical deforestation and loss of biodiversity. The need for both national and global action remains stronger than ever.

The same uncertainties that contribute to environmental degradation, directly or indirectly, are also hindering the effectiveness of policy instruments designed to correct market failures. This can be seen, for example, in the frustratingly slow progress made in the sustainable management of tropical timber concessions. Elsewhere, macroeconomic uncertainties stemming from business cycles and fluctuating energy prices have already put in test the viability of greenhouse gas emissions permit markets, most notably the European Union Emissions Trading Scheme (EU ETS). Incorporating institutional realities in the policy design and choosing policy instruments that perform the best in an unpredictable environment may be the key factors contributing to the ultimate success of national and global policy responses. Even if the institutional context enables us to achieve only a second-best policy outcome, it is still better than the alternative of total policy failure.

The three essays in this dissertation each contribute and extend the past research that analyzes the effects of uncertainty and risk on environmental outcomes and policy instrument design. The first essay examines the effect of political regime turnovers on tropical deforestation by first developing a formal land use model and then applying a novel empirical approach to identify these effects. The second essay analyses the design of performance bonds in tropical timber concessions where government's repayment ability may be of concern and detection of contract violations is imperfect. The third essay compares the abatement cost outcomes under two alternative permit policies, intensity and fixed allowances, in an economy that is subject to both productivity and energy price uncertainty.

Agricultural land expansion has been identified as the single most important factor driving tropical deforestation. There are a variety of underlying factors that in turn drive agricultural land expansion, but active government policies in form of subsidies and land reforms are certainly a significant catalyst for land conversion. The first essay of this dissertation begins from the observation that most of the tropical countries have undergone recurring political regime changes during the past decades. These regime changes have frequently been accompanied with policies that include land reforms, land confiscations, and push to settle the frontier lands to ease population pressures. These policies have in turn deteriorated property rights and favored land conversion to agriculture, thus resulting in accelerating deforestation. The above argument is formally modeled using a simple competitive land use model. The predictions from the model are then tested using a novel empirical approach. We find a significant and persistent effect from new political regimes on agricultural land expansion, from both autocratic and democratic. Increasing level of income, on the other hand, has tended to reduce the rate of tropical deforestation in Latin America and Asia.

Unsustainable concession management practices and myopic extraction have significantly contributed to forest degradation and deforestation in the tropics. To guarantee future economic and environmental value of tropical forests, the application of reduced impact logging (RIL) techniques is deemed as a necessary condition for achieving sustainable forest management. The second essay of this dissertation analyzes the use of performance bonds in enforcing RIL in tropical timber concessions. We build a simple two-stage model of concession design that incorporates the risk of moral hazard in the form government's repayment ability and imperfect enforcement environment which is a widespread problem in most tropical concessions. It is also common that concession harvesters face financial constraints that may hinder them from posting a high enough bond payment. We propose a bonding scheme that leads to full implementation of RIL, or in the presence of binding participation constraint, a second-best RIL level. Bond simulations provide a realistic assessment of the severity of repayment risk and imperfect enforcement on the successful implementation of performance bonds, and the required bond level to achieve full RIL under such circumstances. Our results suggest that the needed REDD+ funding for performance bond schemes may be much higher than anticipated, depending on degree of institutional challenges.

Cap-and-trade policies have been and continue to be at the forefront of policy options in the reduction of anthropocentric greenhouse gas emissions (GHG). These schemes fix the quantity of total emissions through permit issuance, and then enable trading among permit holders with the goal of achieving the least overall cost of abatement. Most notably, the EU ETS launched its first phase in 2005 and is currently entering its third phase in 2013, while many other countries are currently in the process of including similar policies in their respective climate change legislation. Fixing the amount of emissions years in advance, however, leads to uncertainty about the ultimate cost of abatement. The third, and the final, essay compares the uncertain abatement cost outcomes under two competing permit allowance policies: intensity and fixed allowances. The attraction of intensity based emissions targeting derives from its ability to reduce abatement cost uncertainties that are mainly due to unanticipated short-run changes in economic activity. Following previous literature, we use a real business cycle (RBC) model to simulate policy outcomes under the two policies with an emissions reduction target of 20% from the business as usual (BAU) steady state. In our model, the abatement cost uncertainty stems from both stochastic business cycles and energy prices. Our results suggest that with reasonable model parameterization, fixed allowances outperform intensity allowances in terms of the expected cost of abatement. This difference in cost outcomes crucially depends on the approximation method applied when linearizing the RBC model. We also simulate policy outcomes under differing model parameterizations to find critical values for energy price and productivity processes that determine when intensity allowances gain advantage over fixed allowances.

The plan of the dissertation is as follows. The second section presents the essay “Changing Political Regimes and Tropical Deforestation”. The third section consists of the essay “Performance Bonds in Timber Concessions”. The fourth section presents the essay “Fixed vs. Intensity Permit Allowances”, while the last section offers concluding remarks.

2 CHANGING POLITICAL REGIMES AND TROPICAL DEFORESTATION

2.1 ABSTRACT

Expansion of agriculture is a main cause of tropical deforestation. Government policies and weak property rights contribute to this process by encouraging landowners and landless to accelerate land clearing. Using panel data common to previous studies, we add the dimension of new political regimes, democratic and non-democratic, and investigate how the rate of agricultural land expansion in tropical countries depends on the nature and persistence of each regime. We find that both new autocratic and democratic regimes have accelerated the expansion of agricultural land, thus yielding support to some of the findings in the earlier literature. Interesting differences emerge between regions, with the impact being most pronounced in Latin America. We interpret these results mainly in the context of increasing tenure and ownership insecurity, which in turn is driven by the tendency of new regimes to implement land reforms as a form of social and economic policy or voter payback. The argument is developed more formally using a simple competitive land use model with political regime dependent confiscation risk and agricultural subsidy policy.

2.2 INTRODUCTION

Tropical deforestation and its underlying causes have been an area of active research at least for the past three decades. It is widely agreed that the main driver of forest loss has been the rapid expansion of agricultural land. Other significant causes are road building, illegal logging, industrial harvesting through concessions, and fuelwood collection by local communities (Pfaff et al. 2010). Population pressures and economic development have also been commonly identified as important overall drivers. In many instances, however, the actions and policies of the governments, in addition to institutional characteristics of the countries, certainly work to magnify the extent of deforestation. Insecure property rights and subsidies for agriculture favor clearing land over keeping native or plantation forests. Political instability, perceived through quick turnover of regimes, and accompanying ownership uncertainty further reduce the profitability of long term investments, such as forestry, favoring instead some form of extensive agriculture (Bohn and Deacon 2000).

A considerable number of tropical forest countries have gone through some degree of political upheaval, such as revolutions and military coups, during the past half century. For example, the first part of 1990's witnessed multiple democratization processes in Africa alone, and the Latin American countries have been oscillating between autocratic and democratic regimes since the Second World War. The ownership of productive land has frequently been at the core of the controversial issues surrounding postcolonial countries, and thus unsurprisingly, has provided a spark for many political conflicts leading to regime changes (Prosterman and Riedinger 1987). To consolidate their power, or to preserve old privileges, new political regimes have recurrently enacted policies to redistribute land, commonly including provisions granting land ownership to migrants who clear forests.[1] The effects of these land reforms on tropical deforestation in turn may depend on the success and persistence of each new regime in power.

The purpose of this chapter is to highlight the impact of the political economy on tropical deforestation from a perspective that extends past work (Bohn and Deacon 2000; Edward Barbier 2001; Lopez and Galinato 2005; Buitenzorgy and Mol 2010). Using panel data and robust estimation methods, we examine how changes in political regime type affect the rates of tropical deforestation through agricultural land expansion. We propose a simple competitive land use model similar to Amacher et al. (2008) that captures the main effects of a new political regime on the economy's land allocation decision. New regimes may cause changes in the agricultural margin either through regime dependent land confiscation risk or through changes in agricultural subsidies, or both. This model and its predictions form the theoretical basis for our empirical investigation that in turn is closely related to Barbier (2001) and Rodrik and Wacziarg (2005).

Most recently, Buitenzorgy and Mol (2010) examine the causal relationship between democratization and deforestation in cross-sectional setting using regime data compiled by Polity IV Project.[2] We too make use of the Polity IV project to encode a set of regime transition indicator variables in a panel data context. This allows us to derive more reliable coefficient estimates and distinguish between new and established regimes. The same empirical strategy

[1] These reforms have been varying in their scale and scope, and in underlying intentions. Some have included direct expropriation and redistribution of private land, whereas others have aimed at encouraging peasants to colonize frontier lands. Adams (1995) observes that many historical land reforms in tropical countries have been purely opportunistic in their motives.

[2] Bohn and Deacon (2000) also employ a similar type of an approach to identify the political factors influencing the investment environment. Their data on political attributes, however, come from a different source and the results with respect to deforestation are based on a limited cross-section study.

was recently applied by Rodrik and Wacziarg (2005) to identify the impact of democratization on economic growth. Buitenzorgy and Mol (2010) combined forest cover data for the developed and developing world, but our work instead concentrates on explaining the expansion of agricultural land in tropical forest countries, and we go beyond cross sectional data by using a panel spanning 70 tropical countries from 1961 to 2008.[3]

Our main finding is that both new democratic and autocratic regimes are statistically and quantitatively significant causes of higher rates of agricultural land expansion in tropical countries. The expansion of agriculture in turn drives tropical deforestation at the agricultural margin. In terms of our analytical model, relative rents from agriculture become higher after a regime change, thus expanding the agricultural margin at the expense of forests. Our results give support to the findings in Barbier (2001) where political instability was shown to be a significant and positive cause of agricultural land expansion. Our approach, however, enables us to identify the effects of both autocratic and democratic regime changes and their persistence on agricultural land expansion. We also make a contribution to the recent literature on the effect of democratization vs. economic growth on environmental outcomes (e.g., Midlarsky 1998; Buitenzorgy and Mol 2010). We find that new democratic regimes accelerate the expansion of agricultural land whereas established democracies do not. We furthermore find that higher income levels as measured by GDP translate to decreased agricultural land expansion in Latin America but the opposite holds in Africa. Finally, corruption control plays an interesting role through its interaction with the level of income, and its effect differs across regions.

In the context of our theory model, we can interpret our main empirical findings through the hypothesis of reduced ownership security, which itself is caused by political instability and government policies that encourage land conversion.[4] The same underlying cause of deforestation has been discussed extensively in the past literature (e.g., Deacon 1994; Mendelsohn 1994; Deacon 1995; Deacon 1999; Bohn and Deacon 2000; Amacher et al. 2008). For example, Mendelsohn (1994) demonstrates that even a small increase in the probability of

[3] Barbier (2001) and Barbier and Burgess (2002) recommend using agriculture land data because of problems with the reliability of existing forest cover data. Remote sensing data have recently become more readily available for some tropical countries, but these data are still too limited for the purpose of this study.

[4] Alston et al. (2000) explain how Brazilian land policies incentivize both landowners and squatters to clear the rainforests for pasture. They find that land reform programs have been responsible for 30 percent of deforestation, or approximately 15 million hectares, between 1964 and 1997.

confiscation leads squatters to favor more "destructive" forms of agriculture.[5] It is also possible that new regimes invest in road building at the agricultural margin and provide direct subsidies for farmers, thus accelerating the deforestation process by lowering land access costs.

Although new regimes may enact land reforms for various reasons, some common threads have been pointed out in the literature. For example, a new autocratic regime may implement a land reform in order to appease the poor majority and thus prevent the possibility of a future revolution (Acemoglu and Robinson 2001).[6] Similarly, Grossman (1994) models land reforms as an optimal response on behalf of the landowning class that faces a "threat of extralegal appropriation of land rents".[7] On the other hand, redistribution of wealth is also in the interest of democratic regimes since they need to consolidate support among the poor and also cater to the ambitions of the majority (Midlarsky 1998). As in the case of autocracies, the most obvious way to redistribute wealth is to enact a land reform or to give out public land. Landless people can then claim an ownership stake on underdeveloped land by converting it to more productive uses like agriculture (Mendelsohn 1994).[8]

Alternatively, cultivation driven deforestation may occur through development policies aimed at improving the efficiency of the country's resource use. For example, new regimes might want to increase the output of the domestic agricultural sector. The skewed distribution of ownership, however, has led to a situation where large tracts of productive land lie idle, while sustenance farmers are forced to find living on marginal, and often environmentally fragile, lands (Deininger and Binswanger 1999). Thus land clearing subsidies or direct expropriation, where previously underused land areas are given to landless poor, potentially leads to a higher

[5] Deacon (1994) identifies cronyism and the inability of the government to enforce property rights as the two main factors feeding political uncertainty, which in turn deteriorates the profitability of long term investments. Bohn and Deacon (2000) provide evidence that political instability decreases investment share of total output, thus implying a reduction in forest capital as well.

[6] These mostly modest land reforms have been carried out with the support of the landowning class in the hopes of preventing subsequent more severe infringement of their land holdings (Adams 1995).

[7] Pfaff (1999) describes how in Brazil the military regime's push to colonize the Amazonian Basin in the 1970's was related to their effort to reduce pressures for social unrest due to growing population.

[8] Binswanger (1991) and Alston et al. (2000) provide evidence that such land policies in Brazil have contributed to deforestation through conflicting interests and land clearing incentives. The landowners expelled tenants and embarked on expanding extensive ranching activities after learning about land reform plans (Deininger and Binswanger 1999). In Cameroon the expectations of the 1974 land reform, where the government was planning to confiscate parts of the community forests for commercial exploitation, led villagers to rapidly expand croplands in order to establish ownership claim (Karsenty 2010b).

utilization rate of the land.[9] Redistribution of land can thus lead to land clearing in the form of slash-and-burn agriculture, where areas previously deemed as unprofitable for agriculture are now converted to crop production by the new users.[10] For example, Barbier (2010) makes the observation that the expansion of agriculture to environmentally fragile areas seems to be driven by growing number of rural poor.

The structure of this paper is as follows. In the second section, we present a simple model of competitive land uses and show under what conditions increasing ownership uncertainty, specifically impinging on the forest resources, induces expansion of agricultural land. In the third section, we outline our empirical strategy and the econometric model. The fourth section describes the data and the fifth presents the results with a discussion, while the last section concludes.

2.3 MODEL OF COMPETITIVE LAND USE

In this section, we present a simple model of competitive land use that captures the effect of a new political regime on deforestation process. The goal here is to build a parsimonious analytical framework that can then be used to motivate our econometric model, and to interpret the empirical results in the subsequent sections. The model extends land rent based approaches to include the regime dependent risk of expropriation of land rents and agricultural subsidies.

Change in political regime can be captured via a binary variable $\psi \in \{\psi_0, \psi_1\}$ where ψ_0 means status quo and ψ_1 means new regime. There are two variables that are directly dependent on the political regime: agricultural access subsidy variable, $S_a(\psi)$, and forest rent confiscation probability, $\rho_F(\psi)$. Regime change, autocratic or democratic, will change the value of both of these two variables. We do not know the direction of these changes a priori. It is likely however that new regimes provide more agricultural access subsidies to encourage land conversion, and that the confiscation risk of forestry rents becomes relatively higher.

Land is assumed to be of heterogeneous quality, and the quality of each parcel can be ranked with a scalar variable q, $0 \leq q \leq 1$ (Lichtenberg 1989). This variable captures factors such as distance to markets, tree species, and soil productivity. Each unit parcel is of uniform quality.

[9] International development and loan institutions have also encouraged land conversion to agricultural on their part as a condition for development aid. Democratization has furthermore been an essential requirement for the eligibility to receive external funding from international lending institutions.

[10] The goal of the land reforms in countries like Brazil, Bolivia, and Colombia has been to realign the highly skewed distribution of wealth (Deininger and Binswanger 1999). In many cases, land reform policies are designed so as to penalize owners who keep their land “underdeveloped”.

Let $K(q)$ denote the cumulative distribution function of q, i.e., the set of parcels having at most the quality level q. The total amount of land in a country is then given by:

$$L = \int_0^1 k(q)dq \tag{1}$$

where $k(q)$ is the density function of the cumulative distribution function $K(q)$.[11] There are two possible land uses for each parcel in the economy: agriculture and forest production.[12] Both agriculture and forestry produce land rents, and these rents are increasing in land quality. The economy allocates each parcel of land to its most profitable use.[13] Any parcel that has negative land rents from both agriculture and forestry is left undisturbed as virgin forest.

Any parcel of quality q that is allocated to forestry produces timber at time t given by a production function $F(l_f, q)$ where l_f denotes forestry labor input.[14] Timber production is increasing in both labor and land quality, and there is an exogenous timber price, p_f. Accessing a forest parcel and transporting timber to the market place is costly and requires roads. This cost is captured by function $C_f(R, q)$ where R is the road variable. We assume that access and transportation costs are decreasing in both R and q. The latter property captures the fact that parcels with higher land quality are also located closer to the markets. Political risk adjusted per parcel present value returns from forestry can be written as

$$W(\psi) = \int_0^\infty [1 - \rho_f(\psi, q)] \left(p_f F(l_f, q) - wl_f - C_f(R, q)\right) e^{-rt} dt \tag{2}$$

where r is the discount rate and w denotes wages. Notice that confiscation probability $\rho_f(\psi, q)$ now depends also on the land quality. This allows for certain parcels to face higher political risk, for example, forests closer to agricultural margin.

[11] Although we are assuming that q is a continuous variable here, we still refer to individual parcels as having a certain level of quality.

[12] This assumption undoubtedly simplifies the complex and region specific process of deforestation, but we can justify it on two grounds. First, it enables us to focus on our main argument that new regimes have a more active stance vis-à-vis land reforms, which in turn has an impact on the expansion of agricultural frontier in the tropics. Secondly, our specification does allow our goal of capturing the impact of political regime across different countries with varying land-uses, such as intensive agriculture, shifting cultivation, cattle ranching, plantation forestry, and timber concessions, while controlling for those variables known to be important to deforestation from previous work.

[13] This is a common assumption made in the economic analysis of land-use decisions. The same approach has been used extensively in the past work on tropical deforestation (e.g. Mendelsohn 1994; Deacon 1994; Chomitz and Gray 1996; Pfaff 1999; Angelsen 2007; Amacher et al. 2008).

[14] Later, we make a distinction between concession (extractive) forestry rents and plantation (productive) forest rents.

Agricultural production on any given parcel of quality of q yields output at time t given by a production function $G(l_a, q)$ where l_a denotes agricultural labor input. The production function is increasing in both arguments, and there is a global agricultural price index p_a. As in the case of forestry, accessing the parcel and transporting agricultural products to the market place is costly. This cost is captured by a function $C_a(R, q)$ which is decreasing in both arguments. Per parcel present value returns from agriculture can be written as

$$A(\psi) = \int_0^\infty \left(p_a G(l_a, q) - w l_a - C_a(R, q) + S_a(\psi)\right) e^{-rt} dt \qquad (3)$$

where we have assumed that the wage index w is the same as in the case of forestry production.[15]

We define the total forest land in a country as the total sum of parcels allocated to undisturbed virgin forests and parcels allocated to forestry production.[16] Let q_{vf} denote the land quality where forestry rents are zero, $W(\psi) = 0$. This point determines the undisturbed virgin forest margin. Notice that q_{vf} is a function of the exogenous variables.[17] The following assumptions ensure that unique interior solutions for the land use switching points exist:

$$\begin{aligned} &W^* < A^* \text{ for } q = 1 \\ &W^* > A^* \text{ for } q = q_{vf} \end{aligned} \qquad (4)$$

where the net present values for each parcel have been maximized with respect to the labor input variables.[18] Agricultural production is more profitable on higher quality parcels and forestry is more profitable on lower quality parcels. Parcels with $q < q_{vf}$ are left undisturbed. Figure 2.1 illustrates the meaning of the above assumption by plotting the maximized rents, W^* and A^*, as a function of land quality, q. The point where the curves intersect defines the agricultural margin, q^*. Any shift in the margin to the left that is due to changes in exogenous variables is interpreted as deforestation.

To formalize the allocation decision depicted in Figure 2.1, denote the portion of each land parcel allocated to forestry production as h_f, and the portion of each parcel allocated to

[15] Agricultural land may also be subject to expropriation risk when a new regime comes to power. We have not, however, incorporated this risk in our theory model as it would not change the main tenet of our analysis. Additionally, the confiscation risk impinging on forest land can be thought of as the relative risk of land use.
[16] Forest parcels allocated to harvesting activities can be also thought of as the frontier land or as degraded forests. Deforestation occurs when agriculture takes over these parcels. We discuss this in more detail below.
[17] We derive comparative statics results below.
[18] We assume that the objective functions are well behaved and have a unique maximum for each land quality.

agriculture as $h_a = 1 - h_f$. The economy then allocates each parcel with quality $q \geq q_{vf}$ between the two land uses based on the following maximization problem:

$$max_{h_f}\, PV = \int_{q_{vf}}^{1} \left[h_f W^*(\psi) + \left(1 - h_f\right) A^*(\psi)\right] k(q) dq \tag{5}$$

where W^* and A^* are the maximized values of land rents for each parcel. The optimal labor input decisions, l_a^* and l_f^*, are the corresponding solutions to the per parcel maximization problem.

The first-order condition for the problem in (5) can be written as

$$W^*(\psi) - A^*(\psi) = 0 \tag{6}$$

This implicitly defines the switching point, q^*, called the agricultural margin, that divides the whole land area into two compact subsets of forestry and agriculture uses. Formally, the total areas allocated to forestry and agriculture can then be defined as

$$\begin{aligned} L_f &= \int_{0}^{q_{vf}} k(q) dq + \int_{q_f}^{q^*} k(q) dq = K(q^*) \\ L_a &= \int_{q^*}^{1} k(q) dq = 1 - K(q^*) \end{aligned} \tag{7}$$

Condition $L = L_a + L_f$ holds, where L denotes the fixed total amount of land, L_a is the area under agriculture, and L_f is the area under forestry. Notice that any change in either area leads to an equivalent but opposite change in the other area.

2.3.1 AGRICULTURAL MARGIN

The comparative statics results of this model inform our empirical expectations with respect to key variables. They determine how exogenous forces affect the agricultural margin, q^*, and thus the land allocation decision. If the agricultural margin shifts to the left in Figure 2.1, we take this to mean deforestation. If the margin shifts to the right, we take this to mean expansion of plantation forestry.[19]

[19] Plantation forests are not necessarily a substitute for native forests or even for degraded forest stands. The real definition of deforestation is therefore more nuanced and contested than the one we apply here. Notice, however, that our main goal is to assess the impact of new regimes on agricultural expansion.

Define a parameter vector for the continuous variables, $\Delta = (p_a, p_f, w, R)$, and differentiate the second expression in (7) with respect to the parameter vector to get

$$\frac{dL_a}{d\Delta} = -k(q^*)\frac{\partial q^*}{\partial \Delta} \quad (8)$$

The partial derivative on the right hand side of equation (8) can be derived by implicitly differentiating the first order condition in equation (6). The effect of regime change on agricultural margin is derived using discreet methods. We then arrive at the following predictions (see Appendix A for derivation):

$$\frac{dL_a}{dp_a} > 0; \frac{dL_a}{dp_f} < 0; \frac{dL_a}{dw} \gtreqless 0; \frac{dL_a}{d\psi} \gtreqless 0; \frac{dL_a}{dR} \gtreqless 0 \quad (9)$$

We discuss each of these results individually and their relation to the regime dependent risk.

Agricultural Produce Price Index

The sign of the effect of p_a on agricultural expansion is unambiguously positive: higher prices translate to more land clearing for agriculture, and thus to deforestation at the margin.

Timber Price

Higher timber prices translate to expansion of forestry to previously cultivated land areas. This can be interpreted as expansion of plantation forestry. The magnitude of this effect depends on the political regime risk, and the higher the risk of confiscation, the smaller the change at the margin, q^*.

Labor Unit Price

Since a change in w has an effect on both plantation forestry and agricultural land rents, the overall effect on the agricultural margin is ambiguous. The political regime variable affects the magnitude of this effect and may decide the direction as well. For example, suppose that labor costs decrease because of rapid population growth. Then, if the confiscation risk facing plantation forestry is sufficiently high, the agricultural margin will expand at the cost of forests.

Regime Variable

The effect of a regime change is ambiguous and depends on the sign of the following expression (see Appendix A):

$$J = A(\psi_1) - W(\psi_1)$$

<u>Case 1:</u> $J > 0$

Agricultural rents are now higher than forest rents at the old margin q^*, thus leading to an expansion of agricultural area until the economy reaches a new point q^{**} where $J = 0$ holds again. This outcome occurs if the new regime favors agriculture over forest production. The new regime may subsidize encroachment of agriculture to areas previously under concession harvesting: $S_a(\psi_1) > S_a(\psi_0)$. It may also directly confiscate forest areas at the margin through land reforms and allocate them to farmers who then convert the land to cultivation: $\rho_f(\psi_1, q) > \rho_f(\psi_0, q)$.

Case 2: $J < 0$

Now plantation forestry expands to previously cultivated areas until the economy reaches a new point q^{**} where $J = 0$ holds again. This outcome occurs if the new regime either reduces agricultural subsidies, $S_a(\psi_1) < S_a(\psi_0)$, or reduces the risk of forest confiscation, $\rho_f(\psi_1, q) < \rho_f(\psi_0, q)$.

Roads Variable

Expansion of roads has an ambiguous effect on the agricultural margin since it reduces transportation and access costs for both plantation forestry and agriculture. However, the higher the political regime risk facing plantation forestry, the more likely it is that road building benefits agriculture more, thus leading to an expansion agriculture and deforestation at the margin.

2.3.2 NATIVE FOREST MARGIN

Next, we derive the comparative static results with respect to the virgin forest land area.[20] A decrease in this land area is assumed to mean expansion of concession forestry. The forest land area left as undisturbed is defined as

$$L_{vf} = \int_0^{q_{vf}} k(q)dq = K(q_{vf})$$

The comparative statics are then (see Appendix A for derivation):

$$\frac{dL_{vf}}{dp_a} = 0; \frac{dL_{vf}}{dp_f} < 0; \frac{dL_{vf}}{dw} > 0; \frac{dL_{vf}}{d\psi} > 0, \frac{dL_{vf}}{dR} < 0 \tag{10}$$

We again discuss each of these cases individually and their relation to the regime variable.

Agricultural Produce Price Index

[20] Changes at this margin are not the focus of our econometric study, but we derive these results for the sake of completeness and as guidelines for future research.

Variable p_a has no effect on virgin forest area since in our model, agricultural land expands on areas where concession harvesting is practiced, that is, at the margin q^*.

Timber Price

Changes in timber prices have an unambiguous effect on virgin forests. Higher timber prices attract more timber firms and result in expansion of concession harvesting at the margin. If the regime risk is high, the expansion will be smaller as the concession firms may risk losing their land rents.

Labor Unit Price

Variable w also has an unambiguous effect on the virgin forests. For example, suppose that wages decrease due to population growth. This results in expansion of concession forestry as labor costs are reduced.

Regime Variable

The effect of a regime change is ambiguous. It depends on the sign of forest rents $W(\psi_1)$ evaluated at the old margin q_f. If $W(\psi_1) > 0$, concession harvesting expands on virgin forest areas, whereas if $W(\psi_1) < 0$, virgin forests overtake areas previously allocated to concession harvesting. The first outcome occurs when new regimes actually reduce riskiness of concession harvesting. The second outcome occurs when new regimes increase risks associated with concessions, leading harvesters to abandon old areas due to uncertainty.

Roads Variable

Road building has an unambiguous effect on virgin forest land: more roads reduce the transportation and access costs, thus making expansion of concession harvesting more attractive.

2.4 ECONOMETRIC MODEL

Our goal in this section is to postulate an econometric model that captures the effect of the political regime variable, ψ, on the agricultural land margin, q^*, and thus whether new regimes induce higher or lower rate of deforestation at this margin. Define the percentage change in agricultural area in country i at time t as

$$a_{it} = 100 * \frac{L_{a,it} - L_{a,it-1}}{L_{a,it-1}} \qquad (11)$$

Based on our theory model, we can then write a_{it} in a reduced form as a function of exogenous variables and a random disturbance term:

$$a_{it} = a\left(p_f, p_a. w_{it}, \psi_{it}, R_{it}, \boldsymbol{z}_{it}\right) + \eta_{it} \tag{12}$$

where $i = 1, \dots, N$ and $t = 1, \dots, T$. Vector $\boldsymbol{z}_{it}$ includes other exogenous variables that are known to affect a_{it} directly or indirectly through other variables. The term η_{it} is the stochastic component of our model. It captures unobservable time-specific and country-specific effects as well as other purely random fluctuations coming from outside the model (e.g., measurement errors). The assumptions made about the stochastic term also determine the best estimation strategy.

We next make an auxiliary assumption vis-à-vis the road variable. Road building is assumed to be a function of the lagged change in agricultural land area, the regime variable, and other variables such as quality of institutions, national income, and population growth.[21, 22] More formally, we have

$$R_{it} = R\left(a_{i,t-1}, \psi_{it}, \boldsymbol{s}_{it}\right) \tag{13}$$

where vector $\boldsymbol{s}_{it}$ contains all the other relevant variables.[23] We hypothesize that the lagged variable $a_{i,t-1}$ has a positive effect on road building, meaning that if agriculture expanded in the previous period, then we are also seeing more roads build in the current period. New regimes are also likely to invest in road building in frontier areas as a development strategy (Cropper et al. 1999; Pfaff 1999). Notice that the assumption in (13) makes all the comparative statics results in the previous section ambiguous. It is now possible, for example, that an increase in timber prices actually pushes agricultural land to expand to previously forested areas because of the dynamic effect on road building and the resulting reduction in transportation costs. Similarly, an increase in variable p_a causes an expansion of concession forestry to virgin forest areas because of the expansion in road building.

Substituting (13) into (12) and assuming a linear functional form, we have the following dynamic model:

$$a_{it} = \beta_0 + \gamma a_{i,t-1} + \boldsymbol{\psi}_{it}^{'}\boldsymbol{\beta}_1 + \boldsymbol{x}_{it}^{'}\boldsymbol{\beta}_2 + \eta_{it} \tag{14}$$

---

[21] Data on roads is unfortunately scant and would not allow construction of a large enough sample that is required for consistent estimation (see discussion for estimation method below).

[22] López and Galinato (2005) and Galinato and Galinato (2011) postulate a structural model where road building and crop area, the direct causes of deforestation, are simultaneously determined. They then estimate the contribution of each indirect source of deforestation to the direct causes. The focus of our study is to determine the effect of a regime change on agricultural land expansion and this effect can be through road building, subsidies, or confiscation risk.

[23] Cropper et al. (1999) define similar type of an equation for road building.

Vector $\boldsymbol{x}_{it}$ contains the set of control variables including proxy variables for some of the variables in (12). Control variables include, for example, the level of national income as measured by GDP and its square. This allows us to test for the Environmental Kuznets Curve hypothesis, the existence of a turning point for deforestation-income relationship. Other control variables are described in the data section in more detail. The stochastic term takes the following general form:

$$\eta_{it} = \alpha_i + \omega_t + \varepsilon_{it} \tag{15}$$

Following the standard approach in panel data analysis, we allow for both unobservable individual effects, α_i, and unobservable time-wise effects, ω_t. The individual effects may exhibit correlation with the independent variables in equation (12), i.e. a fixed effects model (FE), or alternatively, they can be viewed as random draws from an i.i.d. distribution with zero mean and common variance, i.e., a random effects model (RE). Usually FE model is preferred in country level settings such as ours, but this hypothesis is testable.[24]

2.4.1 ESTIMATION

A dynamic FE model with a lagged dependent variable yields inconsistent parameter estimates when using a within or first-difference (FD) estimator. This inconsistency, however, disappears in the case of a within estimator as $T \to \infty$ (Nickell 1981). Alternatively, one can apply an instrumental variable method proposed by Anderson and Hsiao (1982), or a GMM-estimator proposed by Arellano and Bond (1991) to get consistent estimates. Both of these methods, however, rely on FD transformation. This is not innocuous in the context of our study since we use constant binary variables to capture the effect of a regime change on the agricultural margin. Laporte and Windmeijer (2005) show that in cases like these, FD estimator performs poorly if the actual treatment effect is not constant in time. Within estimator, on the other hand, tends to be considerably more robust to this type of specification error. Hence, we use a within estimator and rely on T asymptotics. Inconsistency of the within estimator may also result from unobserved or omitted time-varying variables that are correlated with the control variables or the regime change variable. For example, there is a possibility that a_{it} and some of the right-hand side variables in (14) are simultaneously determined (e.g. López and Galinato 2005). Using exclusion restrictions and a Hausman test, we assess whether contemporaneous correlation

[24] The advantage of fixed effects model is that we are able to control for unobserved individual effects that may bias coefficient estimates in cross-sectional studies if they correlated with independent variables.

between the idiosyncratic error, ε_{it}, and a subset of covariates raises concerns over consistency of our estimates.

2.5 DATA

We follow Barbier (2001) and use country level data on annual changes in agricultural area as the dependent variable.[25] Reliability of such data is always a concern, and ideally, we would like to use observations based on more accurate methods such as remote sensing. This is not, however, feasible in the context of our study since to achieve consistent estimates requires a large sample of countries observed over a long time period. Our data come from the following sources: the World Bank's WDI and WGI databases, Penn Tables, and the Polity IV Project. Tropical countries are defined as the countries that have the majority of their land mass located between the tropics (Barbier and Burgess 1997; Barbier 2001). Our final sample is an unbalanced panel dataset including 66 countries and spanning years from 1961-2007.[26] Table 2.1 provides variable descriptions and Table 2.3 presents sample descriptive statistics.

Two shortcomings with our dataset are the lack of price and wage data. These are some of the main components implied by our theory model as well.[27] This information is unfortunately scant, or in many cases, nonexistent. Assuming global timber and agricultural prices we are, however, able to capture their effects through time specific error component that is common to all countries at time t. Variables for cereal yield and agricultural export share also serve as good proxies to the value of agricultural products in different countries. Level of real GDP and GDP growth rate on the other hand provide good proxies for changes in real wages. In order to control for institutional differences, we include a corruption index variable in our dataset. Corruption is frequently found to be an important explanation for unsustainable forest management (e.g., Ferreira and Vincent 2010). The index scores countries on a scale between -2.5 and 2.5, where smaller values mean higher level of perceived corruption. We use a time-averaged index value for each country and then interact this average index with other control variables of interest (Galinato and Galinato 2011).

[25] We have removed observations with zero values since we are mainly interested in cases where there actually have been changes in the expansion rate. To check for potential selection problem, we estimate a Heckman selection model and cannot reject random selection. Thus removing zero observations should not be of concern. We have also removed observations that have exceptionally large values (the lower and upper 1st percentiles).

[26] See Table 2.2 for the list of countries.

[27] Information on road building is also an important missing element (López and Galinato 2005). Data on roads is limited and would not allow construction of a large enough sample.

Next we describe the set of political regime variables that are new to our empirical approach. Using Rodrik and Wacziarg (2005) we have recreated their set of indicators that serve to identify a change in each country's political regime. They use information reported by the Polity IV Project (2002) to encode political regime transitions, whereas we use a newer version (2009) of the same source. Dummy variables "new democratic regime" and "new autocratic regime" take on values 1 starting from the year of a major regime change depending, of course, on the direction of the change. Note that the definition of a major regime change is given by the Polity IV Project (Marshall et al. 2009). These dummy variables continue having value 1 for the subsequent five years unless the regime is disrupted during that period. If the new regime survives the first five years, then the dummy variables "established democratic regime" and "established autocratic regime" take on values 1 thereafter until they are possibly again disrupted by a new major regime change. We also augment the original set of dummy variables in Rodrik and Wacziarg (2005) to include two indicator variables that capture the preceding two years prior to a democratic and autocratic regime change, recognizing that there may be some preemptive policy shifts before a new regime formally takes over.[28]

This complete set of indicators enables us to investigate the impact of different phases of a new political regime in more detail. For example, the average life-span of a military regime is five years (Brooker 2009). These types of regimes are usually concentrated on getting a few specific objectives completed before stepping down. It is interesting therefore to see whether the first years of a new regime have distinct impact on the expansion rate of agriculture as the level of uncertainty on land rents might be at its highest. Notice that the baseline case here is "no regime changes of any kind" during the sample period. Thus the dummy variables capture the effect of a regime change compared to status quo, whether that is a democratic or autocratic regime. Also, it is important to note that transitions from one regime to another are not clear cut or instantaneous necessarily which somewhat complicates the identification of the year of a regime change.[29]

[28] We assume here that the preceding two years are enough to capture the expectations of a regime change and any uncertainty caused by a prospective land reform.

[29] For example, a revolution could sweep in during one year or it could require a prolonged civil war before any clear outcome is perceivable. In many cases, the outcome is actually muddled where the new regime lies somewhere in between the two regime types. In encoding the indicator variables, we have followed the definitions provided by Polity IV in a consistent manner in order reduce ambiguities.

2.6 RESULTS AND DISCUSSION

The estimation results from our empirical model are presented in Table 2.4. The estimated model includes fixed country specific and time specific effects. Robust standard errors are reported in the parentheses below the coefficient estimates. We have interacted the political regime variables and GDP variables with region specific dummy variables.[30] This enables us to determine whether coefficients differ between regions. These region specific interaction terms are presented in the second (Africa) and the third (Asia) columns, whereas the first column represents the baseline estimates which are for Latin America. Additionally, we have added interaction terms for GDP and corruption index. Corruption index itself is time invariant and therefore included in the country specific effects. Notice that our final specification does not include squared GDP term as it was deemed statistically insignificant.

The political regime coefficient estimates provide interesting clarification to the ambiguities in our theory model's predictions. The effects of regime changes seem to be region dependent for the most part. Starting with new democratic regime variable, it is significant at 5% level for Latin America, but there is no statistically significant difference between the regions. Established democracy variable is not significant implying that once democratic regime has survived the first five years it has no tendency to accelerate expansion of agriculture. New autocratic regime variable is significant and positive for Latin America but negative and significant for Africa. This means that in Africa new autocracies have not had a major impact on agricultural land expansion. Established autocracy variable has the same pattern but now also the interaction term with Asia has a positive and significant coefficient. This implies that in Asia established autocracies have accelerated agricultural expansion even more than in Latin America. Preceding years to autocracy have not had statistically significant effect on the dependent variable, whereas preceding years to democracy have had a positive and significant effect in Latin America but negative and significant effect in Africa.

The lagged dependent variable is statistically significant but the coefficient is small, implying low persistence.[31] GDP growth rate has a positive effect on the dependent variable, whereas increases in cereal yield lead to decreases in the rate of expansion of agricultural land. Weaker exchange rate of the local currency in relation to US$ has a positive effect on the dependent variable. Higher population has a positive effect as well. The coefficient for GDP per

[30] We also tried including interaction terms with other control variables but these were not important.
[31] Dynamic IV and GMM estimates for the lagged dependent variable did not differ much from the within estimate.

capita is negative and significant in the case of Latin America, but the interaction term with Africa is positive and significant. This means that higher income level has reduced or reversed agricultural expansion in Latin America, whereas in Africa the opposite holds. Also the corruption interaction term has differing effects across regions. In Latin America, better control of corruption makes GDP to have even more pronounced negative effect on agricultural land expansion. This could mean, for example, that improved corruption control together with income growth implies better property rights enforcement. In Africa and Asia, however, the opposite holds. In these two regions, higher income levels result in higher rate of agricultural expansion when control of corruption is also improving.

GDP and GDP growth variables may potentially violate exogeneity assumption. We use the U.S. real GDP deviations from linear time trend line interacted with trade openness as an instrument to test the exogeneity assumption.[32] This instrument captures the effect of global economic conditions and these effects presumably differ depending on the openness of the economy, hence the interaction form. Moreover, after controlling for agricultural export share, these changes in global economy do not affect the rate of agricultural land expansion. This constitutes as our exclusion restriction. Based on a Hausman test (e.g., Wooldridge 2002), we cannot reject exogeneity at 10% level for either GDP or GDP growth, and therefore, we do not proceed to use instrumental variables estimation methods.

Figure 2.2 presents regional examples of the effects of the first five years of new regimes on the rate of agricultural land expansion. At year zero (not shown in the figure), both Latin America and Africa have their respective steady state agricultural expansion rates, which we assume to be the average values found in Table 2.3. In year one, there is a regime switch and the new regime persists for five years. After that, we assume that both regions return back to their steady state values. Notice that we are not including the effects from the preceding years or the effects from the new regimes becoming established regimes after the first five years. As can be seen from the graph, the effect is most pronounced in Latin America in the case of a new autocratic regime. The rate of expansion is more than doubled. Also new democratic regime in Latin America has a significant effect on the rate of expansion. In Africa, new autocratic regimes have much smaller effect. Notice that since the coefficient estimates for new democratic

[32] Trade openness is defined as the sum of imports and exports divided by GDP.

regime are not statistically different between the regions, the graphs for Asia and Africa would resemble the one for Latin America.

There are some clear interpretations for our collective results. Starting with Latin America, it is well known that this region has witnessed multiple attempts to reform landownership during our sample period, and in some countries, like Mexico, the drive to reform was initiated even earlier. Powerful landlord classes have historically controlled vast tracts of land in many of these countries, and the inequality of ownership has been high. Large estates called "haciendas" and owned by landlords have continued to play a significant role in the political and socio-economic setting. This explains why ownership of land still continues to be a controversial issue and also the cause of land reform and settlement policies under both new autocratic and new democratic regimes. These results are also supported by empirical findings in Barbier (2001). He finds that a general political stability indicator variable is a significant and positive predictor of agricultural land expansion in Latin America. Our interpretation goes further in showing that political regime is important, and as such the results for Latin American countries are best in line with our theoretical predictions. New regimes have a more active stance concerning land use policies exactly because land ownership has been and continues to be at the core of the social and economic issues causing political instability.

Our estimation results for Africa call for an alternative interpretation. Referring to Table 2.3, the descriptive statistics show that new autocracies in this region have been relatively more long-lived than elsewhere. This could imply that the leaders of these autocratic regimes are less worried about being overthrown and thus less inclined to embark on reformist policies. They might also have become more reliant on the rents from other types of natural resources such as oil and minerals. This means that they have not needed to take into consideration the needs of the general population, or the landless, to the same extent as in other circumstances. In Africa, tribal and family hierarchies have furthermore been the traditional and dominant form of societal organization. The impact of new regimes may therefore be smaller than elsewhere as tribal chiefs and other communal leaders have acted as filters between the central power and the tribes' land use decisions. Our results showing that agricultural expansion is reduced during the two years prior to a new democratic regime may capture the effect of prolonged civil wars and chaos.

In many Asian countries, similar to the experiences in Latin America, landlord classes have historically controlled large tracts of land, which have then been cultivated through tenancy and sharecropper arrangements. Such institutions have been less common in Africa (Daley and Hobley 2005), and this additionally can help in explaining the similarities in results between Asia and Latin America, on the one hand, and differences between Africa and the two other regions on the other. There are some anecdotal examples of authoritarian leaders who have used redistribution of land as a political weapon in Asia. For example, Ferdinand Marcos, the authoritarian leader of Philippines from 1965 to 1986, redistributed private land to small farmers under his program "Operation Land Transfer."[33]

2.7 CONCLUSIONS

We began our analysis by proposing a simple land allocation model with regime dependent confiscation risk and agricultural subsidy policy. The theory model provides ambiguous predictions with respect to the effects of new political regimes on the agricultural margin. The purpose of the empirical part is to clarify these theoretical ambiguities, and we make some interesting findings with respect to the region specific differences in these effects. We find that in Latin America and Asia both new democratic and new autocratic regimes have increased the expansion of agricultural land. In Africa, however, new autocracies have not had similar kind of effect on the agricultural margin and new democratic regimes have similarly had weaker positive effect. Our results show that autocratic regimes that have survived the first five years have a tendency to further accelerate agricultural land expansion in both Latin America and Asia. In Africa, this effect has been again considerably smaller. Established democratic regimes have had no statistically significant effect.

Bohn and Deacon (2000) conclude their work with an optimistic note. They deem that the recent "trend toward democracy and reduced political instability worldwide" provides a good prospect for the future of global forests. The main findings of this chapter are not as optimistic, at least with respect to tropical forests in some regions. Once we include new politically constructed data on regime implementation and persistence and success, we find that democratization should not be viewed automatically as a panacea that leads to reduced pressures on the exploitation of tropical forest resources. New democratic regimes might simply favor the socio-economic and political stability implications of wider access to agricultural land over the other land use alternatives (Midlarsky 1998). On the other hand, our empirical results show that

[33] This policy is cited as responsible for gaining wide support of the population for the ruling regime. Land expropriations, however, targeted mainly Marcos's political enemies such as the communist movement (Borras Jr. 2001).

in Latin America, increasing level of income reduces pressures to clear land for agriculture and therefore decreases the rate of deforestation.

Our results provide empirical support for the hypothesis that new regimes, whether autocratic or democratic, favor the political dividends in the form of wider access to agriculture over longer term investments in forestry. Barbier (2010) further notes that the demand for new agricultural land in Latin America, Africa and Asia is unlikely to be reduced. He projects that, within the next forty years, over one-fifth of the expansion in crop production will rely on the creation of new cultivated land area rather than on more intensive use of existing agricultural area, and that two thirds of the expansion area will come at the expense of primary forests. Brooker (2009) on the other hand predicts that the 21st century will witness its share of regime changes, both democratic and non-democratic. The future of the remaining world tropical forests will most likely remain uncertain according to our results, and it will crucially depend on the relative economic values of alternative land uses, but also, without a doubt, on the political pressures to guarantee wider access to cultivated land among the populace.

Figure 2.1: Agricultural margin, q^*, and native forest margin, q_f

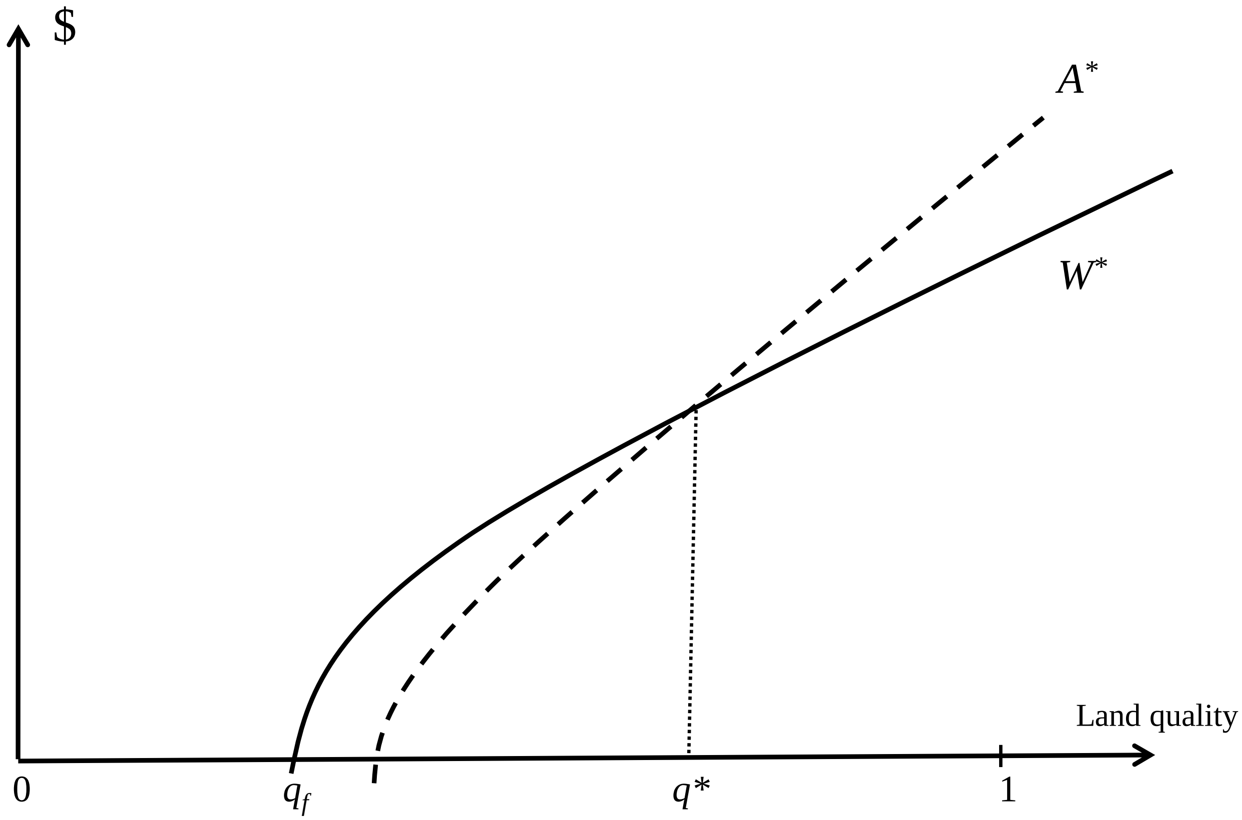


Figure 2.2: New regime effect (first five years) on agricultural land expansion

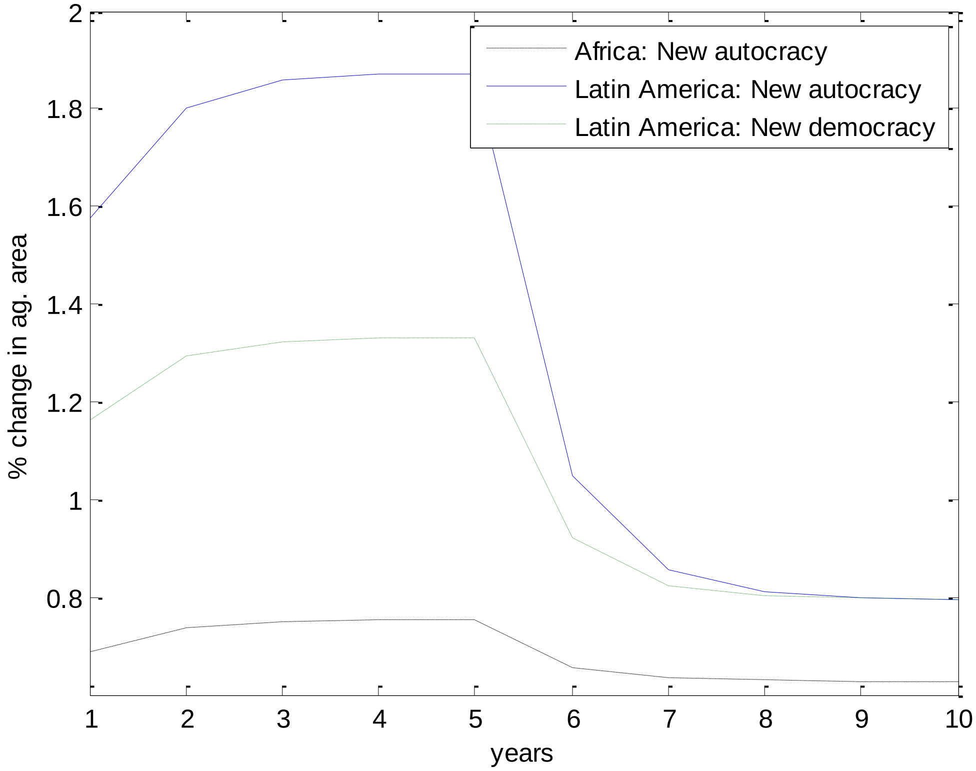


Table 2.1: Variable definitions

Dependent variable:

- Percentage change in agricultural area from last year's value. Agricultural land is defined as the land area that is arable, under permanent crops, and under permanent pastures (WDI, FAO).

Control variables:

- Cereal yield (kg per hectare)
- Agricultural export share of total merchandise exports (%)
- GDP per capita (Constant 2000 US$)
- GDP growth (% annual change)
- Exchange rate to US$
- Total population
- Corruption index variable, time averaged over period 1996-2007 (World Bank WGI)

Regime change:

- New Democratic Regime (first five years, or if interrupted during that period, then the years prior to the interruption)
- New Autocratic Regime (first five years, or if interrupted during that period, then the years prior to the interruption)
- Established Democracy (subsequent years or until a new interruption)
- Established Autocracy (subsequent years or until a new regime interruption)
- Preceding two years prior to a democratic regime change
- Preceding two years prior to a autocratic regime change

Table 2.2: List of countries

Angola, Belize, Benin, Bolivia, Botswana, Brazil, Burkina Faso, Burundi, Cambodia, Cameroon, Central African Republic, Chad, Colombia, Comoros, Dem. Rep. Congo, Rep. Congo, Costa Rica, Cote d'Ivoire, Djibouti, Dominican Republic, Ecuador, El Salvador, Ethiopia, Fiji, Gabon, Gambia, Ghana, Guatemala, Guinea, Guyana, Haiti, Honduras, India, Indonesia, Jamaica, Kenya, Liberia, Madagascar, Malawi, Malaysia, Mali, Mauritania, Mauritius, Mexico, Mozambique, Nicaragua, Niger, Nigeria, Panama, Papua New Guinea, Peru, Philippines, Rwanda, Senegal, Sierra Leone, Sri Lanka, Sudan, Tanzania, Thailand, Togo, Uganda, Venezuela, Vietnam, Rep. Yemen, Zambia, Zimbabwe.

Table 2.3: Descriptive statistics

Sample means and standard deviations

Variables	All Countries (N=1309)	Africa (N=550)	Latin America (N=487)	Asia (N=272)
Annual change in agricultural land (%)	0.803	0.628	0.795	1.170
	(1.378)	(1.202)	(1.354)	(1.657)
GDP per capita/1000 (Constant 2000 US$)	1.294	0.540	2.350	0.927
	(1.358)	(0.872)	(1.425)	(0.648)
GDP growth (% annual change)	3.982	3.705	3.722	5.005
	(4.727)	(5.195)	(4.499)	(3.943)
Exchange rate to US$/1000	0.353	0.326	0.072	0.907
	(1.481)	(0.643)	(0.314)	(3.02)
Total population (in 10 millions)	4.86	1.461	2.393	1.614
	(14.3)	(2.14)	(3.81)	(28.1)
Cereal yield (kg per hectare)	1.641	1.065	1.892	2.355
	(0.851)	(0.546)	(0.699)	(0.848)
Agricultural export share	0.107	0.154	0.054	0.106
(% of merchandise exports)	(0.152)	(0.198)	(0.067)	(0.119)
Average corruption index	-0.545	-0.730	-0.437	-0.366
	(0.444)	(0.447)	(0.396)	(0.380)
New democratic regime	0.122	0.111	0.136	0.121
(first five years dummy variable)	(0.328)	(0.314)	(0.343)	(0.327)
Established democracy	0.183	0.111	0.294	0.129
(subsequent years dummy variable)	(0.386)	(0.314)	(0.456)	(0.335)
New autocratic regime	0.070	0.087	0.064	0.044
(first five years dummy variable)	(0.254)	(0.282)	(0.244)	(0.206)
Established autocracy	0.126	0.204	0.084	0.044
(subsequent years dummy variable)	(0.332)	(0.403)	(0.278)	(0.206)
Preceding years to democracy	0.047	0.033	0.055	0.059
(prior two years)	(0.211)	(0.178)	(0.229)	(0.236)
Preceding years to autocracy	0.031	0.029	0.029	0.040
(prior two years)	(0.174)	(0.168)	(0.167)	(0.197)

Table 2.4: Within estimator results

Two-way fixed effects model with regional interaction terms

Dependent Variable: annual percentage change in agricultural land		Regional interaction terms: Africa	Regional interaction terms: Asia
Lagged dependent variable	0.236***		
	(0.047)		
GDP growth (%)	0.018**		
	(0.007)		
Exchange rate to US$/1000	0.110***		
	(0.040)		
Population (in 10 millions)	0.010***		
	(0.003)		
Cereal yield/1000	-0.316**		
	(0.122)		
Agricultural Export Share/100	0.304		
	(0.327)		
GDP per capita/1000	-0.261**	0.472***	-0.228
	(0.112)	(0.173)	(0.157)
GDP x corruption	-0.702***	1.189***	3.384***
	(0.199)	(0.350)	(0.510)
New democratic regime	0.411**	-0.297	-0.110
(first five years)	(0.182)	(0.229)	(0.234)
Established democracy	0.234	0.205	0.040
(subsequent years)	(0.203)	(0.324)	(0.285)
New autocratic regime	0.824***	-0.729***	0.137
(first five years)	(0.222)	(0.267)	(0.311)
Established autocracy	0.837***	-0.791***	0.840***
(subsequent years)	(0.215)	(0.250)	(0.299)
Preceding years to autocracy	0.571	-0.631	-0.221
(prior two years)	(0.453)	(0.467)	(0.473)
Preceding years to democracy	0.324*	-0.795**	-0.330
(prior two years)	(0.185)	(0.327)	(0.254)
F-test	4.54***		
Breusch-Pagan LM-test	8.28***		
Hausman test	1221***		

3 PERFORMANCE BONDS IN TIMBER CONCESSIONS

3.1 ABSTRACT

We evaluate effectiveness of performance bonding for tropical forest concession management in achieving first and second best outcomes concerning reduced impact logging (RIL) standards. As a novel contribution, we introduce a simple model of two-stage concession design, and focus on the impact of three complications: harvester participation constraints, government repayment risk, and imperfect enforcement. We find several new and interesting results, in particular, imperfect enforcement and bond risk may deter implementation of bonding schemes as either the bond payment has to be set higher or the penalty mapping has to become more punitive. Policy implications, including potential for mechanisms such as REDD+ in improving the bonding outcomes, and the degree of financial support required to guarantee full implementation of RIL, are examined. We find that the necessary REDD+ finances required to support performance bonding schemes may be much higher than expected.

3.2 INTRODUCTION

Poor design and harvesting practices in industrial timber concessions are commonly identified as significant, albeit indirect, causes of tropical deforestation. High grading, illegal logging, and collateral stand damages have led to forest degradation, whereas roads have provided access routes to slash-and-burn agriculture with ensuing deforestation. The standard way governments have regulated these actions is via direct restrictions and limitations but also through taxes, or royalties, for harvesting either based on volume or area, with the idea of seeking a first-best Pigouvian solution. Sole reliance on these instruments has, however, received criticism due to their apparent failures in encouraging sustainable forest management practices. Many, including Ruzicka (2010) recently, have argued for a better evaluation of the obstacles hindering the use of non-tax market alternatives such as bonding in concession design.

Environmental performance bonds have received some attention in the literature as a promising complement to royalties for governments seeking to both capture rents and ensure harvesters follow concessions rules (e.g., Paris et al. 1994; Boscolo and Vincent 2000; Leruth et al. 2001; Macpherson et al. 2010; Ruzicka 2010). The idea is that performance bonds create a stronger incentive for harvesters to comply with concession rules and at the same time provide the government with critical funds to compensate for environmental damages when they do occur.[34] Bonds have not, however, gained much traction in practice for a wide variety of reasons. At the most basic level, setting "the right" bond payment has been difficult. In many developing countries, bond repayment risk and concessionaires' liquidity constraints also raise concerns about the practicability of bonding schemes. Performance bonds nevertheless possess properties that can make them attractive in forest concessions, if designed well.[35]

The purpose of this chapter is to analytically examine the properties of bonding schemes and to identify their potential shortcomings in the context of Reduced Impact Logging (RIL) standards for forest concessions. Previously, Boscolo and Vincent (2000) and Macpherson et al. (2010) have examined the effectiveness of bonds in enforcing RIL standards, whereas Boltz et al. (2003) conclude that the harvesters may not fully implement RIL techniques without additional incentives. Our novel contribution is to concentrate on three well-identified complications: liquidity (credit) constraints on the part of the harvester, imperfect enforcement, and repayment risk stemming from the government's potential inability to pay back the bond at the end of the concession.

The first of these complications is caused by "thin" financial markets, a condition prevalent in many tropical countries, that prevents smaller scale concessionaires from sufficient collateral needed to obtain credit in the first place (Simula et al. 2002; Canby and Raditz 2005; Pescott et al. 2010; Grossheim 2011). Imperfect enforcement has been frequently identified as one of the most problematic features of tropical timber concessions. Obstacles to enforcement can be multifold, such as poor monitoring capabilities, inadequate judicial systems and corrupt governments. Vast concession areas moreover create an environment conducive to low enforcement, contract violations and illegal logging (Callister 1999; Hardner and Rice 2000; Contreras-Hermosilla 2002; Amacher et al. 2012). The third complication stems partly from unpredictable institutional arrangements typical of many of the tropical countries. Governments

---

[34] Mathis and Baker (2002) track the fundamental concept of "assurance" schemes to "materials-use fees" originating from Solow (1971) and Mills (1972). Other examples come from refundable deposit schemes in beverage industry (Sterner 2003), and mine reclamation in the U.S. and Australia (Sullivan and Amacher 2009). Leruth et al. (2001) advocate the use of performance bonding arguing that they reduce public monitoring costs by relying mainly on a final inspection.

[35] Having guaranteed access to funds needed to mitigate potential contract violations is especially relevant in institutional settings where ex-post financial retribution for damages may be uncertain and costly to attain (Boyd 2001). Furthermore, environmental bonds can be used to reveal the true market value of the forest resource when it is combined with competitive bidding procedures (Leruth et al., 2001).

may not be able honor promises to repay the bond at the end of the concession contract, or bureaucratic red tape may make repayment time unreasonably long.[36]

Our analysis represents the first theoretical assessment of performance bonding for tropical concessions under the assumption that there is moral hazard, i.e., the government forest owner may not be able to ensure paying the bond back with probability one, and additionally the harvester may face liquidity constraints. We take a simple static approach that illustrates clearly many of the important issues and results that would still be present in a more complicated model. We will derive the necessary and sufficient conditions that guarantee full RIL implementation by a cost minimizing harvester and discuss when this can and cannot be expected and what its implications are for successful bond design, detailing various second-best outcomes that result when the first-best solution is not attainable. We find, not surprisingly, an important role for supranational parties that provides another important context for REDD+ mechanisms.[37] Using model simulations, our approach allows us to compute the necessary REDD+ transfer that still guarantees full RIL implementation when government repayment risk and imperfect enforcement are present. We also find the critical level of repayment risk that determines whether full RIL realization is possible to achieve given the harvester's participation constraint.

The plan of the chapter is as follows. The next section reviews the issues surrounding the recommendations and debate over environmental bonds for concessions. We proceed by presenting a model of concessions design and bonding in a perfect institutional setting and introduce participation constraint. Section 3 analyses the impact of repayment risk on the harvester's compliance decision and participation ability. Section 4 examines the repercussions of imperfect enforcement on the bond design. Section 5 uses model simulations to assess the practical impact of the various complications analyzed in the previous sections. Finally, the last section offers concluding remarks and policy implications.

---

[36] Institutional uncertainty causes skepticism especially with respect to the transparency and fairness of the final assessment method. Credit constraints are further exacerbated by the presence of such concerns since creditors may require a higher risk premium, or they will simply refuse to extend credit.

[37] Reducing emissions from deforestation and forest degradation (REDD) is one of the main focuses of the ongoing UNFCCC climate change treaty negotiations. REDD+ is a comprehensive policy concept that incorporates variety of approaches and financial incentives that aim at enhancing the forest carbon stocks in developing countries, and encouraging conservation and sustainable forest management practices (Nasi et al. 2011; Pfaff et al. 2010; Karsenty 2012).

3.3 CONCESSIONS AND PERFORMANCE BONDING

This section develops the most basic concession bond model with perfect enforcement and no government repayment risk. The subsequent sections extend this model to incorporate more realistic features that are prevalent in many tropical timber concessions. Before elaborating a model of a bond issuing government and bond paying firm, some background concerning the problem is needed. Forest concessions typically involve the government allocating the forest use rights to a private concessionaire or contracting with a firm for forest management services, all of which require firms to fulfill a wide range of contract clauses (Gray 2002; Karsenty et al. 2008). The main challenge facing the government is how to guarantee concessionaires' adherence to contract rules in an institutional setting characterized by imperfect enforcement and omnipresent corruption, all of which impede tropical developing governments from managing concession design (Amacher et al. 2007).

In the context of industrial logging concessions, performance bonds have been actively discussed for the past two decades as an alternative to poorly designed royalty systems that are not effective at capturing rents or creating incentives for sustainable harvesting, at least since Paris et al. (1994).[38] While there have been some actual experiments with forest concession performance bonds in the Philippines and Malaysia during the 1990's, the policy outcomes were disappointing. Too low of an initial bond payment has been faulted as the main cause for policy failure (Coria and Sterner 2011). Ruzicka (2010), however, argues that performance bonding schemes have never really been tried properly and calls for further investigation of their potential for concessions. Most recently, Nasi et al. (2011) also suggest that performance bonding schemes have potential to enforce environmental goals in concession design. Similar in spirit to what a bond might represent, Amacher et al. (2012) show that the size of a penalty levied against environmental damages that must be mitigated after a concession is completed can be used to control for high grading.

Boscolo and Vincent (2000) and more recently Macpherson et al. (2010) investigate the effectiveness of performance bonding schemes and renewability audits in industrial forest concessions using simulation studies which link their analytical model to practical data. Both

[38] See for example Karsenty (2010), Leruth et al. (2001), Macpherson et al. (2010), Merry and Amacher (2005). Particularly relevant for our study, Leruth et al. (2001) show that royalty rates may fail to encourage the adoption of environmentally less harmful logging practices pointing out that the negative externality is only weakly related to the quantity harvested, thus rendering the classical Pigouvian solution ineffective. Instead of improving the harvest method, the concessionaire may simply cut costs by adopting an even more harmful harvest technology.

studies find that performance bonding schemes can be successfully used to enforce reduced impact logging practices in forest management. Based on their simulation analysis, Macpherson et al. (2012) conjecture that although RIL is found to be superior in comparison to conventional logging methods in net present value terms, concession loggers may still choose to only partially adopt RIL and instead use harvest practices that directly improve profitability. For example, Putz et al. (2008) observe that logging companies employ few forest engineers and few foresters and thus have insufficient competency in RIL techniques.

Despite the promise of these studies, they do not investigate the institutional imperfections common in many tropical countries that could undermine the effectiveness and feasibility of concessions bonding schemes. For example, Merry and Amacher (2005) predict that Brazilian loggers would be highly suspicious of bonding schemes due to distrust of public institutions. Shogren et al. (1993) list moral hazard, liquidity constraints, and legal restrictions on contracts as potential disadvantages associated with performance bonds in environmental regulation.[39] Determining the correct bond payment in the presence of such complications becomes another vexing issue. If the bond is set too low, then it may fail to deliver expected compliance with terms of the concessions contract, whereas too high of a bond might burden the industry up to a point where the entry costs become prohibitive.[40] Liquidity or credit constraints that may either prevent government repayment of bonds to harvesters, or prevent harvesters from posting an initial bond for a concession, naturally also become more severe as the potential for major environmental damages increases.[41] In an imperfect institutional environment, the firms may also expend more resources on legal actions that aim at challenging any losses on the principal payment (Shogren et al., 1993). All the above issues are certainly relevant in the context of tropical logging.

[39] The issue of moral hazard affects the behavior of both the principal and the agent. For example, the principal (government) may choose to confiscate the bond even if the agent (firm) has performed according to the rules, and thus the firms, having realized that they will lose the bond, will simply ignore all costly precautionary measures.

[40] Mathis and Baker (2002) provide a useful comparison of the views how the bond payment should be set. These views were originally discussed in Costanza and Perrings (1990) and in Shogren et al. (1993), but there is disagreement. The former proposes that a bond payment should be set so that it can cover for the "worst probable" environmental damages, whereas the latter requires the bond to be set to equal the level at which it can induce the agent to comply with regulation. Mathis and Baker (2002) call the first view as a form of social insurance aimed at "indemnifying the society" against potential environmental damages, whereas the second resembles more of a deposit-refund system that simply encourages the agent to adopt an environmentally less harmful technology.

[41] Public authorities may also use high bond payments as an instrument to skim financially the strongest (or best connected) participants and thus discriminate against smaller candidates.

In order to accommodate these many observations and realities, we proceed by modeling a situation where the government owns a forest stand,[42] the concessionaire is a large privately-owned firm,[43] henceforth called the concession harvester, and there are reduced impact logging (RIL) standards within the concession contract that specify a list of preharvest procedures and harvesting techniques required from the harvester.[44] The goal of the government is to achieve the highest possible level of application of RIL standards in the concession operation, as this offers the highest protection for the forest.[45] Following Boscolo and Vincent (2000) and Macpherson et al. (2010), we define a continuous index variable $x \in [0,1]$ that represents the exact extent of RIL methods used by the harvester. The lower bound, $\underline{x} = 0$, means no application (business as usual), and the upper bound, $\overline{x} = 1$, means full RIL application.[46] Hence, the index variable x can be thought of as the percentage of RIL procedures that were actually applied during the harvesting.[47] Conversely, $1 - x$ denotes the percentage of RIL procedures that were not applied.

The harvester's convex RIL cost function is defined as $c(x)$ which is increasing and continuously differentiable over a convex and closed set $[0,1]$. Private RIL costs include capital and labor related costs as well as any other related opportunity cost (these may include forgone profits from not engaging in illegal activity).[48] We assume that $c(0) = 0$ holds, although this is not critical. The interpretation for the convex cost function is that the final RIL activities, such as retaining some of the most valuable species standing in the forest, are much costlier to the

[42] The concession stand can be of heterogeneous structure consisting of multiple different species and diameter classes. This assumption is not however crucial for our analysis.

[43] Most of the firms bidding for concession contracts are large harvesting companies with potential to invest in RIL. Many harvesters also have international connections. There are some local harvesters with limited capital equipment that are unlikely to possess resources to adopt RIL. Our analysis here pertains to the larger harvesters.

[44] Putz et al. (2008) define reduced impact logging as "intensively planned and carefully controlled timber harvesting conducted by trained workers in ways that minimize the deleterious impacts of logging."

[45] We do not explicitly model environmental damages in the following discussion. We simply assume that full application of RIL procedures is socially optimal and hence "first best".

[46] Blas and Perez (2008) provide the following list defining RIL requirements: the delimitation of protected forests within concessions; the determination and use of minimum tree diameter at breast height (dbh); the development of a management plan and a logging inventory; minimizing the width and density of the logging roads network; planning of logging roads; setting a maximum ceiling on number of trees felled by hectare; use of directional felling; optimizing timber transport roads network; and planning of timber yards.

[47] Alternatively, the index variable x can represent the proportion of trees that have been treated and harvested according to the RIL standards. Or the index variable can also denote the share of total forest area under RIL management.

[48] Although the literature provides mixed evidence on the relative profitability of RIL over conventional logging practices (Medjibe and Putz 2012), our analysis will take it as given that switching to RIL methods means real costs for the harvester, in one form or another. Boltz et al. (2003) and Medjibe and Putz (2012) find that RIL techniques may incur much higher opportunity costs than conventional logging.

harvester than initial site preparation work such as road building and mapping.[49] Finally, we assume the information on the shape of the cost function, $c(x)$, is symmetric knowledge (e.g., Amacher and Malik 1996). This assumption is realistic as RIL requirements are usually designed by NGOs, are typically known and common knowledge, and the information on the costs of compliance is often readily accessible and part of extension activities in tropical concession countries.[50]

Government sets the bond, B_0, and designs a bond function $B(x; B_0)$	Harvester chooses level of compliance with RIL rules.	Government deducts possible penalties for noncompliance.

Figure 3.1: Timing of events

To enforce RIL standards, the government requires a bond deposit, B_0, from the concession harvester at the beginning of the contract. To make the bond payment operational, the government devises a bond penalty function $B: [0,1] \to \mathbb{R}^+$ that maps the harvester's level of compliance to corresponding penalties. This function may in principle take any monotone decreasing form, although we rule out "all-or-nothing" bonds.[51] Figure 3.1 illustrates the timing of events in our concession model.[52] First, the harvester pays the initial bond payment, B_0, and then takes this entry decision and the penalty mapping, $B(x; B_0)$, as given when deciding the level of RIL compliance. Based on the harvester's RIL decision, the government proceeds to

[49] A convex cost function can be also interpreted as implying that the harvester first fulfills those RIL requirements that have a low marginal cost, and as the level of compliance increases (as we get closer to $x = 1$), the harvester has to comply with rules that have higher marginal costs in terms of x.

[50] We retain the simplification of known costs to focus on other features of the performance bond schemes that would only be reinforced with asymmetrical knowledge of compliance costs or with cost uncertainty.

[51] "All-or-nothing" bonds have been successfully applied in other contexts such as reforestation and mine closure compliance enforcement. In those cases, the regulator releases the bond once the level of compliance has been deemed adequate. In case of RIL standards, all-or-nothing bonds may not, however, be as appropriate for at least three reasons: RIL includes multiple steps that have to be performed during and before the harvesting activity and not as a final procedure; if the harvester fails to comply, the regulator cannot go back and reapply RIL after trees have been harvested; and the harvesters may distrust any bond scheme where the bond release would depend on the last inspection in an otherwise cumulative compliance process. These reasons lend support for using a bond function which explicitly maps bond penalties based on the percentage of compliance.

[52] In a more dynamic setting, reputational effects may become an important consideration (Costello and Kaffine 2008). We leave this for future research.

deduct any penalties from the bond as dictated by the penalty mapping. Hence, we assume that the government is fully able to commit to the bond penalty rule.[53]

For any ex-ante target RIL level $x_0 \in (0,1]$ set by the government, where $x_0 = 1$ means the full RIL target level, we require the penalty function $B(x)$ to satisfy two compliance based conditions: $B(x_0) = 0$ and $B(0) = B_0$.[54] In other words, fully complying with the government's RIL target level, x_0, results in no penalties and zero compliance results in complete initial bond confiscation.[55] The harvester receives back any amount that is left over from the original bond deposit after deducting for penalties. We can therefore think of the bond penalty function explicitly laying out the liability rules imposed on the harvester for all possible concession outcomes.[56] Unlike this chapter, Boscolo and Vincent (2000) and Macpherson et al (2010) both define a linear bond function $B(x) = B_0 - xB_0$, or simply $B(x) = B_0(1 - x)$. This type of bond function, however, uses only the bond payment as an instrument but does not utilize the information about the harvester's cost structure. We expand on this latter point in what follows.

We postulate that the harvester's problem is one of compliance cost minimization as a function of RIL intensity:

$$min_x\{c(x) + B(x; B_0)\} \qquad (16)$$

The sum inside the curly brackets denotes the harvester's total cost of RIL compliance under the bond scheme. It has two components: the private cost of compliance, $c(x)$, which is increasing and convex in *x*, and the bond penalty function, $B(x; B_0)$, which is decreasing in *x*. We have written B_0 explicitly as a parameter of the bond function to make it clear that the properties of the bond function depend on the bond payment.

---

[53] See Amacher and Malik (1996) for a discussion on the role of commitment in environmental regulation.

[54] The government may have to aim at a less than full RIL target level if it knows ex-ante that the maximum bond payment the harvester is able to pay due to capital constraints is not sufficient to guarantee the full RIL target $x_0 = 1$. In the absence of such capital constraints the government would naturally always choose $x_0 = 1$ as its ex-ante target level and then adjust the bond payment, however high, to guarantee this outcome. The impact of a binding participation constraint is explained in the next subsection.

[55] Alternatively, we could use a setup where the government's target RIL level is always at $x_0 = 1$ and let the harvester's *compliance level* vary given the bond payment. We instead use a setting where the government decides the target level x_0 given the bond payment and then aims at *full compliance* with the prescribed target level. The two approaches are equivalent.

[56] A monotone and decreasing bond function makes it somewhat difficult to consider situations where we would like to punish different RIL violations more or less severely. This would add only complexity without additional insights to our analysis. So we assume here that the "ordering" of violations does not matter. Only the extent of deviation from the target compliance matters.

The government designs the bond function $B(x; B_0)$ given its knowledge of the harvester's problem in equation (16) and the properties of $c(x)$. This leads to the following proposition:

Proposition 1

Let $B(x_0; B_0) = 0$ and $B(0: B_0) = B_0$ for some RIL target level of $x_0 \in (0,1)$. Then x_0 is the unique solution to the harvester's problem in equation (16) if and only if the condition

$$B(x; B_0) > c(x_0) - c(x) \qquad (17)$$

holds for any other RIL level $x \neq x_0$ given a bond payment B_0 that satisfies $B_0 > c(x_0)$.

Proof:

The harvester chooses a unique x_0 if and only if $c(x_0) + B(x_0; B_0) < c(x) + B(x; B_0)$ holds for all $x \neq x_0$. Since $B(x_0; B_0) = 0$ by assumption, the proposition follows.

Corollary 1: Full RIL target ($x_0 = 1$)

For a unique solution at $x_0 = 1$, the condition $B(x; B_0) > c(1) - c(x)$ has to hold for all $x < 1$ given a bond payment B_0 that satisfies $B_0 > c(1)$.

Proposition 1 provides bounds for the level and the curvature properties of the bond function given the harvester's cost structure and target RIL level. It simply means that in order to guarantee full compliance with the target level x_0 the harvester must face a higher total cost for choosing any other alternative. The right-hand side of condition (17) stands for the cost savings from not complying, and the bond penalty has to be greater than this to discourage non-compliance. Moreover, the right hand side of (17) is a strictly decreasing and concave function for values $x \leq x_0$ since we have assumed a strictly convex cost function. Hence from now on, we focus solely on bond functions that are strictly concave in the range $[0, x_0]$.[57] It is worth pointing out here that the presence of participation constraints, which we will discuss more below, forms the distinguishing feature of any bonding scheme in comparison to a pure penalty scheme where no ex-ante bond payment is required.

[57] Although not necessary, we restrict our focus on strictly concave bond functions for mathematical convenience.

Proposition 2

Given the target level of RIL x_0, the simplest continuous and non-negative bond function $B(x; B_0)$ that still satisfies the condition in Proposition 1 is given by

$$B(x; B_0) = \begin{cases} B_0 - c(x) - \dfrac{a}{x_0} x, & x < x_0 \\ 0, & x \geq x_0 \end{cases} \quad (18)$$

where $B_0 = c(x_0) + a$ and $a > 0$. This function is decreasing, as required, since the condition $B'(x; B_0) = -c'(x) - \frac{a}{x_0} < 0$ holds for all RIL compliance levels $x < x_0$, and it is constant elsewhere.

Corollary 2: Full RIL target ($x_0 = 1$)

Given the full RIL target, the candidate bond function becomes $B(x; B_0) = B_0 - c(x) - ax$. Any bond payment $B_0 = c(1) + a$ with $a > 0$ achieves full RIL implementation.

Proposition 2, which is proved in Appendix B, provides a candidate bonding scheme that satisfies the conditions in Proposition 1. Hence, this function guarantees a unique cost minimizing point at x_0. We restrict it to be non-negative since negative values would in effect mean that the government pays a subsidy for the harvester's compliance.[58] Figure 3.3 illustrates a bonding scheme that satisfies the conditions in Corollary 2, hence achieving full RIL implementation. Notice that the bond function in Proposition 2 is characterized by two underlying parameters: x_0 and a. The government in effect chooses these values given the harvester's participation constraint. We discuss the role of bond participation cost next.

3.3.1 BOND PARTICIPATION CONSTRAINT

Entering a bond scheme is costly for the harvester. This is captured by a convex bond cost function $F = F(B)$ that is increasing in the level of required bond deposit, B. This function captures the harvester's borrowing costs, including transaction costs related to liquidity

[58] This may, however, provide a way for REDD+ type of funding to move the concession outcome to full RIL application. We develop this in more detail in what follows.

constraints, or alternatively the opportunity cost of using its own capital.[59] For example, as is the case in many tropical countries, concessionaires must resort to external funding for the bond payment as they lack sufficient funds prior to the concession.[60] The bigger the bond the more expensive it is to borrow funds, that is, $F_B > 0$ holds (e.g., interest payments are increasing in B). Most importantly, when the harvester enters the concession contract, the bond cost is sunk and does not enter the harvester's cost minimization problem in equation (16). Later, we introduce the effect of repayment risk on the bond cost function.

The harvester participates as long as bond costs do not exceed some threshold level, defined here as $\bar{F}$. That is, the harvester enters the concession bond scheme if and only if $F(B) \leq \bar{F}$. We assume that this parameter $\bar{F}$ is exogenously given, but conceivably, it could be a function of such things as timber prices, availability of competing investment opportunities, and the harvester's liquidity in financial markets. Naturally, bigger concession harvesters have better access to capital than smaller ones, which means that $\bar{F}$ is likely to be higher for big, multinational firms than for local harvesters. The maximum bond payment, denoted by $\bar{B}$, is given by the inverse mapping of the participation cost function: $\bar{B} = F^{-1}(\bar{F})$. This simply means that when access to funds or availability of capital is better, the harvester is able to post a larger bond at the limit as $\bar{F}$ is higher.

If the highest possible bond payment $\bar{B}$ satisfies the condition $\bar{B} > c(1)$, then Corollary 1 and Corollary 2 hold and achieving full RIL compliance target level $x_0 = 1$ is feasible. We call such cases as the "first-best" bond schemes. Notice that in principle the government can set the bond payment B_0 anywhere between $c(1)$ and $\bar{B}$, or more precisely, $B_0 \in (c(1), \bar{B}]$.[61] If the condition for the first-best is not satisfied, then the government has to design a bond scheme where the target RIL level is such that $x_0 < 1$. We call such cases as the "second-best" bond schemes. Since the government's goal is to achieve the highest possible RIL target level, then choosing the highest possible bond payment $\bar{B}$ to achieve this goal makes sense. This leads to the following proposition which modifies Proposition 2 to include the second-best scenario and is proven in Appendix B:

---

[59] Even if the government offered to pay interest on the bond payment during the holding period, it is very unlikely that this interest rate would coincide with the harvester's private discount rate that may potentially be much higher.

[60] In case of a functioning surety market, the function $F(B)$ captures the premium the harvester has to pay to a surety company in order to receive bond guarantees.

[61] We do not model how the government may choose the first best bond payment. Potentially, the public's demand for environmental insurance may guide this decision.

Proposition 3

Given a target RIL level $x_0 < \bar{x}$, *where* $\bar{x} = c^{-1}(\bar{B})$ *and* c^{-1} *denotes the inverse mapping of the cost function, the simplest continuous and non-negative bond function* $B(x;\bar{B})$ *that is feasible under the binding participation constraint is given by*

$$B(x;\bar{B}) = \begin{cases} \bar{B} - c(x) - \dfrac{a}{x_0}x, & x < x_0 \\ 0, & x \geq x_0 \end{cases} \qquad (19)$$

where $\bar{B} \equiv F^{-1}(\bar{F})$ *and* $a = \bar{B} - c(x_0)$.

In the second-best case, the government's problem has become one of simply choosing some target RIL level $x_0 < \bar{x}$ since the maximum bond payment $\bar{B}$ is exogenously given. The harvester when faced with a bond scheme that satisfies Proposition 3 chooses the unique cost minimizing point x_0.[62] The government does not have an incentive to ask for any smaller bond payment $B_0 < \bar{B}$ as the harvester's participation decision would be unchanged and smaller bond payments would decrease the upper bound $\bar{x}$.[63] Note in this case that by providing a subsidy the government could potentially improve the concession outcome. We compute the required subsidy to move the concession outcome to first-best in the simulation section.

3.4 BOND REPAYMENT RISK

We now allow for the possibility that the harvester loses the entire bond – it is never paid back - with probability *r*, regardless of the level of compliance with the RIL rules. This probability captures, for instance, the risk of fiscal crisis or political turbulence in the country of the concession, or other factors that have an impact on the risk that the government will default on the bond repayment. The harvester may also expect there to be some degree of turnover in the government's payrolls which may increase the uncertainty over the ultimate bond release criteria and timetable. Figure 3.2 shows the timing of the events in our extended model. The main difference in comparison to our earlier baseline case is that we introduce repayment risk in

[62] A linear bond function of the form $B(x) = \bar{B}(1 - x)$ is suboptimal given a binding participation constraint. In this case harvester always chooses a point $x_1 = x(\bar{B})$ which is implicitly given by the first order condition $c'(x) = \bar{B}$. This point may not coincide with the government's target level x_0.

[63] If the government values environmental insurance more than the harvester's borrowing costs, then in the second best case, it should always demand for the highest possible bond payment as this provides the highest indemnification for the society in the case of a contract violation.

the final inspection phase, because this is when the bond would be paid back depending on harvester compliance. We assume here that the whole bond is paid back at the end of the RIL inspection and therefore there is no gradual release of the bond as the RIL compliance proceeds. Gradual release of the bond would most likely be unrealistic since the administrative costs and inspection intensity may become overwhelmingly high, especially in places where the quality of institutions is low.[64]

Government sets the bond function and the bond payment, B_0	Harvester chooses level of compliance with RIL rules	Bond defaulted with probability r, and bond function honored with probability $(1-r)$

Figure 3.2: Timing of Events

If the harvester believes that repayment will not be honored, then this will reduce the effectiveness of a bond instrument. Since this is a risk to the harvester, we assume that the harvester is risk neutral as a baseline. Risk neutral harvesters have been assumed in much of the concessions literature, and in general most harvesters bidding on concessions are larger firms for which this assumption is reasonable (Amacher et al., 2007; Macpherson et al., 2010). The harvester's RIL problem is now reframed as one of expected cost minimization:

$$\begin{aligned} & min_x\, E\{c(x) + B(x; B_0)\} \\ &= min_x\{c(x) + (1-r)B(x: B_0) + rB_0\} \end{aligned} \quad (20)$$

where $E(\cdot)$ is the expectation operator and B_0 denotes the bond payment. The last line in equation (20) means in effect that the risk neutral harvester gives a $(1-r)$ weight to the bond function being honored and weight r to losing the bond.

As in the baseline case above, the government designs a bond scheme that aims at achieving some target RIL level denoted again by x_0. This leads to an analogous proposition:

<u>Proposition 4</u>

[64] In surface mining operations in the U.S. the reforestation bond is released in phases after successful completion of each required step (Sullivan and Amacher, 2009).

Let $B(x_0; B_0) = 0$ *and* $B(0: B_0) = B_0$. *To guarantee a unique RIL solution at* $x_0 \in (0,1)$, *the government has to design a bond scheme such that the condition*

$$B(x; B_0) > \frac{c(x_0) - c(x)}{1 - r} \qquad (21)$$

holds for any other RIL compliance level $x \neq x_0$ *given a bond payment* B_0 *that satisfies* $B_0 > \frac{c(x_0)}{1-r}$.

Proof:

The harvester chooses a unique x_0 if and only if

$$c(x_0) + (1 - r)B(x_0; B_0) + rB_0 < c(x) + (1 - r)B(x; B_0) + rB_0$$

holds for all $x \neq x_0$. The left-hand side captures the harvester's costs at the compliance level x_0 and the right-hand side captures the cost of choosing any other RIL alternative. Since $B(x_0; B_0) = 0$ by assumption, the proposition follows.

Corollary 3: Full RIL target ($x_0 = 1$)

For a unique RIL solution at $x_0 = 1$, *the condition*

$$B(x; B_0) > \frac{c(1) - c(x)}{1 - r}$$

has to hold for all $x < 1$.

Proposition 4 means that, in order to still guarantee a unique solution at x_0, the presence of repayment risk forces the lower bound for the bond function $B(x; B_0)$ to be at a strictly higher level than in Proposition 1 given the same RIL target x_0. This can be seen clearly from comparing the two propositions: in Proposition 4 the term in the denominator is less than one and therefore the expression in the right hand side is larger than the one given in Proposition 1. When $r = 0$, the condition becomes the same as in Proposition 1, and when $r \to 1$, the right-hand side approaches infinity, and thus no bond scheme can achieve compliance. The RHS in Proposition 4 is therefore an adjustment to the difference in costs of complying and not complying by the probability of losing the bond, which increases this expected cost difference. At the limit, when the government confiscates the bond with certainty, the bond function $B(x; B_0)$ has no leverage on the harvester's compliance decision.

Figure 3.4 provides a graphical example of the effect of the repayment risk on a candidate bond scheme. Here the government's target is full RIL implementation, hence the bond function $B(x; B_0)$ hits the horizontal axis at $x = 1$. The lower dashed line represents a bond scheme that would have been designed in the absence of repayment risk, whereas the upper dashed line represents the necessary adjustment that is required in order to guarantee full compliance with the target level in the presence of such risk. Intuitively, repayment risk diminishes the effectiveness of the bond instrument in enforcing compliance, as the harvester believes that his actual RIL decision may become irrelevant in the inspection phase. Consequently, a government that still wishes to achieve the same level of RIL treatment as in the baseline case has to adjust the bond scheme and the bond payment accordingly. Repayment risk always increases the required bond deposit when holding the target level constant.

In an analogy to the Proposition 2 with no repayment risk, we now propose a new bond scheme that is adjusted to take the presence of repayment risk into account. This also enables us to assess the magnitude of REDD+ payments needed to move the concession outcome to full RIL treatment ($x_0 = 1$) in cases where the presence of repayment risk has originally curtailed it being achieved. Now we have the following proposition, with proof in Appendix B:

<u>Proposition 5</u>

Given the RIL target level x_0 and repayment risk parameter r, the simplest continuous and non-negative bond function $B(x; B_0)$ that still satisfies the condition in Proposition 4 is given by

$$B(x; B_0) = \begin{cases} B_0 - \dfrac{c(x)}{1-r} - \dfrac{a}{x_0}x, & x < x_0 \\ 0, & x \geq x_0 \end{cases} \qquad (22)$$

where $B_0 = \frac{c(x_0)}{1-r} + a$ and $a > 0$. This function is decreasing, as is required, since the condition $B'(x; B_0) = -\frac{c'(x)}{1-r} - \frac{a}{x_0} < 0$ holds for all $x < x_0$, and it is constant elsewhere.

<u>Corollary 4:</u> Full RIL target $x_0 = 1$

When $x_0 = 1$, *the bond function proposal becomes* $B(x; B_0) = B_0 - \frac{c(x)}{1-r} - ax$. *Any bond payment* $B_0 = \frac{c(1)}{1-r} + a$ *with* $a > 0$ *achieves full compliance. When* $r = 0$, *we get the same result as in the baseline case without repayment risk. As riskiness increases, the required bond payment also increases and therefore achieving full RIL target level becomes harder when the harvester faces a binding participation constraint.*

When comparing Proposition 2 and Proposition 5, it can be seen that repayment risk has a twofold effect on the bond function: first, the bond payment B_0 has to be set higher than in the baseline case, and second, the slope of the bond function $B'(x; B_0)$ has to be set steeper, or more "punitive". These results are in line with our discussion relating to Proposition 4. Intuitively, the government has to adjust the bond scheme to account for the diminished effectiveness of the bond instrument. Consequently, when repayment risk is present, the government may not be able to achieve the same RIL treatment level as in the baseline scenario if using identical bond payments. Notice, however, that these differences become relevant only when the harvester faces binding participation constraints.[65] In the simulation section we provide an example of how even a moderate repayment risk may lead to total noncompliance when the bond scheme is not adjusted to take this effect into account. These results provide further insights into why previous experiments with bond in concession management may have failed.

3.4.1 BOND PARTICIPATION CONSTRAINT

When repayment risk exists, the harvester now faces a bond cost function $F = F(B, r)$ that is increasing in the level of required bond deposit, *B,* as was the case in the earlier section, but also increasing in the parameter, r. The latter captures the perceived riskiness of the performance bond relative to safer investment. For example, this could simply mean that the harvester has to pay a higher interest rate if the government's ability to repay the bond has been rated lower.[66] More formally, the bond cost function is increasing in risk, i.e., $F_r > 0$ holds. We also assume that condition $F_{Br} > 0$ holds, meaning that the marginal borrowing cost is

[65] In the absence of participation constraints, the government can always ask for a higher bond payment to neutralize the impact of repayment risk.
[66] In case of surety bonds, the surety company may suspect that the government has a moral hazard problem and therefore may partially confiscate the bond. This makes the surety company to increase its premium.

increasing in risk as well. Intuitively, bigger bond payments become increasingly costly under repayment risk.

If the harvester's participation constraint is such that the maximum bond payment satisfies $\bar{B} > \frac{c(1)}{1-r}$, where $\bar{B} = F^{-1}(\bar{F}, r)$, then achieving the first-best is feasible. In this case, any bond payment B_0 such that $B_0 \in \left(\frac{c(1)}{1-r}, \bar{B}\right]$ is possible. The parameter a in Proposition 5 is then defined as $a = B_0 - \frac{c(1)}{1-r}$. If, however, $\bar{B} \leq \frac{c(1)}{1-r}$ then the government chooses $\bar{B}$ as the second-best bond. This guarantees the highest possible RIL treatment target that is feasible given the harvester's participation constraint. The following proposition modifies Proposition 3 to incorporate repayment risk:

Proposition 6

Suppose that $\bar{B} = \frac{c(\bar{x})}{1-r}$ and therefore, $\bar{x} = c^{-1}\left(\bar{B}(1-r)\right)$, where c^{-1} is the inverse of the cost function and $\bar{x}$ defines the upper bound for RIL compliance. Given a target level $x_0 < \bar{x}$, the simplest continuous and non-negative bond function $B(x;\bar{B})$ that is feasible under the binding participation constraint is given by

$$B(x;\bar{B}) = \begin{cases} \bar{B} - \dfrac{c(x)}{1-r} - \dfrac{a}{x_0}x, & x < x_0 \\ 0, & x \geq x_0 \end{cases} \tag{23}$$

where $\bar{B} \equiv F^{-1}(\bar{F}, r)$ and $a = \bar{B} - \frac{c(x_0)}{1-r}$ and where F^{-1} denotes the inverse of the participation cost function.

Proof: The result follows from adjusting the proofs for Propositions 3 and 5, and by making the substitution $B_0 = \bar{B}$.

When comparing Proposition 3 and 6, the effect of repayment risk on the second-best bonding scheme becomes clear. First, the maximum bond payment $\bar{B}$ is lower given the same participation constraint $\bar{F}$. This occurs because the repayment risk increases the harvester's bond costs. With a lower bond payment the government can achieve a lower RIL treatment outcome. Secondly, repayment risk diminishes the effectiveness of the bond payment, and therefore, the upper bound $\bar{x}$ is unambiguously lower than in Proposition 3. This means that with a given bond payment the government cannot achieve as high of a treatment target as was the case in the absence of repayment risk. This result follows from the fact that the bond function has to be designed steeper to punish the harvester more for marginal noncompliance in order to counteract the effect of repayment risk. Since the government cannot increase the bond payment, $\bar{B}$, to adjust for the steeper bond function, the resulting outcome is that the bond function will necessarily hit the horizontal axis at a lower level of RIL treatment than in Proposition 3.

3.4.2 CRITICAL LEVEL OF REPAYMENT RISK

As suggested in the above discussion, whether or not the government is able to design a bond scheme that guarantees full RIL target level $x_0 = 1$ depends on the participation constraint and the repayment risk. In this section, we derive the critical risk level, r^*, below which the government is still able achieve full RIL target given the values for all the other variables. The following proposition captures the main result:

<u>Proposition 7</u>

Let $B_1 \equiv \frac{c(1)}{1-r}$ denote the lower bound for the first-best bond payment, and let $F(B_1, r^*) = \bar{F}$ hold for some critical risk level $r^* > 0$. The critical risk level is then implicitly given by the condition

$$F\left(\frac{c(1)}{1-r^*}, r^*\right) = \bar{F} \qquad (24)$$

By applying the implicit function theorem, we conclude that:

$$\frac{\partial r^*}{\partial \bar{F}} > 0; \quad \frac{\partial r^*}{\partial c(1)} < 0$$

The critical risk level is increasing in the harvester's participation constraint, that is, a harvester with better access to capital can handle a higher level of repayment risk. The critical level of risk is decreasing in the cost of RIL compliance, that is, when compliance becomes more costly, achieving full RIL treatment becomes infeasible with lower and lower levels of risk. In the simulation section, we compute the critical risk level given our functional form assumptions and parameterization.

3.5 IMPERFECT ENFORCEMENT

In this subsection, we consider a more realistic enforcement environment with which the government is forced to operate. The timing is the same as in Figure 3.1, but now the government uses imperfect detection technology to detect the harvester's RIL compliance level. The quality of the government's enforcement technology is captured by the parameter e. The harvester takes its value as given at the beginning of the concession, as in most of the enforcement literature (e.g. Amacher and Malik, 1996). There is an endogenous RIL compliance detection probability given by $\rho(x, e)$ that is a function of enforcement quality, e, and also of harvester's compliance decision (Amacher et al., 2012; Macpherson et al., 2010). The probability of detection is increasing in enforcement quality, e, and decreasing in RIL compliance, x. More formally, the conditions $\rho_e > 0$ and $\rho_x < 0$ hold. The former assumption is intuitive; the latter on the other hand means that the bigger the deviation from the prescribed target level the more likely is detection.[67] It also means that when the ex-ante target RIL level is low to begin with, detecting noncompliance is easier as there are fewer requirements to be fulfilled and subsequently detected. As the government aims at a higher level of RIL treatment, it also needs to improve enforcement by hiring experts and other personnel to assess harvester's performance. Therefore with the same level of enforcement quality, e, detecting noncompliance becomes harder the higher the target level is set.[68]

Assuming a strictly positive level for the enforcement quality, the detection function has the following bounds:

$$\rho(0; e) = 1$$

$$\rho(x_0; e) = \rho_0(e) \qquad (25)$$

The first bound means that the government is able to detect total noncompliance with certainty. The second condition means that when the harvester is fully complying with RIL target level of x_0, then the probability for detecting noncompliance, that is, a slight deviation from x_0, is defined as some lower bound $\rho_0(e)$ that depends on level of enforcement quality. If

[67] As an example, assume that the harvester has chosen $x = 3/4$. The government then detects the resulting noncompliance with probability $\rho(3/4; e)$ and finds full compliance with probability $1 - \rho(3/4; e)$.

[68] Alternatively, this detection probability can also represent the degree of corruption among the inspectors. If, for example, the inspectors are susceptible to industry capture, the harvester can in effect discount the threat of bond penalties since it knows that the inspectors are likely to forgo reporting violations. We do not, however, explicitly include the possibility of corrupt inspectors and bargaining in our analysis.

noncompliance goes undetected, then the harvester receives the entire bond back regardless of the actual outcome.[69]

Assuming again risk neutrality, the harvester's problem becomes one of expected cost minimization given the quality of the government's enforcement technology:

$$\begin{aligned} & min_x E\{c(x) + B(x; B_0)\} \\ & = min_x\{c(x) + \rho(x,e)B(x;B_0) + [1-\rho(x,e)]B(x_0;B_0)\} \\ & = min_x\{c(x) + \rho(x,e)B(x;B_0)\} \end{aligned} \tag{26}$$

where we have used the condition $B(x_0; B_0) = 0$ to eliminate the last term from the second line. Knowing the harvester's behavior given in (11), the government's goal is to again design a bond scheme that achieves some target level of RIL compliance denoted by x_0. This leads to the following proposition proven in Appendix B:

<u>Proposition 8</u>

Let $B(x_0; B_0) = 0$ *and* $B(0: B_0) = B_0$. *To guarantee a unique RIL solution at* $x_0 \in (0,1]$, *the condition*

$$B(x; B_0) > \frac{c(x_0) - c(x)}{\rho(x,e)} \tag{27}$$

has to hold for any other RIL compliance level $x \neq x_0$ *given a bond payment* B_0 *such that* $B_0 > c(x_0)$. *This condition, however, does not guarantee a decreasing bond function because now* $B_0 > c(x_0)$ *is not sufficient for a decreasing function.*[70] *We examine this feature in more detail below.*

Proposition 8 provides the necessary and sufficient conditions that the bond function has to satisfy in order to for the harvester to choose full compliance with the RIL target x_0. The condition in equation (27) resembles the condition (21) in Proposition 4 except now the denominator is also a function of RIL compliance. The intuition remains the same: the government has to make sure that the bond penalty for noncompliance is always greater than the

[69] It is easy to think of a situation where the government instead receives a noisy signal from the actual outcome, for example, as a draw from a probability distribution that includes the actual outcome (say the actual outcome is the mode of the distribution). As an example of such a modeling choice, if the harvester chooses value $x = 1/2$, then the government might receive a signal that gives $\tilde{x} = 3/4$. The government would then deduct a penalty from the bond based on the information given by this signal.

[70] If the bond function is increasing and has values that are larger than the initial bond payment defined as $B_0 \equiv B(0; B_0)$, then the government would in effect need to wield an extra penalty.

harvester's cost savings from not fully complying. Since imperfect enforcement reduces the effectiveness of the bond function similarly as was the case with repayment risk, the government needs to take this into account when designing the bond scheme, hence the adjustment in the denominator.

The main difference in comparison with our earlier analyses is, however, that a bond function that satisfies the condition in Proposition 8 may not be decreasing. This can be seen clearly by taking the derivative of the right-hand side of the expression in equation (27) with respect to x:

$$\rho_x \left[\frac{c(x) - c(x_0)}{\left(\rho(x,e)\right)^2} \right] - \frac{c'(x)}{\rho(x,e)}$$

Since $\rho_x < 0$ by assumption, the above expression may take positive values for some compliance levels. This means that, given some bond payment $B_0 > c(x_0)$, it may be necessary for the bond function to become increasing for some $x \in (0, x_0)$, and possibly even $B(x; B_0) > B_0$ holding for some x in order for it to satisfy Proposition 8. We next propose a bond scheme (proof in Appendix B) that satisfies the condition in Proposition 8 and is also decreasing over the whole range:

<u>Proposition 9</u>

Given the RIL target level of x_0 and the detection probability function $\rho(x,e)$, the simplest continuous and non-negative bond function $B(x; B_0)$ that still satisfies the condition in Proposition 7 and is decreasing over the whole interval is given by

$$B(x; B_0) = \begin{cases} B_0 + \dfrac{[1 - \rho(x,e)]c(x_0) - c(x)}{\rho(x,e)} - \dfrac{a}{x_0}x, & x < x_0 \\ 0, & x \geq x_0 \end{cases} \tag{28}$$

where $B_0 = c(x_0) + a$ and $a \geq 0$. To guarantee a decreasing bond function for all $x < x_0$, we furthermore require that the following "slope condition" is satisfied:

$$\frac{a}{x_0} > \frac{\rho_x[c(x) - c(x_0)] - \rho(x,e)c'(x)}{[\rho(x,e)]^2} \tag{29}$$

for all $x < x_0$ and where ρ_x denotes the derivative of $\rho(x,e)$ with respect to x. This means in effect that, as in the case of repayment risk, imperfect enforcement may cause the required bond payment B_0 to be higher than in the baseline case.

Corollary 5: Full RIL target ($x_0 = 1$)

Given the target level $x_0 = 1$, the bond function becomes

$$B(x; B_0) = B_0 + \frac{[1 - \rho(x,e)]c(1) - c(x)}{\rho(x,e)} - ax \quad (30)$$

Any bond payment such that $B_0 = c(1) + a$ and where parameter $a \geq 0$ satisfies

$$a > \frac{\rho_x[c(x) - c(1)] - \rho(x,e)c'(x)}{[\rho(x,e)]^2} \quad (31)$$

for all $x < 1$ achieves full compliance with the target level.

Proposition 9 is analogous to Propositions 2 and 5 with one important exception being the slope condition. Given the condition in Proposition 8 it may be possible that the bond function is at a higher level than the bond payment, B_0. Since this would in effect mean that the government designs a penalty-bond hybrid, we rule this possibility out by requiring that a and x_0 are adjusted to guarantee a decreasing bond function, hence the slope condition. Effectively, this means that the government would first increase the parameter a, that is ask for a higher bond payment, and if this would not be enough to satisfy the slope condition, then the government would have to decrease the level of required RIL treatment, x_0. Notice that when the constraint on the parameter a is binding due to the participation constraint $\bar{F}$, that is, when it is not possible to ask for a bigger bond payment, then the government has to resort to decreasing the target level x_0. Imperfect enforcement may therefore reduce the level of RIL that is feasible. In the simulation section, we demonstrate using numerical examples how the above results may have a significant impact on the real world concession bond design, and also compute the required subsidy to move a second-best bond scheme to the first-best using the conditions in Corollary 5.

3.5.1 PARTICIPATION CONSTRAINT

The bond cost function, $F(B)$, has the same properties as in the baseline case in section 3.3 and the constraint $F(B) \leq \bar{F}$ continues to hold. If the maximum bond payment $\bar{B} = F^{-1}(\bar{F})$ is such that $\bar{B} > c(1) + a$, where $a \geq 0$ satisfies the slope condition in Corollary 5, then achieving full RIL treatment is feasible. In this case, any bond payment B_0 such that $B_0 \in (c(1) + a, \bar{B}]$ is possible. If $\bar{B} \leq c(1) + a$ for the smallest value of a that still satisfies the condition in Corollary 5, then the government chooses $\bar{B}$ as the second-best bond. This guarantees the highest RIL treatment that is feasible given the harvester's participation constraint. However, if the slope condition in Proposition 9 is still not satisfied, then the government has to adjust the level of RIL target x_0 downwards until the condition is satisfied. In such cases, the parameter a is given by $a = \bar{B} - c(x_0)$. By substituting this into the expression in equation (29), the slope condition in Proposition 9 becomes:

$$\bar{B} > c(x_0) + x_0 \frac{\rho_x[c(x) - c(x_0)] - \rho(x,e)c'(x)}{[\rho(x,e)]^2} \qquad (32)$$

The government adjusts x_0 until the above condition is satisfied for all $x < x_0$. We summarize these results in the following proposition:

<u>Proposition 10</u>

Let $\bar{B} = F^{-1}(\bar{F})$. Suppose that either $\bar{B} \leq c(1)$ holds, that is, achieving full RIL is not possible due to the participation constraint, or that $\bar{B} \leq c(1) + a$ holds for all such values of the parameter a that satisfy the following slope condition:

$$a > \frac{\rho_x[c(x) - c(1)] - \rho(x,e)c'(x)}{[\rho(x,e)]^2}$$

for all $x < 1$. Then the government chooses a second-best target $x_0 < \bar{x}$, where $\bar{x} = c^{-1}(\bar{B})$ and a bond function $B(x, B_0)$ such that

$$\bar{B} > c(x_0) + x_0 \frac{\rho_x[c(x) - c(x_0)] - \rho(x,e)c'(x)}{[\rho(x,e)]^2} \qquad (33)$$

for all $x < x_0$ and

$$B(x; \bar{B}) = \begin{cases} \bar{B} + \dfrac{[1-\rho(x,e)]c(x_0) - c(x)}{\rho(x,e)} - \dfrac{a}{x_0}x, & x < x_0 \\ 0, & x \geq x_0 \end{cases} \qquad (34)$$

where $a = \bar{B} - c(x_0)$.

<u>Proof:</u>

Both expressions can be derived from Proposition 9 using $a = \bar{B} - c(x_0)$ and $B_0 = \bar{B}$ and modifying the proof for Propositions 3.

Here we see that the presence of repayment risk and imperfect enforcement jointly lead to very similar concession outcomes. Both reduce the highest level of RIL treatment that is feasible when the harvester's participation constraint is binding. If the government designs a bond scheme that does not factor in these two features, then achieving the desired target level is not possible as it is most likely set too high. Since imperfect enforcement, corruption and repayment risk are all persistent features of many tropical timber concessions, achieving full RIL application with bond instrument is hard to envision without institutional improvements. To assess the severity of these factors on the success of performance bond schemes, we next turn to model simulations.

3.6 BOND SIMULATIONS

To gain better understanding of how performance bonds work in practice, we use simulations built on the analytical framework laid out in the previous sections. We start by defining the functional forms for the RIL cost function $c(x)$, participation cost function $F(B)$, risk adjusted participation cost function $F(B, r)$, and the detection probability function $\rho(x, e)$. There have been various attempts to quantify the cost of RIL in the literature (Medjibe and Putz, 2012). Holmes et al. (2001) list RIL related costs by each component and each task has a differing cost. Opportunity cost of RIL compliance may become even higher than the actual technical costs. To keep the analysis tractable, we propose the following functional forms for the RIL cost function and the harvester's participation cost function:

$$\begin{aligned} c(x) &= kx^2 \\ F(B) &= d_1 B + d_2 \end{aligned} \qquad (35)$$

where k, d_1, d_2 are parameters that we choose to calibrate the model to fit real world data. The RIL cost function takes a simple quadratic form to capture the increasing costs of implementation, and the participation cost function is simply a linear function in bond size. Parameters d_1 and d_2 can be thought of as the interest rate and fixed borrowing cost, respectively.

To examine the impact of repayment risk, we use a risk adjusted participation cost function:

$$F(B, r) = \frac{1}{1 - r}(d_1 B + d_2) \qquad (36)$$

Notice that when $r = 0$, $F(B, r)$ is the same as in (35), and when $r = 1$, we have $F(B, r) \to \infty$. This means that the harvester cannot enter a bond scheme where the government confiscates the whole bond with certainty. In other words, the harvester is unable to borrow funds from the financial markets to pay for such a bond. To study the effect of imperfect enforcement, we suppose that the detection function takes the following form:

$$\rho(x,e) = 1 - \frac{1}{e}x \qquad (37)$$

where $e \in [1, \infty]$. The above form for the detection function means that the probability of detection is a linear function of compliance level x and increasing in the level of enforcement quality, e.[71] As $e \to \infty$, the government detects all deviations with certainty. The boundary condition for the detection probability becomes $\rho(x_0, e) = 1 - \frac{1}{e}x_0$. When examining the effect of imperfect enforcement we use the participation cost function given in (35).

Concession literature provides mixed evidence on the relative cost of fully implementing RIL. Some studies have found that RIL is more profitable than conventional logging but these studies do not usually account for the various opportunity costs related to sustainable forestry. In our simulations, we assume that fully implementing RIL costs an additional \$100 per hectare, and use this value to pin down parameter k with condition $c(1) = k$ from our cost function specification.[72] The interest rate at which the harvester is able to borrow funds is assumed to be 15% and the fixed borrowing cost is specified as \$5 per hectare. We use two participation constraint values: \$15 and \$25 per hectare. Table 3.1 summarizes the parameter values used in our simulation study.

Figure 3.5 presents the simplest second-best RIL scenario. We set the participation constraint, $\bar{F}$, at \$15. Consequently, the maximum target level and maximum bond payment are $\bar{x} = 0.82$ and $\bar{B} = 66.7$, respectively. For expositional reasons, we assume that the government sets the RIL target level at $x_0 = 0.77$. The government then uses this information to design a bond scheme following the conditions given in Proposition 3. Both the RIL target and the bond payment are shown in Figure 3.5. The harvester fully complies with the target as it is the point that minimizes the total cost of compliance, $T(x)$. It is also easy to calculate the minimum per hectare subsidy required to move the concession outcome to the first-best: $\$100 - \$66.7 = \$33.3$.

---

[71] Notice that for any two compliance levels x_1, x_2 such that $x_1 > x_2$, condition $\rho(x_1, e) < \rho(x_2, e)$ holds. This also means that any deviation from a higher target level is harder to detect than when the target is set lower (see the discussion in the first paragraph of the previous section).

[72] For example, Macpherson et al. (2010) find that approximately \$200 bond payment per hectare is needed to guarantee full RIL implementation. Given that we do not really know the harvester's participation constraint, the exact number used here does not change the insights gleaned from the simulation study.

Figure 3.6 shows a concession outcome with repayment risk 0.3 and a participation constraint of \$25 per hectare. The bond is set at \$83.3 per hectare which is the highest possible bond the harvester can pay given the risk adjusted participation constraint (36). The government therefore has to aim at a second-best outcome, that is, due to the repayment risk, the government cannot target full RIL treatment. Given this bond payment, the maximum target level is $\bar{x} = 0.76$. We assume that the government sets a target $x_0 = 0.71$. The dashed curve with a kink point captures the expected total cost of compliance, $T(x)$, and it attains its minimum value at the target level x_0. Hence the harvester fully complies. To move this bond outcome to the first-best, a minimum subsidy of \$60 per hectare would have to be available. This follows from computing the lower bound for the first-best bond payment using the formula $c(1)/(1-r)$, which becomes \$143 per hectare using our simulation parameterization.

Figure 3.7 shows a situation where the government designs a bond function in a way that does not incorporate the presence of repayment risk. The government may think, for example, that the participation constraint, $\bar{F} = \$83.3$, is simply caused by thin financial markets, and tries to form a second-best bonding scheme following Proposition 3. The target level is set at $x_0 = 0.86$ but the harvester ends up choosing $x = 0$ as this is the point that minimizes the total expected cost. With the same parameter values as in Figure 3.6, the concession outcome is now zero compliance. The government failed to design the bond scheme in such a way to penalize the harvester sufficiently for noncompliance. Also the initial bond payment, B_0, was not high enough to justify the higher level of RIL targeting, $x_0 = 0.86$.

Given the parameter values $\bar{F} = \$25$ and $c(1) = \$100$, the critical risk level is 0.12. This means that if the repayment risk exceeds this threshold, then achieving full RIL treatment is not possible. Figure 3.8 illustrates how critical risk level varies as we change the values of the participation constraint and the full RIL cost per hectare. In the upper graph, we let $\bar{F}$ take different values while holding the full implementation cost at \$100, and in the lower graph, we let $c(1)$ vary while holding the participation constraint at \$25. These graphs confirm the analytical results in Proposition 7. Notice that when the cost of full implementation exceeds the threshold of \$133 per hectare, the critical risk level becomes zero and therefore the presence of even a small repayment risk precludes full RIL targeting. On the other hand, when participation constraint is below \$20, full implementation becomes infeasible in the presence of repayment risk. In both cases, these thresholds correspond to the second-best limits.

In the case of imperfect enforcement, Figures 3.9 and 3.10 present a successful and unsuccessful bond schemes, respectively, given $\bar{F} = 25$. In Figure 3.9, the government has designed a bond scheme following Proposition 10, thus leading to a higher bond and lower level of RIL treatment than what would be the case under Propositions 2 and 3. Now the government targets the maximum level of RIL, $x_0 = 0.88$, using the maximum feasible bond payment given by $\bar{B} = \$133$. This example illustrates how the government has to adjust both parameters a and x_0 since the participation constraint has become binding because of imperfect detection. In Figure 3.10, the government is now following Corollary 2, thus targeting full RIL, and using a bond payment of $110 per hectare. But the harvester chooses $x = 0.61$ as this is the point that minimizes the total expected cost. This is well below the target RIL level of $x_0 = 1$. To move this concession outcome to the first-best, a subsidy of $50 per hectare would be required. This can be computed as the difference between the bond that satisfies the slope condition defined in Corollary 5 and the maximum feasible bond $\bar{B} = \$133$ (see Appendix B). If the participation constraint were $15 per hectare, the subsidy would need to be at least $117 per hectare.

3.7 CONCLUSIONS

Our theoretical analysis and the simulation examples explore the ways in which repayment risk and imperfect enforcement together with a binding participation constraint can undermine the effectiveness of bonding schemes in inducing RIL compliance, and propose conditions that need to be satisfied in order to reach the desired RIL treatment target in timber concessions. We present several new and important findings. We show that both imperfect enforcement and repayment risk increase the required level of bond payment and may force the government to aim at a lower RIL target level when the participation constraint is binding. We define and quantify the concept of critical risk and derive the "slope condition" that has to be satisfied by a decreasing bond function in the presence of imperfect enforcement. These findings collectively shed some new light on the question why performance bonding schemes in concession design have not been successful and how they may be improved.

The main policy implication stemming from our above analysis and the simulation results is that the necessary REDD+ finances required to support performance bonding schemes can be much higher than what anticipated. Our results show that these sums can be quite significant when repayment risk and imperfect enforcement are present, thus emphasizing the need for a comprehensive approach that focuses on capacity building and transparency in concession management and administration. Careful assessment of the institutional and enforcement realities in each concession setting is needed to estimate the limitations of bond instruments in attaining full RIL treatment outcome. Failure to do so can lead to gross errors as highlighted in our simulations examples. REDD+ related finances may, however, carry the extra benefit of reducing repayment riskiness directly as international entities are more likely to have a lower default risk. In this case, it may also be worthwhile to consider establishing credit lines for financial institutions specializing in surety markets.

As we have stressed throughout the chapter, the distinguishing feature of a bonding scheme is the presence of a participation constraint. This provides a natural route for REDD+ finances to lift the concession outcome to the first-best. In practice, a bond-subsidy scheme would entail a promise to pay the harvester any subsidy after the completion of the required RIL procedures. Such a hybrid scheme would still entail the harvester having to post a bond, thus guaranteeing the government access to funds that at least partially compensate for potential contract violations. Bond-subsidy schemes also carry the additional benefit of introducing a third party element, such as a surety entity, to ascertain that the harvester fully complies with the RIL target and receives the subsidy at the end of the concession harvesting, potentially its own compensation depending on that. Therefore, bonding schemes continue to possess attractive properties which can be utilized to move tropical timber concessions on a more sustainable basis given an appropriate bond design and sufficient financial support.

Figure 3.3: Full compliance

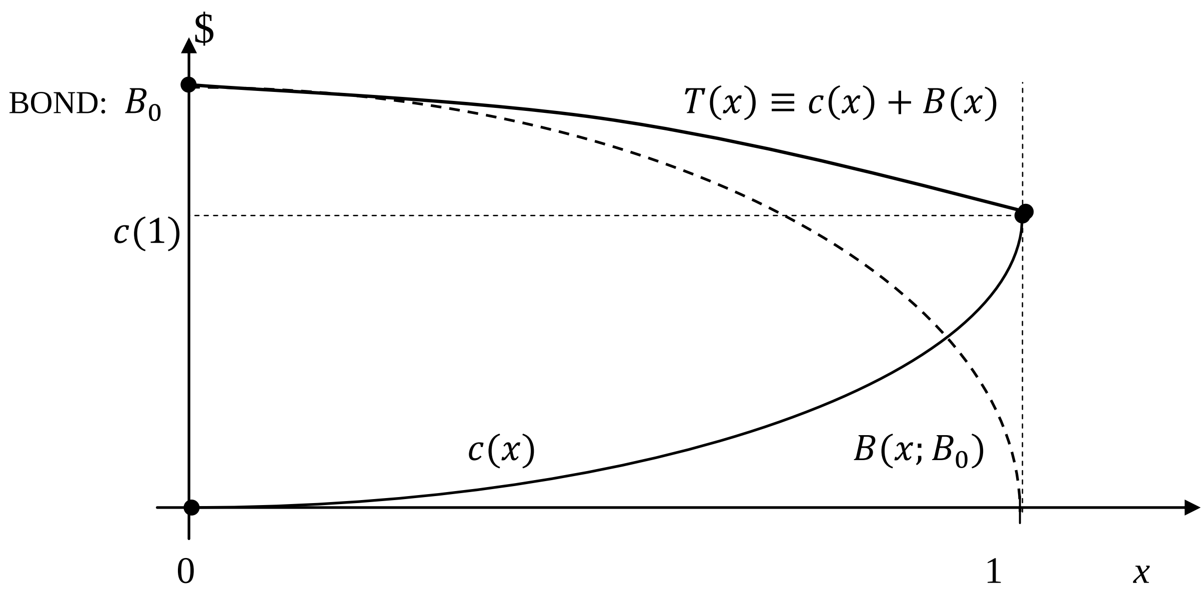


Figure 3.4: Repayment risk

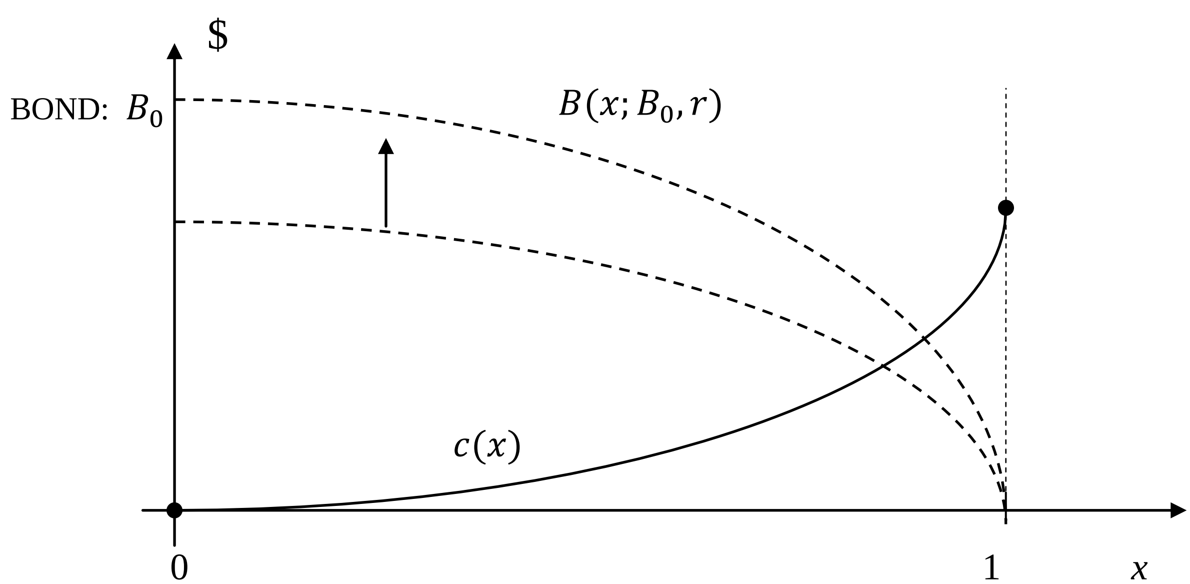


Table 3.1: Parameter values

Parameter	Value	Description
$c(1)$	\$100	Cost of full RIL per hectare
k	100	Cost function parameter
d_1	0.15	Participation cost function
d_2	5	Participation cost function
$\bar{F}$	\$15,\$25	Maximum bond cost per hectare
e	1.2	Quality of enforcement parameter
r	0.3	Repayment risk parameter

Figure 3.5: Second-best bond scheme

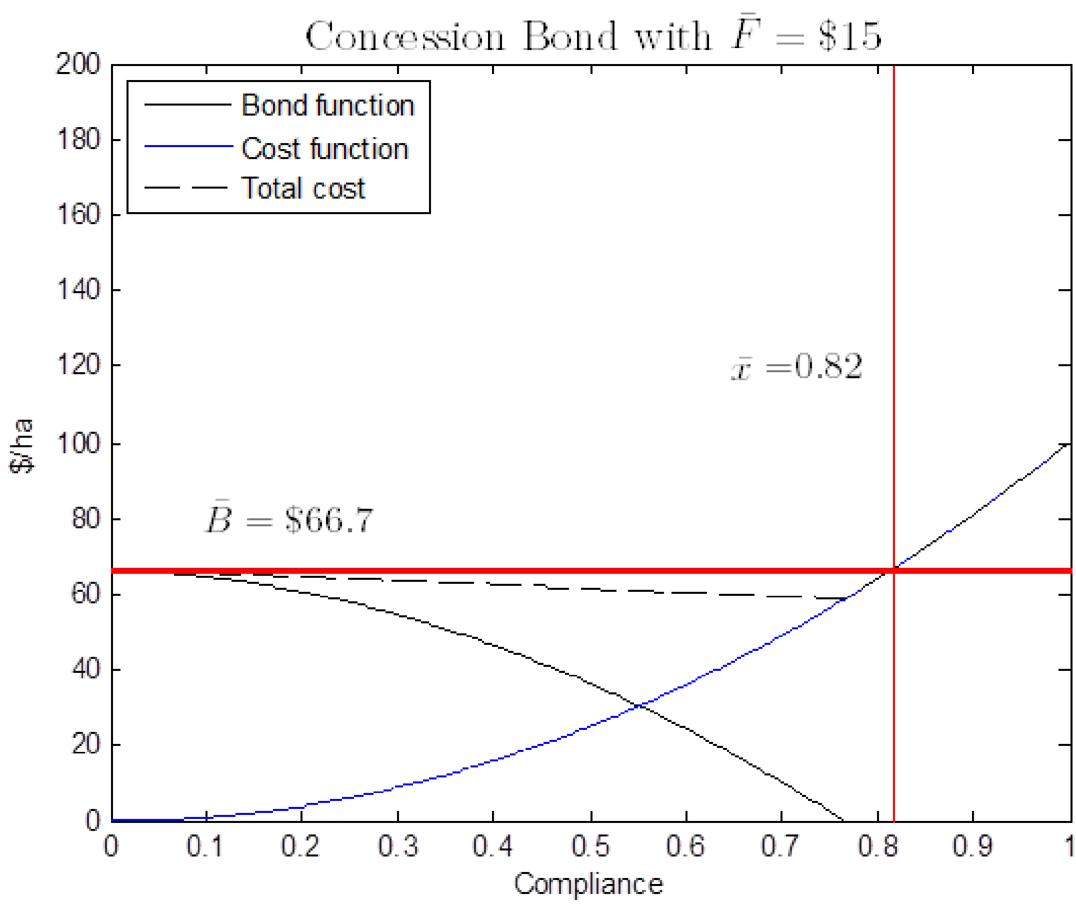


Figure 3.6: Bond scheme with repayment risk

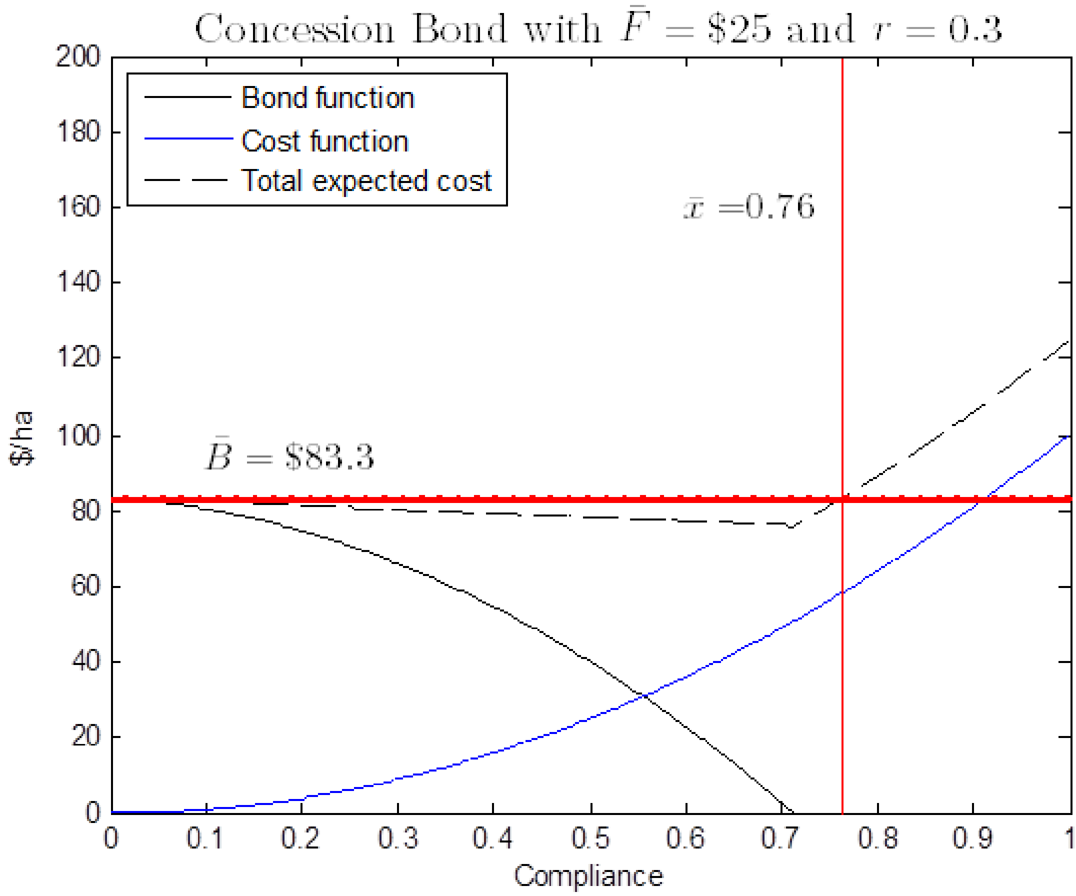


Figure 3.7: An example of bond failure in the presence of repayment risk

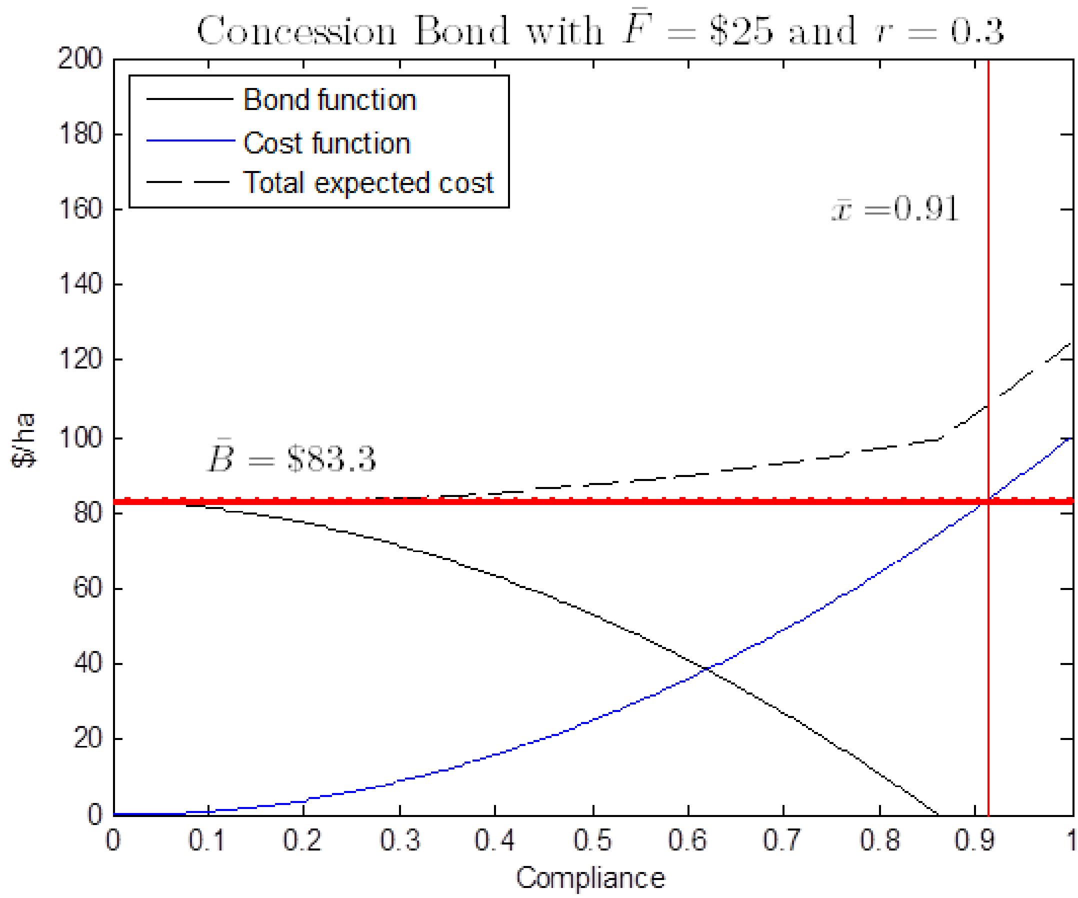


Figure 3.8: Critical risk

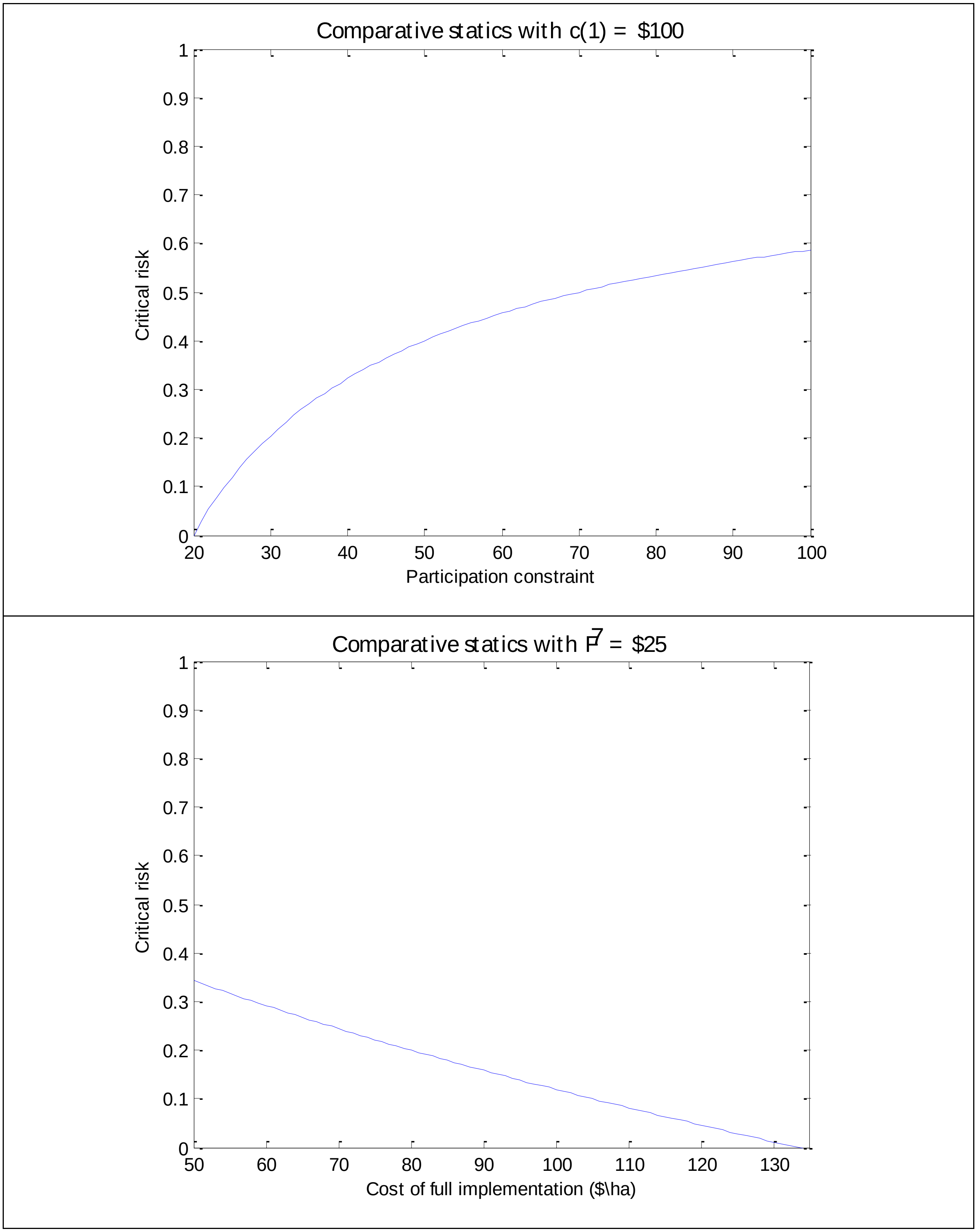


Figure 3.9: Bond scheme with imperfect enforcement ($\bar{F} = \$25$)

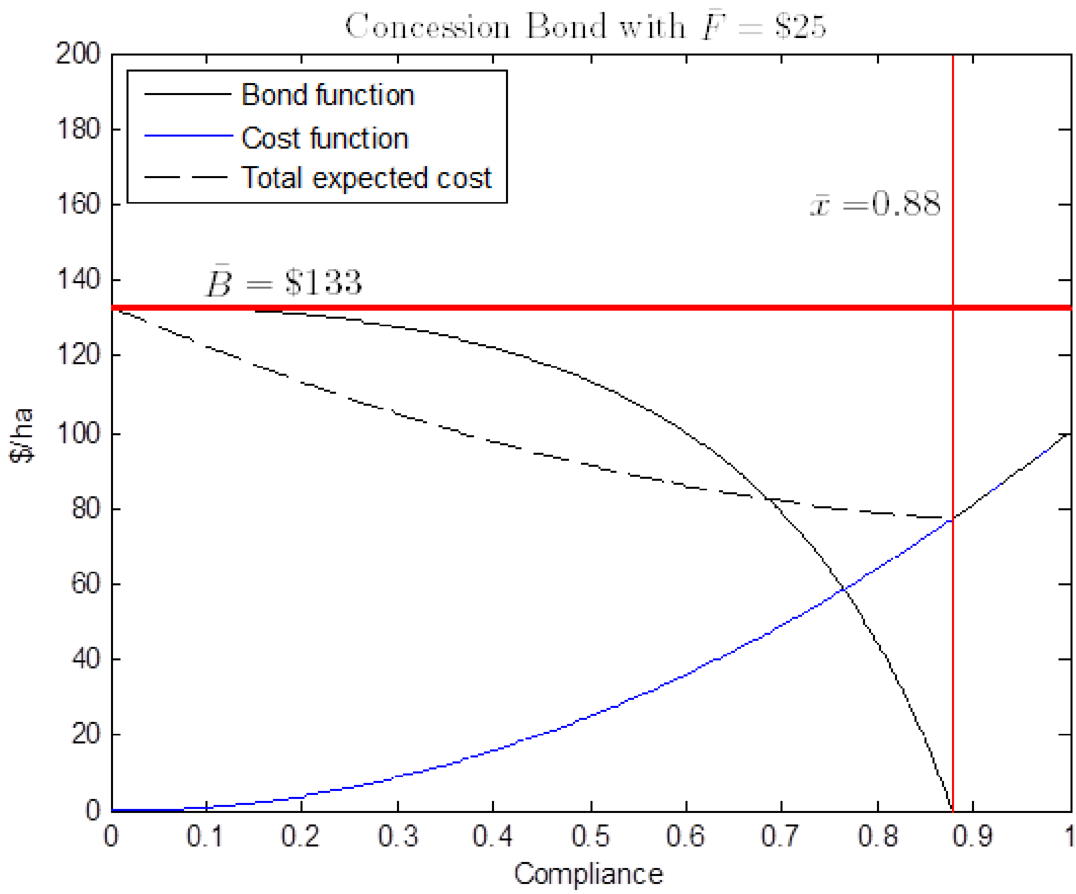
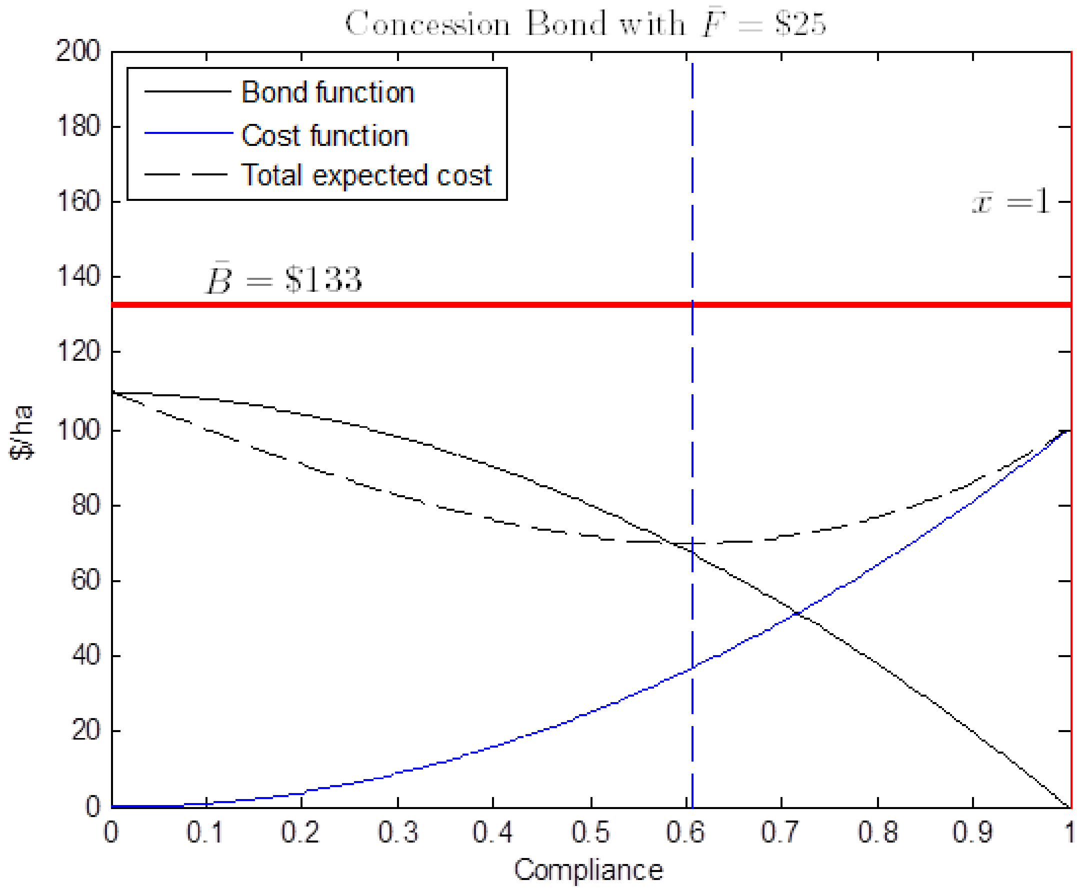


Figure 3.10: An example of a failure of the bond scheme in presence of imperfect enforcement ($\bar{\mathbf{F}} = \$25$)



4 FIXED VERSUS INTENSITY PERMIT ALLOWANCES

4.1 ABSTRACT

Tradable permit markets for carbon dioxide ($C0_2$) emissions respond to short run fluctuations in economic activity as showcased by the recent experiences in the European Union Emissions Trading Scheme (EU ETS). To provide stability in future permit systems, both price and quantity interventions have been proposed. Our research focuses on the relative performance of fixed versus intensity allowances in the presence of both productivity and energy price uncertainty. Both allowance instruments achieve the same steady-state emissions reduction target of 20%, which similar to the current policy proposals, and the regulator then chooses the allowance policy that has the lowest expected abatement cost. We use a standard real business cycle (RBC) model to solve for the expected abatement cost under both policies. We compare the expected cost outcomes using data from the US economy as the baseline scenario, and simulate policy outcomes under differing model parameterizations to determine the critical values after which intensity allowances begin to dominate fixed allowances. Unlike previous studies, our results show that under a reasonable model calibration, fixed allowances outperform intensity allowances by as much as 30% cost difference.

4.2 INTRODUCTION

Cap-and-trade schemes have been at the forefront of policy options in the reduction of greenhouses gas (GHG) emissions. These schemes fix the quantity of total emissions through permit issuance, and then enable trading among permit holders with the goal of achieving the least overall cost of abatement. Most notably, the European Union Emissions Trading Scheme (EU ETS) launched its first phase in 2005 and is currently entering its third phase in 2013. Fixing the amount of emissions years in advance, however, leads to uncertainty about the ultimate cost of abatement. During a period of economic expansion the cost of abatement may become higher than expected, whereas recessions reduce the demand for polluting goods which in turn means lower than expected cost of abatement.[73]

[73] The most recent economic downturn provides a case in point: the functioning of the EU ETS has been highly criticized, with emission allowances trading well below their intended price. This type of wide variability in permit prices can undermine the credibility of the permit system, and may also discourage investment in cleaner technologies and hinder cost efficiency (Zhao 2003; Baldursson and von der Fehr 2004). Additionally, uncertainty

To contain the range of ex-post abatement costs, some countries have adopted intensity based targeting, with the most popular target being GDP. In this case, rather than fixing the quantity of emissions, the regulator fixes the GDP share of emissions, that is, the emissions intensity in the economy.[74] The idea is to allow the quantity of emissions to move together with GDP changes, thus relaxing the constraint when the economy is growing and tightening when slowing down. In the context of a cap-and-trade scheme, emissions intensity targeting would essentially mean adjusting the permit allowance periodically based on the level of economic activity, therefore resulting in more predictability in the permit price signal.[75]

A measure of economic activity such as GDP does not, however, carry all the relevant information related to the firms' cost of abatement. There are other factors and variables that can directly influence the ex-post abatement cost, one example being the price of energy inputs. Consequently, intensity targeting based GDP indexation will not fully remove all the uncertainty vis-à-vis the cost of abatement. The question then becomes, under what circumstances will intensity based permit allowance dominate fixed allowances, or will they always dominate.

The purpose of this chapter is to compare the expected cost of abatement between two alternative policy scenarios: fixed permit allowance versus intensity based permit allowance. We evaluate how energy price and productivity uncertainties affect the relative performance of these two policy instruments. Following Fischer and Springborn (2011) and Heutel (2012), we use a simple real business cycle (RBC) model to simulate fluctuations in economic activity and policy outcomes, but we add stochastic energy prices as a new element. In contrast to their work, our main focus is on the first two moments of the endogenous permit price variable, which in the RBC model is captured by the shadow price of the emission constraint. We then introduce a simple decision framework where the regulator prefers the policy instrument that has the lowest expected abatement cost.[76] The difference between the abatement costs under the alternative policies is fully conveyed in the first two moments of the permit price variable.

---

stemming from the EU Commission's "backloading" plan has furthermore exacerbated concerns over the system's overall credibility (Grubb 2012; Kossoy and Guigon 2012).

[74] For example, Bush administration targeted an emission intensity of 20%.

[75] In practice, this would entail market interventions reminiscent of actions of a central bank that, in the case of emission allowances, would follow a mechanical rule based on intensity targeting. Commitment and credibility may become issues in such a policy design.

[76] Environmental damages are assumed to be the same under both policies since we are framing the emissions reduction target in terms of steady state reduction. Under intensity targeting, the amount of CO_2 emissions does fluctuate in the short-run, but since CO_2 is a long-lived stock pollutant these short-term variations do not matter.

As in Fischer and Springborn (2011), we impose an exogenous 20% emission reduction target from the policy-free steady state.[77] Both policy instruments, therefore, achieve the same long-run emissions reduction goal. Intensity targeting, however, entails more stringent emissions intensity in the steady state than what is the case under a fixed quantity target. The reason is that, with an intensity target, there is an incentive to produce more in order to gain more permits and relax the constraint. Consequently, the expected value of the permit price will be higher under intensity targeting but its variance will be lower than under a fixed allowance.

The comparison between fixing the periodic quantity of emissions versus fixing the periodic emissions intensity boils down to the relative magnitude of the mean and variance of the permit price variable, which itself is the carrier of information about the relative cost of abatement. We start with a baseline model calibration and evaluate which policy dominates in the baseline scenario in terms of expected abatement cost. We then proceed to find the critical levels for persistence and variance of the energy and productivity processes after which intensity allowance begins to dominate fixed allowances. We use both first order and second order approximations when linearizing the model around its steady state since the approximation method has an impact on the magnitudes of the first two moments of the permit price variable.[78]

Our results extend the analysis in Fischer and Springborn (2011) and provide further insight into the comparison between the policy instruments. Unlike their study, we find that fixed allowances may actually outperform intensity allowances in term of expected abatement cost, and the approximation method matters.[79] When using second order approximation, the energy price and productivity uncertainties also influence the expected permit price level. Our results show that this has a more pronounced impact on the expected abatement cost under intensity allowances.

Allowing for less-than-perfect correlation between the index of choice, here GDP, and abatement costs has been studied before in Jotzo and Pezzey (2007). They derive a country specific optimal indexation rule using a static model of global permit trading and endogenous emissions reduction target. Our novel contribution is to identify energy price volatility as the main source of exogenous noise that reduces the contemporaneous correlation between GDP and

---

[77] The 20% reduction resembles the EU reduction target and the target level proposed in Waxman-Markey and Kerry-Lieberman Bills (Fischer and Springborn 2011).

[78] When using first order approximation, certainty equivalence holds.

[79] Fischer and Springborn (2011) use standard welfare metrics to compare policy outcomes, and their analysis is based on first order approximation.

abatement costs, and then use RBC modeling framework to find the critical levels of persistence and shock variance in the productivity and energy processes.[80] These critical values can then be compared to the historical values found in different countries.

The recent experiences in the EU ETS shed some light on how energy prices changes transmit to permit markets. In general, energy prices tend to have a greater impact on energy intensive industries (Grubb 2012). Periods of high energy prices curb demand for fuels and electricity, and as a result, demand for permits also decreases, thus lowering the price of permits. On the other hand, "coal-gas price differential" has had a clear impact on the permit prices in the EU ETS. Increases in oil prices have a tendency to drive natural gas prices higher. This in turn increases the marginal cost of abatement as switching to natural gas becomes more expensive. Hence, permit price response can be positive to increases in oil prices. In our RBC model setup, higher energy prices always reduce demand for permits. We introduce an exogenous energy price process following the specification and estimation results in Kim and Loungani (1992) and Dhawan and Jeske (2005).

The plan of the chapter is as follows. The next section provides a short literature review over the ongoing debate about the relative merits of fixed vs. intensity targets. Section 4.4 lays out the real business cycle model that we use to derive the moments of the permit price process. Section 4.5 presents the derivation of expected abatement cost which the regulator uses when choosing between policy instruments. Section 4.6 defines the functional forms and parameter values used in the baseline case. Section 4.7 presents the results, while the last section offers concluding remarks and policy recommendations.

4.3 INTENSITY TARGETS

During the past decade, there has been a growing interest concerning the relative merits of intensity based regulation versus more traditional price instruments and fixed quotas.[81] Proponents of intensity targeting are in favor of flexibility and reduction of abatement cost uncertainties which may in turn spur investments in cleaner technology. Critics worry about the ensuing uncertainty over emissions reduction targets as the cap is allowed to vary, for example,

[80] For example, Hamilton (1983) finds that an increase in oil prices typically lead by 3-4 quarters a period of slower output growth. Rotemberg and Woodford (1996) estimate that a 10 percent exogenous increase in the price of oil has been followed by an output decline of 2.5 percent 5-6 quarters after the price shock.

[81] Intensity targeting as a potential greenhouse gas (GHG) mitigation policy began receiving more attention in the academic and policy circles in the aftermath of Kyoto Protocol ratification. For a review, see Peterson (2008).

with ups and downs in GDP. For example, Pizer (2005) contends that intensity targets make sense in the context of framing reduction goals for developing countries, but that intensity targets with annual adjustments to emissions cap should not be viewed as a solution to abatement cost uncertainty. Kolstad (2005) on the other hand reasons that intensity-based flexible caps can have potential in reducing abatement cost uncertainty. This in turn may have the beneficial effect of making international agreements in multilateral emission reductions more likely.[82]

The cost advantage of emissions indexation hinges on the premise that GDP and emissions levels are correlated. Jotzo (2006) and Heutel (2012) provide empirical evidence supporting this assumption. Jotzo and Pezzey (2007) and Sue Wing et al. (2009) ask the question whether current cap-and-trade schemes can be improved upon in a way to reduce the inherent abatement cost uncertainties.[83] Their studies find that indexation can deliver improvements in abatement outcomes both in terms of cost uncertainty and emissions levels. Correspondingly, Quirion (2005) and Newell and Pizer (2008) set out to determine the conditions under which intensity targeting ought to be preferred over fixed targets, or vice versa, by choosing the policy that maximizes the expected net benefits from abatement. Following the analytical framework in Weitzman (1974), they find that indexed quantities are likely to perform better when there is stronger positive correlation between the index and abatement cost uncertainty and also relatively small index variance. Furthermore, in the case of GHG reductions, they find that countries with strong correlation between output and emissions combined with relatively low output variance may prefer indexation over fixed quantities.

Fischer and Springborn (2011) and Heutel (2012) are the first studies to compare the performance of different emissions regulation instruments using a RBC model that simulates random economic fluctuations. Whereas the former imposes an exogenous 20% emissions reduction target from a no-policy steady state scenario, the latter focuses on analyzing the optimal policy under endogenous reduction targets. In both papers, the source of business cycle uncertainty stems from serially correlated productivity shocks. Heutel (2012) finds that optimal

[82] Permit banking has been discussed in the literature as a way to reduce abatement cost uncertainty. See for example Newell and Pizer (2003) and Newell et al. (2005). Also setting permit price floors and ceilings to reduce cost uncertainty has received wide attention.

[83] Jotzo and Pezzey (2007) use a single-period, stochastic, globally integrated partial equilibrium model to analyze the advantage of more flexible intensity targeting over fixed targets. Their model allows for varying degrees of indexation and endogenously determined target levels. Sue Wing et al. (2009) apply two criteria to compare the comparative performance of fixed and intensity based emissions targets: First, how well each instrument preserves the initial expectations of the amount of emissions reductions and costs involved, and second, how well each instrument minimizes the volatility of the same variables due to uncertainty about GDP and emissions.

policy allows for relaxation of the cap during economic expansion, and conversely, tightening of the cap during downturns. He also finds that indexing emissions to GDP replicates the optimal policy with a good approximation. Fischer and Springborn (2011), on the other hand, show that fixed caps lead to the lowest level of variability in all variables, except in the shadow price of the constraint, i.e., the permit price. Under intensity targeting, the magnitudes of variance terms do not differ from the no-policy baseline scenario (business-as-usual). Since intensity targeting absorbs the impact of productivity shocks on the emissions constraint, the resulting permit price remains constant in their model. They also find that intensity targets outperform fixed caps when comparing steady state values using standard welfare based metrics.[84] Overall, however, these differences are small and the authors conclude that when deciding between policy instruments, the regulator may want to focus on other metrics instead.[85]

4.4 REAL BUSINESS CYCLE MODEL

The basic RBC model presented in this section follows closely the presentation in Fischer and Springborn (2011). The representative consumer derives utility from consumption, C_t, and leisure, h_t, given by a standard utility function $U(C_t, h_t)$, and sells labor input, L_t, to a firm in a competitive labor market.[86] By normalizing the total time endowment to one, we can write labor allocation as $L_t = 1 - h_t$. The representative firm uses capital, K_t, labor, L_t, and an intermediate polluting energy input, e_t, to produce output, Y_t. The economy's total output (GDP) is defined as

$$Y_t = \mathrm{z}_t F(K_t, L_t, e_t) \tag{38}$$

It is a product of a stochastic productivity term, z_t, which follows a stationary process with $E(z_t) = 1$, and a deterministic production function $F(K_t, L_t, e_t)$.[87] Notice that we are abstracting from economic growth in our model.[88]

---

[84] But the ordering is reversed when they account for the transition phase with elevated level of consumption under fixed caps.

[85] Instead of a welfare comparison, we compare the expected cost of abatement.

[86] We could add environmental benefits from the emissions regulation in the consumer's utility function as an additively separable term. In this case, the utility would only depend on the steady state reduction in emissions and would not be affected by short-run fluctuations. Hence policies that achieve the same steady state reduction in emissions would entail the same amount of utility from environmental benefits. This is a reasonable assumption in the context of CO_2 emissions since they are a long-lived stock pollutant, and short-run fluctuations do not considerably alter their climatic impact.

[87] We have specific functional forms in the calibration section.

[88] It is also possible that accumulation of emissions has an effect on the productivity of the economy, hence making the production function time dependent. We do not model emissions accumulation here since we are assuming that

Capital accumulates according to the equation

$$K_{t+1} = I_t + (1-\delta)K_t \qquad (39)$$

where the parameter δ is the rate of capital depreciation, and I_t denotes investment. Following Kim and Loungani (1992) and Finn (2000), we assume that the firm takes the price of the polluting energy input as given. The economy's resource constraint can therefore be written as

$$Y_t \geq C_t + I_t + p_t e_t \qquad (40)$$

where p_t is a stationary energy price process with $E(p_t) = 1$. The way the energy input enters the resource constraint in equation (40) can be interpreted to mean that the economy imports all of its energy input from the world market and hence is small enough to have no influence on the price (Kim and Loungani 1992).

Emissions, M_t, are proportional to the use of energy inputs and to minimize notation the units of emissions are chosen so that one unit of energy input emits one unit of emissions. Henceforth, variable M_t denotes both energy use and emissions. To reduce the amount of emissions in the economy, the regulator imposes an emissions constraint:

$$M_t \leq T(Y_t) \qquad (41)$$

where $T(Y_t)$ is called the allowance function that take different forms under different policies.[89] We focus on two cap-and-trade policies: 1) intensity targeting with an adjustable allowance, and 2) fixed allowance. With fixed emissions allowance, $\bar{M}$, the allowance function is simply

$$T(Y_t) = \bar{M} \qquad (42)$$

With intensity targeting, the regulator adjusts the amount of available permits based on the realized output in the current period. The emissions allowance function is hence defined as

$$T(Y_t) = sY_t \qquad (43)$$

where s denotes the allowed output share of emissions, or the emissions intensity.[90] The regulator chooses $\bar{M}$ and s, depending on the policy, to achieve any given emissions reduction target.[91]

---

only the steady state emissions level matter in the case of CO_2, and hence the effects would be identical under policies that achieve the same steady state reduction.

[89] The only way to reduce emissions here is through the reduction of polluting energy input used in the economy. This feature neglects the possibility of improving energy efficiency and abatement technology. Our model does, however, allow for substitution between the energy input and labor and capital. Notice that these inputs are not perfect substitutes.

[90] We could also have alternative specifications for the intensity based allowance function. For instance, the regulator could choose the current period's permit allowance in the previous period given his expectation of the level of output: $T(Y_t) = sE_{t-1}(Y_t)$.

Assuming competitive labor and capital markets, the social planner solves the following infinite horizon utility maximization problem:

$$\max_{C_t, L_t} E_t \sum_{t=0}^{\infty} \beta^t U(C_t, 1 - L_t) \tag{44}$$

subject to the resource constraint (40) and the constraint on emissions (41). The parameter β is the discount factor defined as $\beta = 1/(1 + r)$ where r is the discount rate, and E_t denotes the expectation operator given the information available at time t. Define $\hat{\mu}_t = \mu_t / \lambda_t$ where μ_t is the Lagrangian multiplier of constraint (41), and λ_t of constraint (40). The system of first order conditions for the social planner's problem can then be written as (see Appendix C):

$$\begin{aligned}
&\mathrm{z_t} F_L(K_t, L_t, M_t)(1 + \hat{\mu}_t T_Y) = -\frac{U_L}{U_C} \\
&\mathrm{z_t} F_K(K_t, L_t, M_t)(1 + \hat{\mu}_t T_Y) = \beta^{-1} E_t \left(\frac{U_{C,t}}{U_{C,t+1}} + \delta - 1 \right) \\
&\mathrm{z_t} F_M(K_t, L_t, M_t)(1 + \hat{\mu}_t T_Y) = p_t + \hat{\mu}_t \\
&\mathrm{z_t} F(K_t, L_t, M_t) = K_{t+1} - (1 - \delta) K_t + C_t + p_t M_t \\
&M_t = T(Y_t)
\end{aligned} \tag{45}$$

where functions with subscripts denote the derivative of the function with respect to the variable in the subscript. The above system of nonlinear equations characterizes the equilibrium relationships that have to hold in optimum in every period, t. Assuming the existence of a steady state in the system (45), it is implicitly defined for each variable by the following system:

$$\begin{aligned}
&F_L(K, L, M)(1 + \hat{\mu} T_Y) = -\frac{U_L}{U_C} \\
&F_K(K, L, M)(1 + \hat{\mu} T_Y) = \beta^{-1} \delta \\
&F_M(K, L, M)(1 + \hat{\mu} T_Y) = 1 + \hat{\mu} \\
&F(K, L, M) = \delta K + C + M \\
&M = T(Y)
\end{aligned} \tag{46}$$

where all the variables take steady state values (e.g., $K_{t+1} = K_t = K$).[92] Notice that the only difference between the system in (45) and the corresponding conditions in Springborn and

[91] This target level is also related to the environmental damages since the use of polluting input incurs damages. In this chapter, we use an exogenous target of 20% reduction in steady state emissions.
[92] By specifying functional forms for $U(C, h)$ and $F(K, L, M)$, we can explicitly solve for each steady state value. We do this in our simulation section.

Fischer (2011) is the introduction of random energy prices, p_t. Since the expected value of p_t is one, the steady state conditions are identical with their study.

For the purpose of this study, the properties of variable $\hat{\mu}_t$, the shadow value of the emissions constraint, are of primary interest. This variable is the equilibrium permit price in a competitive permit market.[93] Notice that it has been written in terms of output, that is, it is the real price of a permit. Our next goal is to log-linearize the above system (45) around its steady state given in (46), and to solve for the equations of motion that characterize the movement of the endogenous and state variables in the proximity of that steady state (e.g., Uhlig, 1995). For example, the logarithm of the permit price variable, $\log \hat{\mu}_t$, is written as a linear function of the exogenous variables $\log p_t$ and $\log z_t$, and the predetermined variable $\log K_t$.

To log-linearize the system in (45), we start by writing each variable in terms of its percentage deviation from the steady state.[94] Using variable K_t as an example, we make the following two definitions:

$$\begin{gathered} k_t = \log(K_t) - \log(K) \\ K_t = Ke^{k_t} \end{gathered} \tag{47}$$

where k_t denotes (approximately) the percentage deviation from its steady state, K.[95] After substituting for each variable in (45) with its corresponding expression written in terms of percentage deviation from the steady state, e.g., $K_t = Ke^{k_t}$, we linearize the resulting system using first or second order Taylor approximation.[96] Define the following vectors: $v_t = [y_t, c_t, l_t, \tilde{\mu}_t]'$ and $w_t = [\log z_t, \log p_t]'$ where v_t collects the endogenous variables (jump variables) and w_t the exogenous variables. Notice that the variables in vector v_t are now written in terms of percentage deviations from the steady states, denoted by a small case letter or tilde. Also variables in w_t are by definition percentage deviations around zero.

Suppose now that we apply the first order Taylor approximation. We can write the resulting system of linear rational expectation equations in the following generic form (see Appendix C):

$$E_t(Ak_t + Bv_{t+1} + Cv_t) = 0 \tag{48}$$

[93] In reality, the permit markets may not be competitive since some market participants may have market power. Since market structure is assumed to be the same under both policies, this may not have an effect on our abatement cost comparisons. We leave the determination the effect of the market structure for future research.

[94] The presentation here follows Uhlig (1995) and McCandless (2008).

[95] This can be seen from noting that $x_t = \log(1 + \Delta K_t/K) \approx \Delta K_t/K$ where $\Delta K_t = K_t - K$.

[96] In the model simulation section, we use both approximations.

$$Dk_{t+1} + Fk_t + Gv_t + Hw_t = 0$$
$$w_{t+1} = Jw_t + \psi_{t+1}$$

where we have separated equations that include expectations from those that do not. The matrix coefficients, A, B, C, D, F, G, H, are all known from the log-linearization step, and ψ_t is a vector with mean zero stochastic elements.[97] Given the linear system in (48) our goal is to find equations of motion:

$$\begin{aligned} k_{t+1} &= Pk_t + Qw_t \\ v_t &= Rk_t + Sw_t \end{aligned} \quad (49)$$

where matrix coefficients, P, Q, R, S, are all unknown and can be solved, for example, by using the method of undetermined coefficients. In particular, we want to find the equation of motion for $\tilde{\mu}_t$.[98] It will take the following generic form:

$$\tilde{\mu}_t = a_1 k_t + a_2 \log p_t + a_3 \log z_t \quad (50)$$

where coefficients a_1, a_2, a_3 are solutions from solving (49), and $\tilde{\mu}_t = \log \hat{\mu}_t - \log \hat{\mu}$, where $\hat{\mu}$ is the steady state permit price. We use the expression in (50) to derive the expected value and variance of $\hat{\mu}_t$, which, as we show later, convey the information about the expected cost of abatement.

To give an example, suppose that both the energy price process, p_t, and the technology process, z_t, take the following AR(1) forms:

$$\begin{aligned} \log p_t &= \pi \log p_{t-1} + \epsilon_t \\ \log z_t &= \eta \log z_{t-1} + \omega_t \end{aligned} \quad (51)$$

where ϵ_t and ω_t are independent white noise disturbances with mean zero and variance terms σ_ϵ^2 and σ_ω^2, respectively. In the case of first order Taylor approximation, certainty equivalence holds:

$$E(\log \hat{\mu}_t) = \log \hat{\mu} \quad (52)$$

where $\hat{\mu}$ denotes the steady state value. The variance of the permit price process is given by:

[97] We will assume standard linear functional forms for both energy price (ARMA) and productivity processes (AR) with mean zero stochastic terms $\epsilon_{p,t}$ and $\epsilon_{z,t}$ respectively.

[98] When we log-linearize the equilibrium conditions, we are implicitly restricting the permit price to take strictly positive values. We return to this important point in a subsequent section.

$$Var(\log \hat{\mu}_t) = \left[{a_2}^2 + \sum_{i=0}^{\infty} \left(a_1 b_2 \sum_{j=0}^{i} \left({b_1}^j \pi^{i-j} + a_2 \pi^{i+1} \right) \right)^2 \right] \sigma_\epsilon^2 \\ + \left[{a_3}^2 + \sum_{i=0}^{\infty} \left(a_1 b_3 \sum_{j=0}^{i} \left({b_1}^j \eta^{i-j} + a_3 \eta^{i+1} \right) \right)^2 \right] \sigma_\omega^2 \tag{53}$$

where coefficients $a_1, a_2, a_3, b_1, b_2, b_3$ are solutions to the permit price and capital equations of motion (see Appendix D). From (53) we can see that as the variance terms, σ_ϵ^2 and σ_ω^2, increase the variance of the permit price increases as well. Similarly, if either of the persistence terms, π and η, increases, the permit price variance increases as well.

The purpose of the above example is to show how the properties of the productivity and energy price processes are transmitted to the permit price process. This mechanism is described by the equations (52) and (53). Notice that due to certainty equivalence, persistence and variance terms do not have an effect on the expected permit price given in (52). If we used second order Taylor approximation instead, these terms would also enter (52). To determine how much permit price variability responds under the competing policies, we would need to solve for the coefficients $a_1, a_2, a_3, b_1, b_2, b_3$ for both policies since they will differ in general. The first order and steady state conditions under fixed and intensity targets are detailed in Appendix C.

Before solving the above RBC model under the two allowance policies, we need to answer the question how the regulator determines which permit system is better. To do this, we build a decision framework based on abatement cost minimization problem.[99] As we will see, information about the difference in abatement cost between the two policies is captured by the first two moments of the permit price variable, $\hat{\mu}_t$.

4.5 ABATEMENT COST COMPARISON

Suppose that the regulator's goal is to achieve a given emissions reduction target with the smallest expected abatement cost which is measured as the cost of deviating from the business-as-usual (BAU) scenario.[100] The reduction target is exogenously given, for example, as a result

[99] We could use the above RBC modeling framework to compare the welfare difference in terms of consumption between the two policies. The welfare differences are, however, small (Fischer and Springborn, 2011). It is more likely that the regulator is interested to know the abatement cost difference rather than the welfare difference.

[100] We define this in more detail below.

of an international agreement or domestic legislation.[101] Due to the global nature of GHG stock, any benefit from the emissions reduction is fully exogenous from the perspective of the regulator, and furthermore, these benefits are the same under both policy instruments.[102,103]

Following the standard practice in the literature (Weitzman 1974; R. G. Newell and W. a. Pizer 2003; R. G. Newell and W. a. Pizer 2008; Fell et al. 2012), we use a quadratic approximation for the ex-post emissions input cost function around the expected BAU emissions level, $E_0(M_t^{BAU})$.[104] This can be written as

$$C(M_t;\theta_t) = \theta_t\left(M_t - \widehat{M}\right) + \frac{b}{2}\left(M_t - \widehat{M}\right)^2 \tag{54}$$

where we have defined $\widehat{M} \equiv E_0(M_t^{BAU})$ to reduce notational clutter. Randomness in emissions cost is captured by the mean zero random variable θ_t with $E(\theta_t^2) = \sigma^2$. Parameter $b > 0$ together with θ_t determine the curvature properties of the cost function.[105] Notice that (54) is not the same thing as an abatement cost function in our definition. Assuming a representative firm, the cost function in (54) captures the aggregate economy wide abatement cost associated with a particular policy instrument. Figure 4.1 depicts the expected (ex-ante) form of (54), whereas Figure 4.2 shows multiple realizations of (54) for different values of θ_t.

4.5.1 NO POLICY SCENARIO (BAU)

The ex-post marginal cost of emissions is defined as

$$-C'(M_t^{BAU};\theta_t) = -\theta_t - b\left(M_t^{BAU} - \widehat{M}\right) \tag{55}$$

In the absence of regulation, the optimal emissions level, M_t^{BAU}, is given by

$$M_t^{BAU} = \widehat{M} - \frac{1}{b}\theta_t \tag{56}$$

---

[101] In the next section, we define the reduction target in terms of policy free steady state.

[102] This corresponds to a setting such as Kyoto Protocol where the participants have agreed to reduce their emissions by a certain percentage amount from a given baseline year within the next 10 to 20 years. Most of the recent unilateral pledges from, e.g., China, Mexico and Australia, similarly target a certain amount of reduction within the next 20 years. Since only the global atmospheric concentration of CO_2 is what matters, the decision of any single country should be irrelevant to the overall global benefits.

[103] Alternatively, we could just assume that any benefits under the two policies are equivalent, constant, and fully known. Since carbon dioxide is a slowly decaying stock pollutant, the annual variation in emissions around its target level during the regulation period has no impact on final benefits.

[104] This can be thought of as the energy input cost function, but since we are using emissions and energy interchangeably, we retain to emissions cost function terminology.

[105] We assume that parameter b has a value that is not too small, thus guaranteeing an interior solution to the cost minimization problem.

where we have used the first order condition $-C'(M_t;\theta_t)=0$ to derive (56). In Figure 4.2, the points where the ex-post cost curves attain their minima correspond to M_t^{BAU} for different realizations of θ_t. Any deviation from point M_t^{BAU} would be suboptimal. We define the cost of abatement as the inefficiency cost resulting from choosing some emissions level M_t' such that $M_t' < M_t^{BAU}$. The abatement cost can be written as

$$AC(M_t', M_t^{BAU};\theta_t) = C(M_t';\theta_t) - C(M_t^{BAU};\theta_t) \tag{57}$$

Here, the BAU level, M_t^{BAU}, acts as the reference level.

4.5.2 ABATEMENT COST UNDER PERMIT ALLOWANCES

Any allowance policy put in place will in general make the ex-post emissions level, M_t, deviate from the cost minimizing outcome: $M_t \leq M_t^{BAU}$. Notice that under fixed allowance, $M_t = \bar{M}$, whereas M_t^{BAU} can fluctuate periodically, but under intensity allowances, both M_t and M_t^{BAU} fluctuate periodically. Suppose now that the regulator uses emissions allowances to restrict the amount of emissions in the economy, $M_t < \widehat{M}^{BAU}$, and enables permit trading between firms. Assuming that the permit market is competitive and efficient, the representative firm chooses its level of emissions to equate the marginal cost of emissions to the market permit price, $\hat{\mu}_t$:

$$\hat{\mu}_t = -C_t'(M_t;\theta_t) \tag{58}$$

Using (58), we can find the optimal emissions level, M_t^* under either allowance scheme:

$$M_t^* = \widehat{M} - \frac{\theta_t + \hat{\mu}_t}{b} \tag{59}$$

The ex-post amount of abatement is defined as

$$M_t^{BAU} - M_t^* = \frac{1}{b}\hat{\mu}_t \tag{60}$$

Notice that this amount is always positive as long as the permit price is positive as well. We restrict $\hat{\mu}_t$ to only take positive values in our RBC model.[106] Using (60), we can now rewrite the abatement cost function in (57) as

$$AC(M_t^*, M_t^{BAU};\theta_t) = \frac{1}{2b}\hat{\mu}_t^2 \tag{61}$$

The expected cost of abatement then becomes

---

[106] Positive permit price values can be justified by the notion of option value. Since in the steady state the amount of emissions reduction is always below the BAU level, the permit prices retain positive value in the short run.

$$E_0[AC(M_t^*, M_t^{BAU}; \theta_t)] = \frac{1}{2b}[E_0(\hat{\mu}_t)^2 + Var(\hat{\mu}_t)] \tag{62}$$

The above expression is written only in terms of the expectation and the variance of the permit market price, $\hat{\mu}_t$, and parameter b.

From (62), we can see that the regulator prefers the allowance policy that has the smallest sum of the permit price variance and the squared mean permit price. One interpretation for this rule is that the regulator chooses the instrument that minimizes the mean squared error of abatement cost. This "error" can be thought of arising from having an emissions reduction target put in place. In the absence of emissions regulation, the permit price would naturally be invariantly zero under both policies, and therefore, mean squared error would be at minimum. But because of the reduction target, the regulator chooses the instrument that yields the smallest mean squared error.[107] As we will see, the expected permit price under intensity allowance is always higher than with fixed allowance, but the variance is lower under intensity allowance. Hence, what matters is the relative magnitude of the first two moments of the permit variable under each policy.

4.5.3 COST COMPARISON

The difference in the expected abatement cost between intensity and fixed allowances is defined as

$$\Delta_{\mathrm{F-I}} \equiv E_0\left(AC_F\left(M_{t,F}^*, M_t^{BAU}; \theta_t\right)\right) - E_0\left(AC_I\left(M_{t,I}^*, M_t^{BAU}; \theta_t\right)\right) \tag{63}$$

where subscript I stands for intensity allowance and subscript F for fixed allowance. Substituting (62) into (63) and assuming that all the model parameters are invariant between different policies, that is, only the amount of abatement may differ, we finally have

$$\Delta_{\mathrm{F-I}} \equiv \frac{1}{2b}[E_0(\hat{\mu}_t^F)^2 + Var(\hat{\mu}_t^F) - E_0(\hat{\mu}_t^I)^2 - Var(\hat{\mu}_t^I)] \tag{64}$$

If the expression in (64) is positive, then intensity allowance is preferred, whereas if the expression negative, then fixed allowance is preferred. To empirically assess which policy is superior, we would need to have estimates for the mean and the variance of the permit price of under both policies. Since there are no data on intensity allowances, we resort to solving for these moments using the above RBC model.[108]

[107] Quadratic utility function yields a decision rule that minimizes mean squared error.

[108] Notice that we do not model the transitioning phase between the policy free steady state and the resulting new steady state. We focus on comparing the expected costs when the policies are fully in place.

4.6 MODEL SPECIFICATION

In selecting functional forms, we strictly follow Fischer and Springborn (2011) and Kim and Loungani (1992). The representative consumer's utility function takes the following logarithmic form:

$$U(C_t, L_t) = \log C_t + \omega \log(1 - L_t) \qquad (65)$$

where parameter ω is chosen so that the labor allocation decision matches the one found in data. The production function specification is the standard constant returns to scale Cobb-Douglas (CD) production function:

$$F(K_t, L_t, M_t) = K_t^{\alpha} M_t^{\gamma} L_t^{1-\alpha-\gamma} \qquad (66)$$

The productivity variable, z_t, has an expected value of one and it follows a stationary AR-1 process:

$$\log z_t = \eta \log z_{t-1} + \varepsilon_{z,t} \qquad (67)$$

The stochastic term, $\varepsilon_{z,t}$, has a mean zero and is normally distributed, $\varepsilon_{z,t} \sim N(0, \sigma_z^2)$. Energy price variable, p_t, follows an exogenous ARMA(1,1) process as in Kim and Loungani (1992) and Dhawan and Jeske (2008):

$$\log p_t = \pi_1 \log p_{t-1} + \varepsilon_{p,t} + \pi_2 \varepsilon_{p,t-1} \qquad (68)$$

The expected price of energy input is one and $\varepsilon_{p,t} \sim N(0, \sigma_p^2)$.

In order to derive numerical results, we use parameter values from previous studies to calibrate any remaining parameters. For the energy price process, we use the same set of parameter values as Dhawan and Jeske (2008). They use a GDP deflator to deflate the energy price index using quarterly data from 1970 to 2005, and then use these data to estimate an ARMA process. The AR(1) term, η, takes the standard value that is frequently used in other RBC studies as well (e.g. Springborn and Fischer 2011). Finally, the parameters in the CD production function are the same as in Fischer and Springborn (2011). Table 4.1 collects the above and all the remaining parameter values used in the baseline simulation.

4.7 RESULTS AND DISCUSSION

In this section, we derive the first two moments of the permit price variable under the two competing policies and then compute the difference in expected abatement cost. Before doing that, we need to determine the steady state level of emissions in a policy free scenario, M_{NP}. We then impose a 20% reduction target from this steady state emissions level. In the case of fixed allowance, the resulting allowance function can be written as:

$$T(Y_t) = \bar{M} = 0.8M_{NP} \tag{69}$$

In the case of intensity allowance, we have to additionally solve for the intensity target s^* that guarantees the same 20% emissions reduction from the policy free steady state. The allowance function becomes:

$$T(Y_t) = s^* Y_I(s^*) = 0.8M_{NP} \tag{70}$$

where $Y_I(s^*)$ denotes the resulting steady state level of output under the intensity target. Notice that $Y_I(s^*)$ depends on s^*.

To achieve the same 20% reduction, the intensity target s^* has to be set stricter than what the corresponding steady state intensity is under a fixed quota (Fischer and Springborn, 2011). This occurs because the intensity based allowance induces the representative firm to produce more in order to receive more permits, hence the need for a stricter intensity at the steady state. This effect can be seen, for example, by comparing the first-order conditions in Appendix C:

$$\begin{aligned} \mathrm{z_t} F_M(K_t, L_t, M_t) &= p_t + \hat{\mu}_t^F \\ z_t F_M(K_t, L_t, M_t) &= \frac{1}{(1+\hat{\mu}_t^I s)}(p_t + \hat{\mu}_t^I) \end{aligned} \tag{71}$$

The last line reveals how the intensity allowance in effect reduces the marginal cost of using the polluting input in comparison to the fixed allowance policy. By inspecting the first-order conditions for intensity allowances (Appendix C), we can see that the "mark-up" term $1/(1+\hat{\mu}_t^I s)$ enters all of the optimality conditions.

Notice that the equilibrium permit price can be negative in (71). To give an example, with CD production function specification, the optimality conditions in (71) become

$$\begin{aligned} \hat{\mu}_t^F &= \frac{\gamma \mathrm{Y_t}}{\bar{M}} - p_t \\ \hat{\mu}_t^I &= \frac{\gamma - s p_t}{s(1-\gamma)} \end{aligned} \tag{72}$$

Negative permit prices would in effect mean that the constraint is not binding from below. By using logarithmic transformation when solving our RBC model, we are able to circumvent this problem. In effect, we restrict each variable to take only positive values, and therefore, the emissions constraint always binds with positive shadow value. This can be justified by noting that permits have a positive option value due to the steady state reduction target.

Table 4.2 presents steady states of each variable under three different scenarios: no policy (BAU), intensity allowance, and fixed allowance. These results are similar to the ones in Fischer and Springborn (2011) since in steady state, the energy price variable takes value one and this corresponds to the specification in their study.[109] Both policies achieve the same 20% steady state reduction in the polluting good which can be verified by comparing the values of M. Under intensity allowances, permit price variable has a higher steady state value, and also higher level of output, consumption, and capital in the steady state. Emissions intensity, s, is lower (stricter) in the case of the intensity allowance.

Next we solve for the equations of motion using first order Taylor approximation around the steady state. The equations of motion for the state and endogenous variables take the following vector forms:

$$\begin{aligned} k_{t+1} &= P_i k_t + Q_i w_t \\ v_t &= R_i k_t + S_i w_t \end{aligned} \tag{73}$$

where

$$w_{t+1} = J_i w_t + N_i \psi_{t+1}$$

for $i = F, I$. All the variables are written in terms of deviations from the steady state. Given the specifications for the productivity and energy price processes, the two vectors w_t, ψ_t are defined as:

$$\begin{aligned} w_t &= \left(\log z_{t-1}, \log p_{t-1}, \varepsilon_{p,t-1}\right)' \\ \psi_t &= \left(\varepsilon_{z,t}, \varepsilon_{p,t}\right)' \end{aligned} \tag{74}$$

Table 4.3 presents solutions to the equations of motion in (73) for two variables: permit price, $\hat{\mu}_t$, and the only state variable, K_t, both in logarithms.[110] As can be seen from the equation for the permit price variable, intensity allowance fully absorbs the random variation coming from the productivity shock, and also any effect coming from the state variable, k_t. Energy price shocks are transmitted to the permit price under both policies but the coefficients differ. Permit price variable under intensity allowances is less responsive to energy price fluctuations which can be seen by comparing the coefficients. The constant terms denote the steady states in logs.

[109] The main difference between the steady state values in our study and theirs is that we have calibrated the parameter ω in the utility function so that the steady state labor allocation is about 1/3 of total time endowment.

[110] We use Dynare 4.2.4 (Adjemian et al. 2011) to derive these and all the subsequent numerical results.

In Figure 4.3, we graph an example of a permit price process realization using the equations of motion in Table 4.3.

To gain further insight, the equation of motion for the permit price variable can be written as

$$\log \hat{\mu}_t = \bar{a}_0 + \bar{a}_1 k_t + \bar{a}_2 \log z_{t-1} + \bar{a}_3 \log p_{t-1} + \bar{a}_4 \varepsilon_{p,t-1} + \bar{a}_5 \varepsilon_{z,t} + \bar{a}_6 \varepsilon_{p,t} \qquad (75)$$

where the coefficients correspond to the solutions in Table 4.3. Notice that all the variables on the right-hand side are normally distributed. Hence, $\log \hat{\mu}_t$ has a normal distribution with its mean at the steady state value, a_0.[111] Consequently, $\hat{\mu}_t$ has a log-normal distribution. Once we solve for the first two moments of $\log \hat{\mu}_t$ using equation (75), we can then derive the corresponding moments in levels using the following relationships:

$$\begin{aligned} &\log E(\hat{\mu}_t) = E(\log \hat{\mu}_t) - \frac{1}{2} Var(\log \hat{\mu}_t) \\ &Var(\hat{\mu}_t) = \left[\exp\left(Var(\log \hat{\mu}_t)\right) - 1\right] * \exp\left(2E(\log \hat{\mu}_t) + Var(\log \hat{\mu}_t)\right) \end{aligned} \qquad (76)$$

Tables 4.4 and 4.5 present the means and variances of the permit price variables under the two policy instruments. We use both the first and the second order Taylor approximation around the steady state. Table 4.4 reports these values in logarithmic scale, and Table 4.5 reports the values in levels after applying the mappings in (76). We furthermore compute the difference in expected abatement cost in percentage terms, hence cancelling out the parameter b in (64):

$$\frac{\Delta_{F-I}}{\Delta_F} * 100\% = \frac{[E_0(\hat{\mu}_t^F)^2 + Var(\hat{\mu}_t^F) - E_0(\hat{\mu}_t^I)^2 - Var(\hat{\mu}_t^I)]}{E_0(\hat{\mu}_t^F)^2 + Var(\hat{\mu}_t^F)} * 100\% \qquad (77)$$

We use equation (77) to compare the allowance policies and make policy recommendations. Negative percentage value in (77) means that fixed allowance entails lower abatement cost by the corresponding percentage amount, and positive value means that intensity allowance is more cost efficient again by that percentage amount. In Table 4.4, we have not computed (77) since when squaring a negative log value, the ranking is reversed and thus the abatement cost comparison becomes meaningless. As Table 4.4 shows, the second order approximation method yields smaller mean value for both policy instruments. Variance terms are, however, the same with both approximation methods.

Based on the results in Table 4.5, we conclude that fixed allowances dominate the intensity based allowance system. Fixed allowance has 8.76% lower expected abatement cost

[111] The mean coincides with the steady state only when using first order Taylor approximation.

with first order approximation and almost 30% lower with second order approximation. The intuitive explanation for these results is that the mean permit price is always higher under the intensity allowance and the reduction in permit variance is not enough to compensate for the weight given to the higher mean value in (77). Since the sign of the expression in (77) depends on the relative magnitudes of the first and the second moments of the permit price variable, it is evident that the approximation method will affect the results. When using the second order approximation the mean of the permit price does not coincide with the steady state value due to the presence of cross derivatives. In table 4.5, mean values with second order approximation are again smaller than with first order approximation. Interestingly, however, permit price variance is now higher under intensity allowance when using second order approximation. This result is somewhat surprising as we would expect intensity allowance to always have lower variance. By inspecting Table 4.4, we can see that in the logarithmic form, the ranking is as to be expected with both approximations. Hence the reversal of the ranking is due to the mapping in (76). First order approximation preserves the ranking based on variance even after applying (76).

4.7.1 CRITICAL VALUES

Next we examine how the expression in (77) changes as we vary the parameter values that define the persistence and variance of the exogenous stochastic processes. We change each parameter in turn and keep the remaining parameters at their baseline values given in Table 4.1. We also continue applying the mapping in (76). Figure 4.4 shows how the expression in (77) changes, with both first and second order approximations, as the standard deviation of the energy price shock, σ_p, increases. The gap between fixed and intensity allowance diminishes, and when using the first order approximation, there is a switch point at 0.035.[112] As the standard deviation increases further outside the range shown in figure, intensity allowance starts to dominate also with the second order approximation. The explanation for these findings is that, as σ_p increases, the permit price variance increases much more under the fixed allowance than under the intensity allowance, thus ultimately overturning the advantage of having a lower mean permit price under the fixed allowance.

Figures 4.5 and 4.6 tell similar stories vis-à-vis varying the energy price ARMA parameters π_1 and π_2. In effect, increasing these persistence terms increases the energy price variance, which ultimately results in the regulator preferring the intensity allowance over the

[112] The standard deviation estimate in Dhawan and Jeske (2008) is 0.031.

fixed allowance. In Figures 4.5 and 4.6, the cutoff points, when using the first order approximation, are slightly above 0.98 for the AR part, π_1, and around 0.64 for the MA part, π_2. Figures 4.7 and 4.8 show the effect of changing the parameter values defining the productivity process. Higher standard deviation, σ_z, and persistence, η, reduce the gap between the policies, and the closer we get to the productivity process being a pure random walk the more preferred the intensity allowance becomes. The cutoff point for σ_z is around 0.01, and for η around 0.975 when using the first order approximation.

4.8 CONCLUSIONS

The recent studies comparing intensity based emissions targeting and fixed emissions quotas have usually come out in favor of the former. It is true that flexibility in allowance allocation does reduce abatement cost uncertainty, but this comes at the cost of more stringent intensity level to achieve the same reduction target. Our analysis weighs both of these aspects to determine which allowance policy is preferred. The above results show that when using a reasonable model calibration, fixed allowances outperform intensity allowances. Depending on the approximation method, the cost difference in percentage terms can be quite significant. We find that with second order approximation the abatement cost difference is 30% in favor of fixed allowances. With first order approximation, this gap is almost 9% in favor of fixed allowances. Our simulation results also show that as the economic environment becomes more uncertain, intensity allowances begin to dominate fixed allowances. Hence, in some cases where the country faces extreme energy price and productivity uncertainties, intensity allowances may ultimately become the preferred policy option. Interesting future research includes determining an optimal intensity indexation rule that achieves the lowest expected abatement cost.

Figure 4.1: Ex-ante abatement cost curve

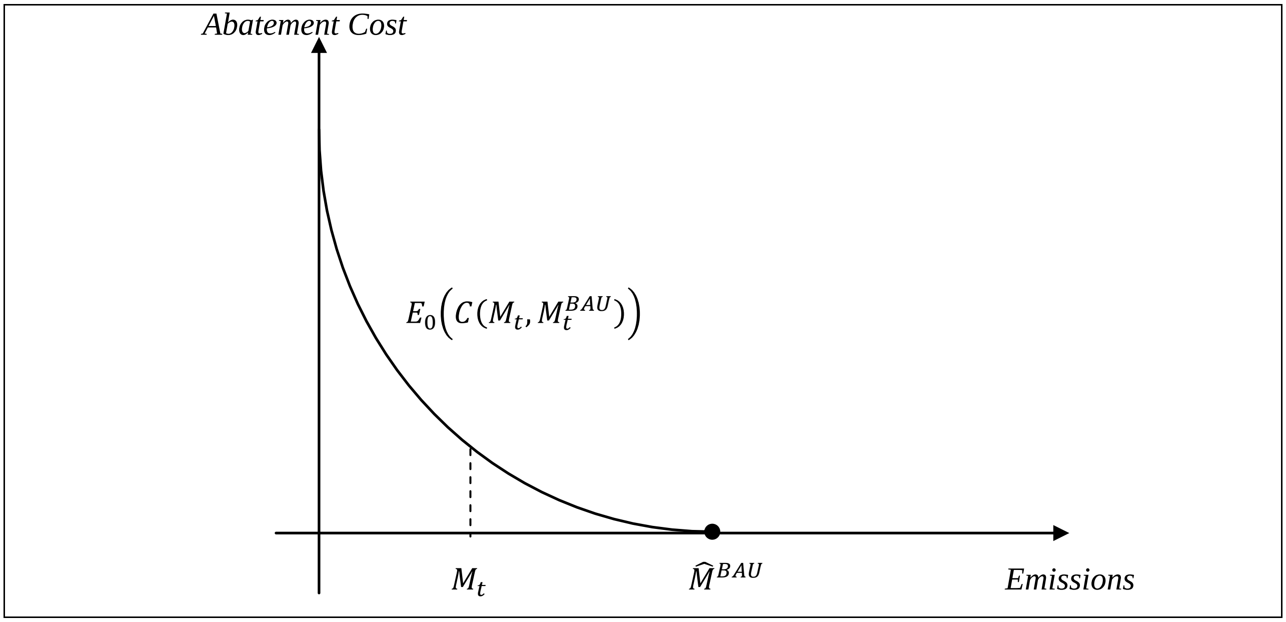


Figure 4.2: Ex-post abatement cost curve

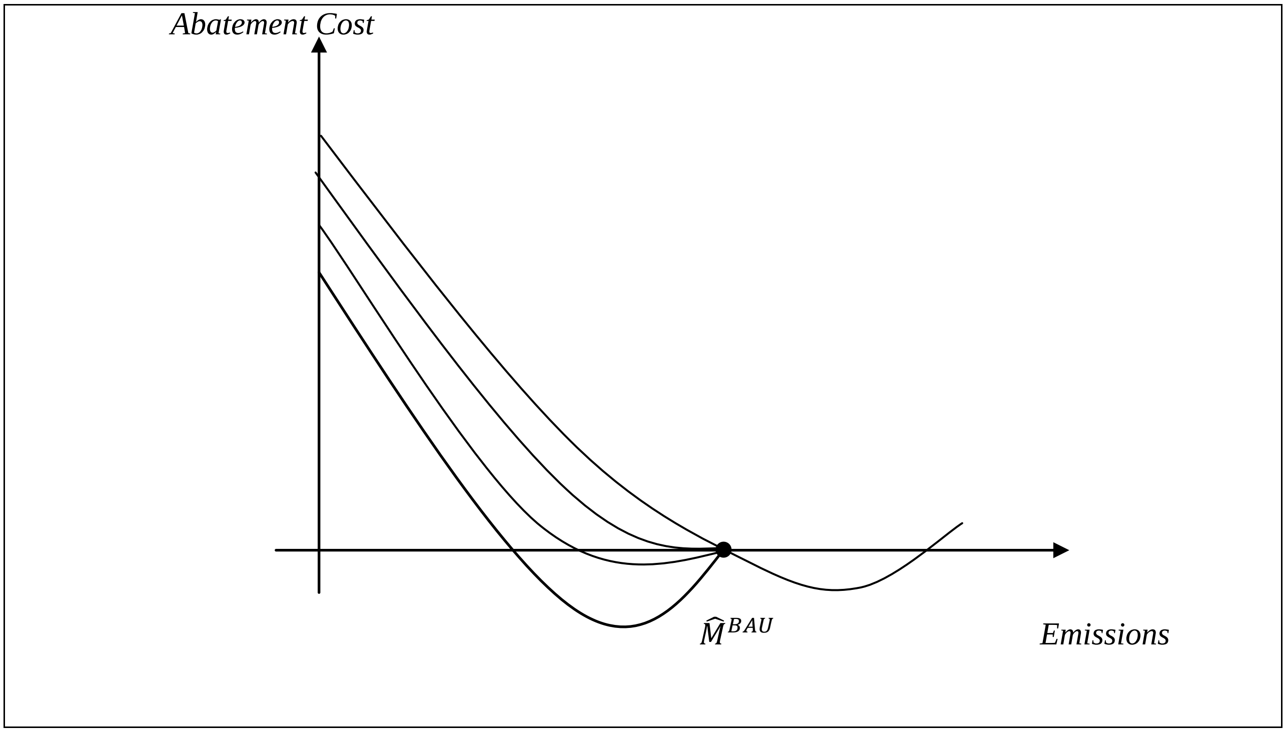


Figure 4.3: Permit price simulation

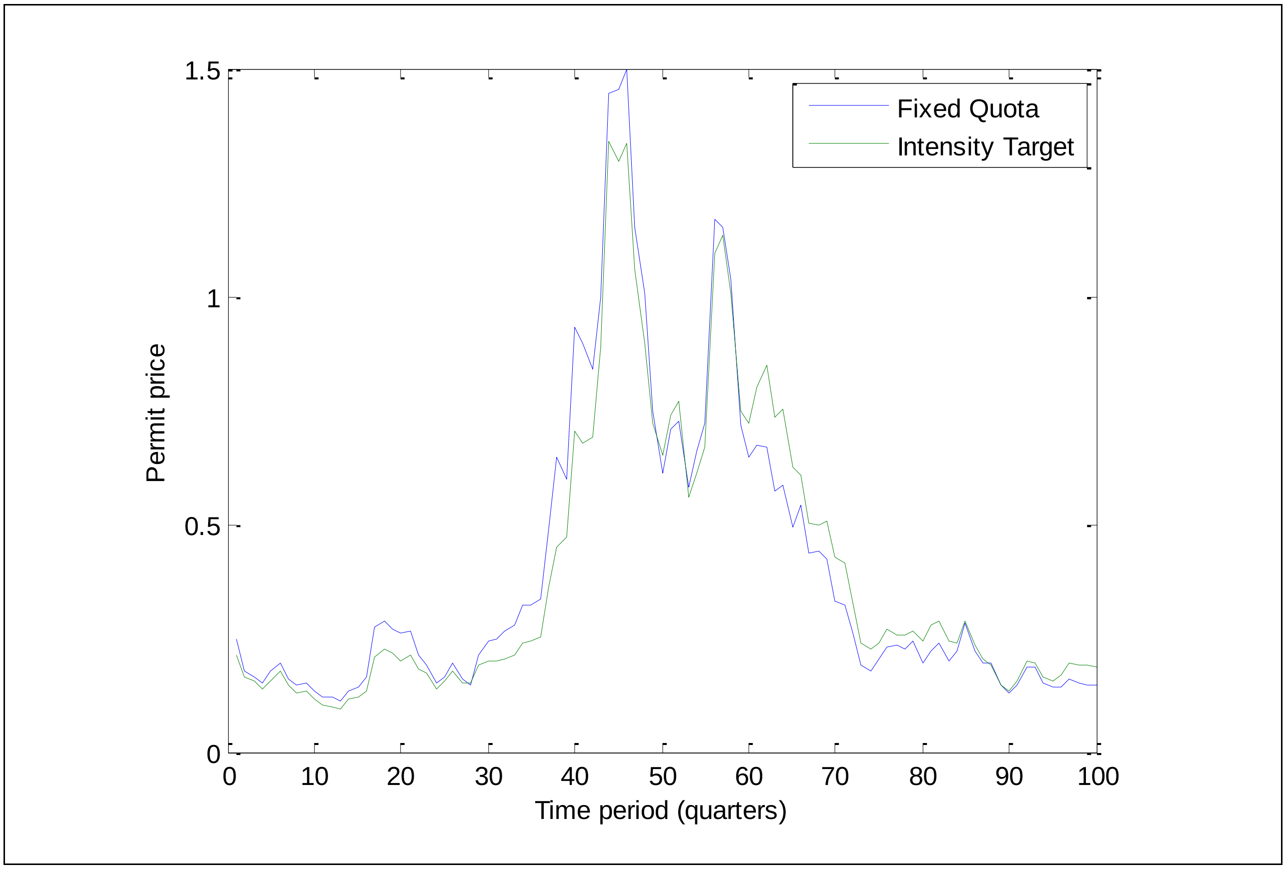
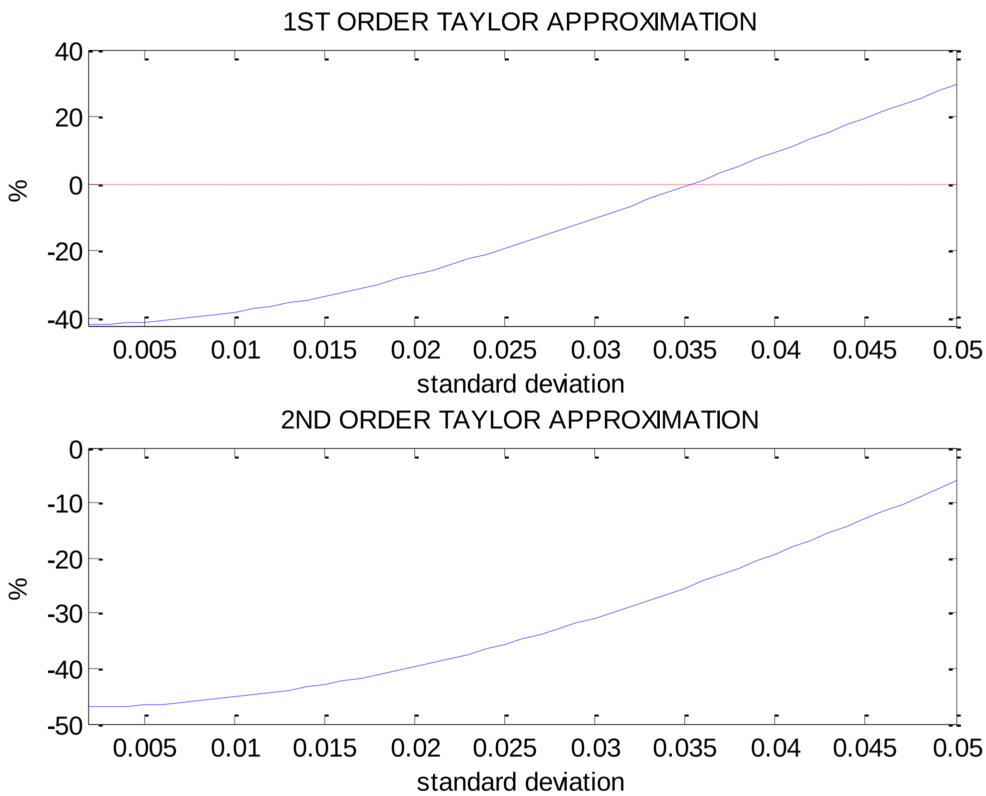


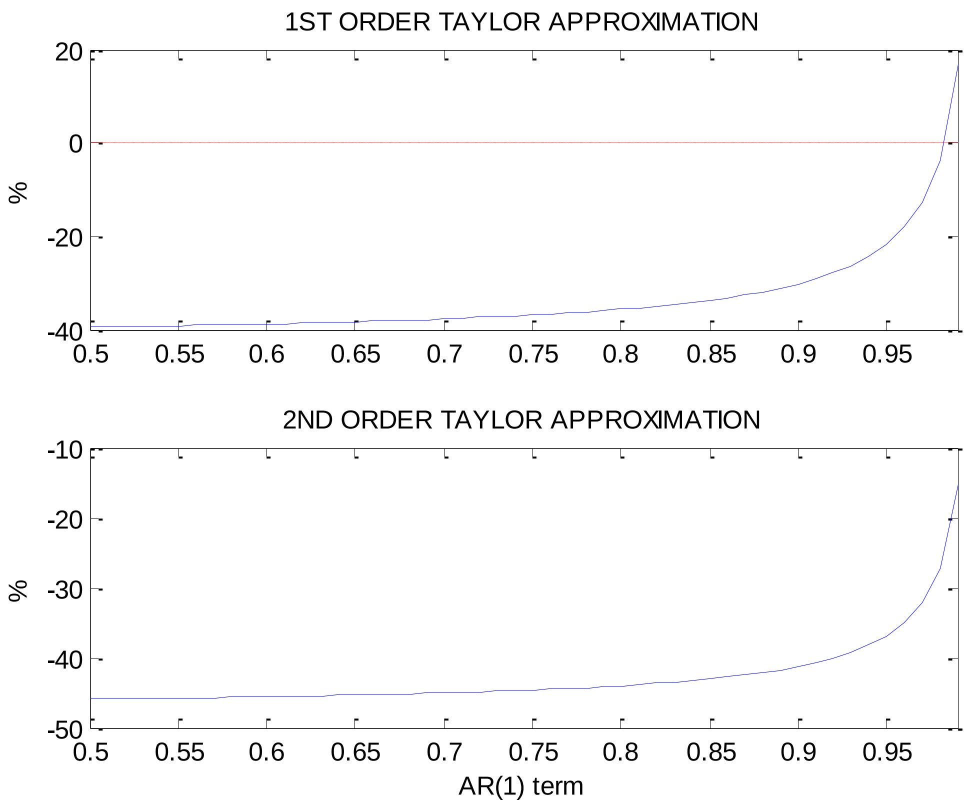
Figure 4.4: Abatement cost difference, energy price shock standard deviation



x-axis: standard deviation, σ_p

y-axis: %-difference between fixed and intensity based allowance. Negative value means that fixed allowances are preferred.

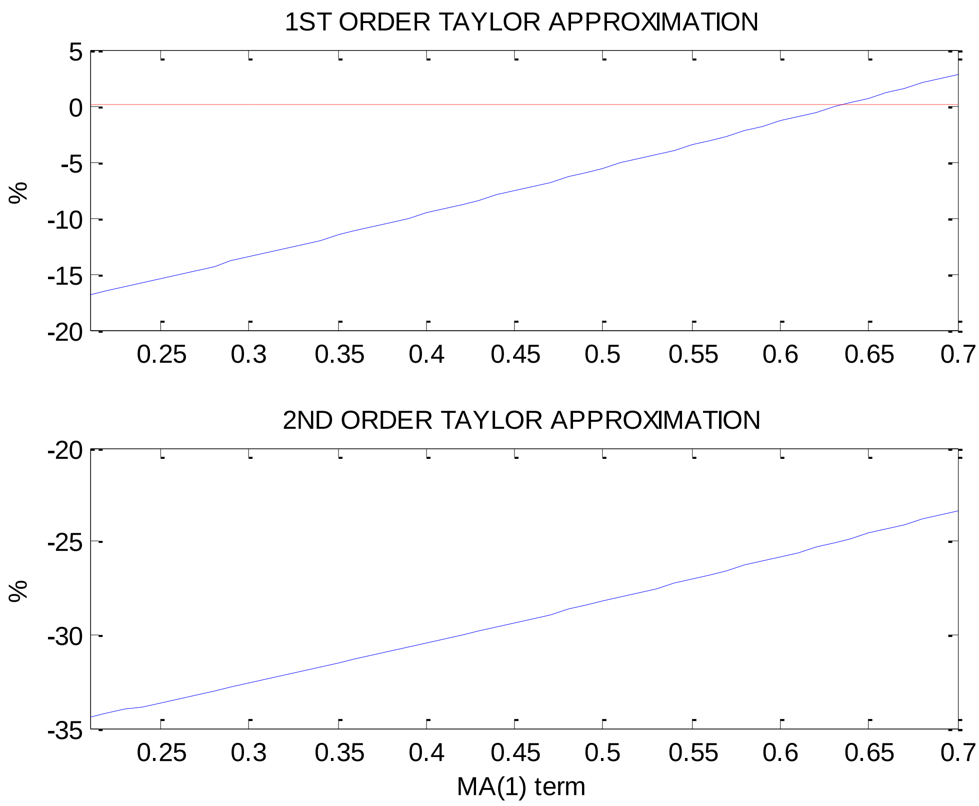
Figure 4.5: Abatement cost difference, energy price AR(1) persistence term



x-axis: AR(1) term, π_1

y-axis: %-difference between fixed and intensity based allowance. Negative value means that fixed allowances are preferred.

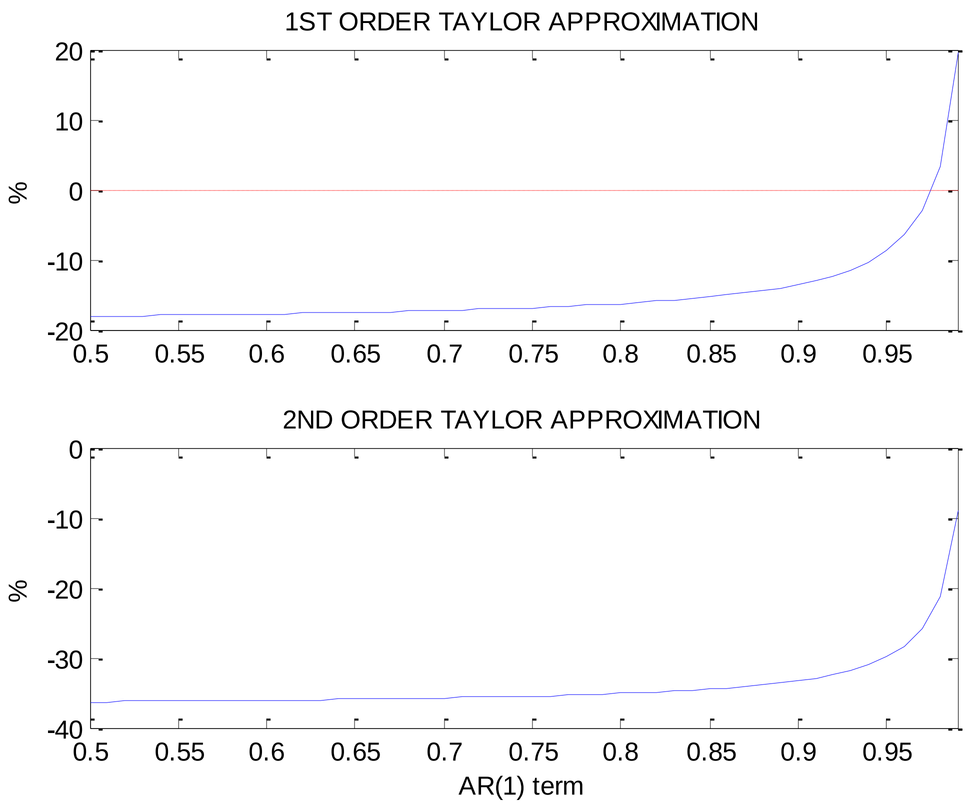
Figure 4.6: Abatement cost difference, energy price MA(1) persistence term



x-axis: MA(1) term, π_2; the range is chosen around the value reported in Dhawal and Jeske (2005)

y-axis: %-difference between fixed and intensity based allowance. Negative value means that fixed allowances are preferred.

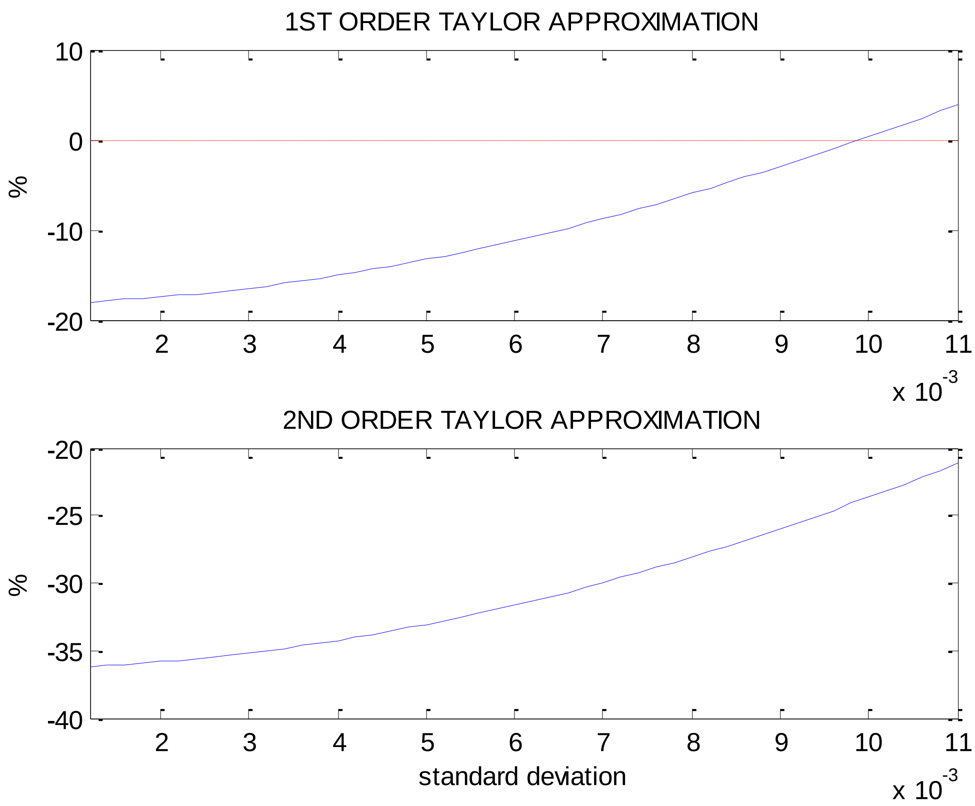
Figure 4.7: Abatement cost difference, productivity AR(1) persistence term



x-axis: AR(1) term, η. We do not compute the value for $\eta = 1$. The closer we get to the productivity process being a random walk, the more preferred intensity allowances become using both first and second approximations.

y-axis: %-difference between fixed and intensity based allowance. Negative value means that fixed allowances are preferred.

Figure 4.8: Abatement cost difference, productivity shock standard deviation



x-axis: standard deviation, σ_z

y-axis: %-difference between fixed and intensity based allowance. Negative value means that fixed allowances are preferred.

Table 4.1: Baseline calibration

β	δ	ω	η	σ_z^2	σ_p^2	π_1	π_2		
0.990	0.025	1.72	0.950	0.007^2	0.031^2	0.975	0.422		
γ	α	$1-\gamma-\alpha$							
0.090	0.330	0.580							

Table 4.2: Steady state values in levels

	$\hat{\mu}$	K	C	M	L	Y	s
No Policy, BAU	0	7.714	0.554	0.074	0.333	0.821	0.090
Fixed Allowance	0.198	7.392	0.542	0.059	0.328	0.786	0.075
Intensity Allowance	0.246	7.689	0.552	0.059	0.333	0.803	0.074

Table 4.3: Equations of motion

$$\begin{pmatrix}\log K_{t+1}^F\\ \log K_{t+1}^I\end{pmatrix} = \begin{pmatrix}2.000\\ 2.040\end{pmatrix} + \begin{pmatrix}0.952\\ 0.954\end{pmatrix} k_t + \begin{pmatrix}0.106 & -0.0003 & -0.0001\\ 0.117 & -0.0076 & -0.0033\end{pmatrix} w_t + \begin{pmatrix}0.112 & 0.003\\ 0.124 & -0.006\end{pmatrix} \psi_t$$

$$\begin{pmatrix}\log \hat{\mu}_t^F\\ \log \hat{\mu}_t^I\end{pmatrix} = \begin{pmatrix}-1.620\\ -1.403\end{pmatrix} + \begin{pmatrix}1.075\\ 0\end{pmatrix} k_t + \begin{pmatrix}7.798 & -4.721 & -2.041\\ 0 & -4.357 & -1.884\end{pmatrix} w_t + \begin{pmatrix}8.208 & -4.757\\ 0 & -4.467\end{pmatrix} \psi_t$$

Table 4.4: Baseline results in logs

	First order approximation	Second order approximation
$E_0(\hat{\mu}_t^F)$	-1.620	-2.186
$E_0(\hat{\mu}_t^I)$	-1.403	-1.880
$Var(\hat{\mu}_t^F)$	0.957	0.957
$Var(\hat{\mu}_t^I)$	0.782	0.782
$\frac{\Delta_{F-I}}{\Delta_F} * 100\%$	-	-
The results are in logarithmic scale. Notice that we cannot determine which instrument has a lower abatement cost because taking a square of a negative number results in reversing the ranking between higher and lower expected permit price.		

Table 4.5: Baseline results in levels

	First order approximation	Second order approximation
$E_0(\hat{\mu}_t^F)$	0.319	0.181
$E_0(\hat{\mu}_t^I)$	0.364	0.226
$Var(\hat{\mu}_t^F)$	0.164	0.053
$Var(\hat{\mu}_t^I)$	0.157	0.060
$\frac{\Delta_{F-I}}{\Delta_F} * 100\%$	-8.76	-30.0
Baseline calibration. Mean and variance of permit price variable under intensity (I) and fixed (F) allowance are reported in levels. Negative value for expected abatement cost difference means that fixed allowance has lower expected abatement cost.		

5 CONCLUSIONS

The future impact of climate change on human lives and societies remain uncertain, but the prospective scenarios seem deeply disconcerting to any prudent observer. The long-term survival of many ecosystems with fragile wildlife habitats is under an increasing threat, and no doubt add to the urgency of decisive action. National and global policy responses to these environmental challenges are inevitably the defining monuments of our next century. The goal of this dissertation is to analyze the impact of political and macroeconomic uncertainty on environmental outcomes and policy instruments. Our results and new methods contribute to the existing literature in natural resource and environmental economics, and provide guidance to the policymakers when formulating responses to the environmental challenges today and in the future.

Tropical deforestation and accompanying land use changes have been significant contributors to anthropocentric GHG emissions. Agricultural land expansion and road building have been deemed as the main direct drivers of this process. The first essay of this dissertation finds that new political regimes tend to increase the rate of agricultural land expansion in tropical countries. This land conversion comes at the expense of previously forested lands, and both democratic and autocratic regimes have contributed to this process. The magnitude of this effect can be significant and persistent as past agricultural land expansion stimulates more road building, and therefore, better access routes for future land conversion. We find that the impact of new regimes is more pronounced in Latin America and Asia, whereas in Africa to a smaller extent. These differences can be mainly explained in terms of differing historical forms of land ownership and colonial legacy. We also find that increasing level of income has reduced the rate of agricultural land expansion in Latin America, but the opposite holds in Africa. The role of corruption furthermore differs across regions. Our collective results suggest that future political instability and heightened demand for agricultural land continue to present a significant threat to tropical forests, and that democratization does not seem to be a sufficient condition for better environmental outcomes. Future research should develop a dynamic theory model and a more flexible regime dummy variable specification. Also country or region specific micro studies with richer dataset would enhance our understanding of how political economy affects deforestation.

Performance bonds have been suggested as a promising new policy instrument to regulate environmental outcomes in tropical timber concessions. They have not, however, gained much traction for variety of reasons. The second chapter of this dissertation identifies repayment risk and imperfect enforcement together with binding participation constraint as important factors hindering the successful implementation of bonding schemes. We show that both imperfect enforcement and repayment risk increase the required level of bond payment and may force the government to aim at a lower RIL target level when the harvester's participation constraint is binding. We define and quantify the concept of critical risk and derive the "slope condition" that has to be satisfied by a decreasing bond function when enforcement is imperfect. These findings collectively shed some new light on the question why performance bonding schemes have not been successful in concession design and how they may be improved. Our simulation results give support to the potentially important role of supranational entities such as REDD+ in lifting bond outcomes to the first-best level. REDD+ finances have the potential of reducing repayment uncertainty and improving the quality of concession enforcement. These improvements enhance the future effectiveness of bonding schemes for any given initial bond payment. Future research in performance bonds should look into dynamic consideration such as reputational effects, and how an optimal subsidy policy should be designed.

A well-functioning and reasonably predictable permit market alleviates the abatement cost uncertainty and also encourages investments in cleaner forms of production. Intensity targeting indexes the number of emissions allowances to GDP, and therefore, it potentially reduces the cost uncertainty in achieving overall emissions reduction target. The third chapter of this dissertation compares the performance of fixed versus intensity allowances when the economy is subject to both energy and productivity uncertainties. We find that the reduction in abatement cost variance under intensity allowances may not be enough to offset the more stringent intensity target level required to achieve the same steady state emissions reduction target. It is true that ultimately intensity allowances begin to dominate fixed allowances as we increase the variance and persistence of the energy and productivity processes, but the corresponding critical points are higher than the historical values found in the U.S. Using the baseline calibration, the abatement cost difference can be as high as 30% in favor of fixed allowances. The magnitude of the cost difference depends on the approximation methods applied when solving the RBC model. With the second order approximation, the degree of uncertainty over the price of energy input and the economy's productivity additionally affects the expected level of permit price which further reduces the attractiveness of intensity allowances for any given level of permit variance. Future research should determine the optimal indexation rule that achieves the lowest expected abatement cost.

6 REFERENCES

Acemoglu, D. and Robinson, J.A., 2001. A Theory of Political Transitions. *The American Economic Review*, 91(4), pp.938–963.

Adams, M., 1995. Land Reform: New Seeds on Old Ground? *ODI Natural Resource Perspectives*, 6.

Adjemian, S. et al., 2011. Dynare: Reference Manual.

Alston, L.J., Libecap, G.D. and Mueller, B., 2000. Land Reform Policies, the Sources of Violent Conflict, and Implications for Deforestation in the Brazilian Amazon. *Journal of Environmental Economics and Management*, 39(2), pp.162–188.

Amacher, G.S., Koskela, E. and Ollikainen, M., 2008. Deforestation and Land Use under Insecure Property Rights. *Environment and Development Economics*, 14, pp.281–303.

Amacher, G.S., Koskela, E. and Ollikainen, M., 2007. Royalty Reform and Illegal Reporting of Harvest Volumes under Alternative Penalty Schemes. *Environmental and Resource Economics*, 38, pp.189–211.

Amacher, G.S. and Malik, A.S., 1996. Bargaining in Environmental Regulation and the Ideal Regulator. *... of Environmental Economics and Management*, 30, pp.233–253.

Amacher, G.S., Ollikainen, M. and Koskela, E., 2012. Corruption and Forest Concessions. *Journal of Environmental Economics and Management*, 63(1), pp.92–104.

Anderson, T.W. and Hsiao, C., 1982. Formulation and Estimation of Dynamic Models Using Panel Data. *Journal of Econometrics*, 18, pp.47–82.

Angelsen, A., 2007. Forest Cover Change in Space and Time: Combining the von Thünen and Forest Transition Theories. *World Bank Policy Research Working Paper*.

Arellano, M. and Bond, S., 1991. Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations. *The Review of Economic Studies*, 58(2), pp.277–297.

Baldursson, F.M. and Von der Fehr, N.-H.M., 2004. Price Volatility and Risk Exposure: on Market-Based Environmental Policy Instruments. *Journal of Environmental Economics and Management*, 48(1), pp.682–704.

Barbier, E.B., 2010. *Scarcity and Frontiers: How Economies Have Developed through Natural Resource Exploitation*, Cambridge University Press.

Barbier, E.B., 2001. The Economics of Tropical Deforestation and Land Use: An Introduction to the Special Issue Use. *Land Economics*, 77(2), pp.155–171.

Barbier, E.B. and Burgess, J.C., 2002. The Economics of Tropical Deforestation. *Journal of Economic Surveys*, 15(3), pp.413–433.

Barbier, E.B. and Burgess, J.C., 1997. The Economics of Tropical Forest Land Use Options. *Land Economics*, 73(2), pp.174–195.

Binswanger, H.P., 1991. Brazilian Policies that Encourage Deforestation in the Amazon. *World Development*, 19(7), pp.821–829.

Blas, D.E. De and Perez, M.R., 2008. Prospects for Reduced Impact Logging in Central African logging concessions. *Forest Ecology and Management*, 256, pp.1509–1516.

Bohn, H. and Deacon, R.T., 2000. Ownership Risk, Investment, and the Use of Natural Resources. *The American Economic Review*, 90(3), pp.526–549.

Boltz, F., Holmes, T.P. and 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, pp.69–81.

Borras Jr., S.M., 2001. State-Society Relations in Land Reform Implementation in the Philippines. *Development and Change*, 32, pp.545–575.

Boscolo, M. and Vincent, J.R., 2000. Better Logging Practices in Promoting Analysis of Tropical Forests: A Simulation Alternative Regulations. *Land Economics*, 76(1), pp.1–14.

Boyd, J., 2001. Financial Responsibility for Environmental Obligations: Are Bonding and Assurance Rules Fulfilling Their Promise? *RFF Discussion Paper*, 01-42.

Brooker, P., 2009. *Non-Democratic Regimes*, Palgrave Macmillan.

Buitenzorgy, M. and Mol, A.P.J., 2010. Does Democracy Lead to a Better Environment? Deforestation and the Democratic Transition Peak. *Environmental and Resource Economics*, 48(1), pp.59–70.

Callister, D.J., 1999. Corrupt and Illegal Activities in the Forestry Sector: Current Understandings and Implications for World Bank Forest Policy. *World Bank Working Paper*.

Canby, K. and Raditz, C., 2005. *Opportunities and Constraints to Investment: Natural Tropical Forest Industries*, Forest Trends, ITTO.

Chomitz, K.M. and Gray, D. a., 1996. Roads, Land Use, and Deforestation: A Spatial Model Applied to Belize. *The World Bank Economic Review*, 10(3), pp.487–512.

Contreras-Hermosilla, A., 2002. Underlying Causes of Forest Decline. *CIFOR Occasional Paper*, 30.

Coria, J. and Sterner, Thomas, 2011. Natural Resource Management: Challenges and Policy Options. *Annual Review of Resource Economics*, 3(1), pp.203–230.

Costanza, R. and Perrings, C., 1990. A Flexible Assurance Bonding Environmental Management System for Improved. *Ecological Economics*, 2, pp.57–75.

Costello, C.J. and Kaffine, D., 2008. Natural Resource Use with Limited-Tenure Property Rights. *Journal of Environmental Economics and Management*, 55(1), pp.20–36.

Cropper, M., Griffiths, C. and Mani, M., 1999. Roads, Population Pressures, and Deforestation in Thailand, 1976-1989. *Land Economics*, 75(1), pp.58–73.

Daley, E. and Hobley, M., 2005. *Land: Changing Contexts, Changing Relationships, Changing Rights*. Urban-Rural Change Team, DFID.

Deacon, R.T., 1995. Assessing the Relationship between Government Policy and Deforestation. *Journal of Environmental Economics and Management*, 28, pp.1–18.

Deacon, R.T., 1999. Deforestation and Ownership : Evidence from Historical Accounts and Contemporary Data. *Land Economics*, 75(3), pp.341–359.

Deacon, R.T., 1994. Deforestation and the Rule of Law in a Cross-Section of Countries. *Land Economics*, 70(4), pp.414–430.

Deininger, K. and Binswanger, H., 1999. The Evolution of the World Bank ' s Land Policy: Principles, Experience, and Future Challenges. *The World Bank Research Observer*, 14(2), pp.247–276.

Dhawan, R. and Jeske, K., 2008. Energy Price Shocks and the Macroeconomy: The Role of Consumer Durables. *Journal of Money, Credit and Banking*, 40(7), pp.1357–1377.

Fell, H., MacKenzie, I. a. and Pizer, W. a., 2012. Prices versus Quantities versus Bankable Quantities. *NBER Working Paper Series*.

Ferreira, S. and Vincent, J.R., 2010. Governance and Timber Harvests. *Environmental and Resource Economics*, 47(2), pp.241–260.

Finn, M.G., 2000. Perfect Competition and the Effects of Energy Price Increases on Economic Activity. *Journal of Money, Credit and Banking*, 32(3), pp.400–416.

Fischer, C. and Springborn, M., 2011. Emissions Targets and the Real Business Cycle: Intensity Targets versus Caps or Taxes. *Journal of Environmental Economics and Management*, 62(3), pp.352–366.

Galinato, G.I. and Galinato, S.P., 2011. The Effects of Corruption Control, Political Stability and Economic Growth on Deforestation-Induced Carbon Dioxide Emissions. *Environment and Development Economics*, 17(01), pp.67–90.

Gray, J.A., 2002. Forest Concession Policies and Revenue Systems: Country Experience and Policy Changes for Sustainable Tropical Forestry. *World Bank Technical Paper, Forest Series*.

Grossheim, C., 2011. Forest Concessions in Peru. In S. M. Weber, B. Stimm, and R. Mosandi, eds. *Silviculture in the Tropics*. Tropical Forestry 8, pp. 53–60.

Grossman, H.I., 1994. Production, Appropriation, and Land Reform. *The American Economic Review*, 84(3), pp.705–712.

Grubb, M., 2012. *Strengthening the EU ETS: Creating a Stable Platform for EU Energy Sector Investment*. Climate Strategies.

Hamilton, J.D., 1983. Oil and the Macroeconomy since World War II. *Journal of Political Economy*, 91(2), pp.228–248.

Hardner, J. and Rice, R., 2000. Rethinking Forest Use Contracts in Latin America. *Environmental Division Working Paper,* Inter-American Development Bank, Washington DC.

Heutel, G., 2012. How Should Environmental Policy Respond to Business Cycles? Optimal Policy under Persistent Productivity Shocks. *Review of Economic Dynamics*, 15(2), pp.244–264.

Holmes, T.P. et al., 2001. Financial and Ecological Indicators of Reduced Impact Logging Performance in the Eastern Amazon. *Forest Ecology and Management*, 5583, pp.1–18.

Jotzo, F., 2006. Quantifying Uncertainties for Emissions Targets. *Economics and Environment Network Working Paper*.

Jotzo, F. and Pezzey, J.C. V., 2007. Optimal Intensity Targets for Greenhouse Gas Emissions Trading under Uncertainty. *Environmental and Resource Economics*, 38(2), pp.259–284.

Karsenty, A., 2012. *Financing Options to Support REDD+ Activities*. Cirad.

Karsenty, A., 2010a. Forest Taxation Regime for Tropical Forests: Lessons from Central Africa. *International Forestry Review*, 12(2), pp.121–129.

Karsenty, A., 2010b. *Large-Scale Acquisition of Rights on Forest Lands in Africa*. The Rights and Resources Initiative, Cirad, Washington DC.

Karsenty, A. et al., 2008. Regulating Industrial Forest Concessions in Central Africa and South America. *Forest Ecology and Management*, 256, pp.1498–1508.

Kim, I.-M. and Loungani, P., 1992. The Role of Energy in Real Business Cycle Models. *Journal of Monetary Economics*, 29(2), pp.173–189.

Kolstad, C.D., 2005. The Simple Analytics of Greenhouse Gas Emission Intensity Reduction Targets. *Energy Policy*, 33(17), pp.2231–2236.

Kossoy, A. and Guigon, P., 2012. *State and Trends of the Carbon Market 2012*, World Bank, Washington DC.

Laporte, A. and Windmeijer, F., 2005. Estimation of Panel Data Models with Binary Indicators when Treatment Effects Are Not Constant over Time. *Economics Letters*, 88(3), pp.389–396.

Leruth, L., Paris, Remi and Ruzicka, Ivan, 2001. Complier Pays Principle: the Limits of Fiscal Approaches toward Sustainable Forest Management. *IMF Staff Papers*, 48(2).

Lichtenberg, E., 1989. Land Quality, Irrigation Development, and Cropping Patterns in the Northern High Plains. *American Journal of Agricultural Economics*, 71(1), pp.187–194.

Lopez, R. and Galinato, G.I., 2005. Trade Policies, Economic Growth, and the Direct Causes of Deforestation. *Land Economics*, 81(2), pp.145–169.

Macpherson, A.J. et al., 2010. Following the Rules : Brazilian Logging Concessions under Imperfect Enforcement and Royalties. *Land Economics*, 86(3), pp.493–513.

Macpherson, A.J. et al., 2012. The Sustainability of Timber Production from Eastern Amazonian Forests. *Land Use Policy*, 29, pp.339–350.

Marshall, M.G., Gurr, T.R. and Jaggers, K., 2009. POLITY™ IV PROJECT.

Mathis, M.L. and Baker, P.B., 2002. Assurance Bonds: A Tool for Managing Environmental Costs in Aquaculture. *Aquaculture Economics and Management*, 6(1-2), pp.1–17.

McCandless, G.T., 2008. *The ABCs of RBCs: An Introduction to Dynamic Macroeconomic Models*, Harvard University Press.

Medjibe, V.P. and Putz, F.E, 2012. Cost Comparisons of Reduced-Impact and Conventional Logging in the Tropics. *Journal of Forest Economics*, 18(3), pp.242–256.

Mendelsohn, R., 1994. Property Rights and Tropical Deforestation. *Oxford Economic Papers*, 46, pp.750–756.

Merry, F.D. and Amacher, G.S., 2005. Forest Taxes, Timber Concessions, and Policy Choices in the Amazon. *Journal of Sustainable Forestry*, 20(2), pp.15–44.

Midlarsky, M.I., 1998. Democracy and the Environment: An Empirical Assessment. *Journal of Peace Research*, 35(3), pp.341–361.

Mills, E.S., 1972. *Urban Economics*, Scott, Foresman and Company, Glenview, Illinois.

Nasi, R. et al., 2011. Sustainable Forest Management and Carbon in Tropical Latin America: The Case for REDD+. *Forests*, 2, pp.200–217.

Newell, R., Pizer, W. and Zhang, J., 2005. Managing Permit Markets to Stabilize Prices. *Environmental and Resource Economics*, 31(2), pp.133–157.

Newell, R.G. and Pizer, W. a., 2008. Indexed Regulation. *Journal of Environmental Economics and Management*, 56(3), pp.221–233.

Newell, R.G. and Pizer, W. a., 2003. Regulating Stock Externalities under Uncertainty. *Journal of Environmental Economics and Management*, 45(2), pp.416–432.

Nickell, S., 1981. Biases in Dynamic Models with Fixed Effects. *Econometrica*, 49(6), pp.1417–1426.

Paris, R, Ruzicka, I and Speechly, H., 1994. Performance Guarantee Bonds for Commercial Management of Natural Forests - Early Experience from the Philippines. *Commonwealth Forestry Review*, 73(2), pp.106–112.

Pescott, M., Durst, P.B. and Leslie, R.N., 2010. *Growing Green Assets : Removing Constraints to Private Sector Investment in Forestry in Asia and the Pacific*, Bangkok: RAP Publication 18, FAO.

Peterson, S., 2008. Intensity Targets: Implications for the Economic Uncertainties of Emissions Trading. In *Economics and Management of Climate Change, Part II*. pp. 97–110.

Pfaff, A. et al., 2010. *Policy Impacts on Deforestation: Lessons Learned from Past Experiences to Inform New Initiatives*. Nicholas Institute Report, Duke Nicholas Institute.

Pfaff, A.S.P., 1999. What Drives Deforestation in the Brazilian Amazon? *Journal of Environmental Economics and Management*, 37(1), pp.26–43.

Pizer, W., 2005. The Case for Intensity Targets. *Climate Policy*, 5(4), pp.455–462.

Prosterman, R.L. and Riedinger, J.M., 1987. *Land reform and Democratic Development*, Johns Hopkins University Press.

Putz, F.E. et al., 2008. Reduced-Impact Logging: Challenges and Opportunities. *Forest Ecology and Management*, 256(7), pp.1427–1433.

Quirion, P., 2005. Does Uncertainty Justify Intensity Emission Caps? *Resource and Energy Economics*, 27(4), pp.343–353.

Rodrik, D. and Wacziarg, R., 2005. Do Democratic Transitions Produce Bad Economic Outcomes? *The American Economic Review*, 95(2), pp.50–55.

Rotemberg, J.J. and Woodford, M., 1996. Imperfect Competition and the Effects of Energy Price Increases on Economic Activity. *Journal of Money, Credit and Banking*, 28(4), pp.549–577.

Ruzicka, Ivan, 2010. Taxation of Tropical Forests: Search for Generalizations After Half a Century of trying. *International Forestry Review*, 12(2), pp.181–186.

Shogren, J.F., Herriges, J. a. and Govindasamy, R., 1993. Limits to Environmental Bonds. *Ecological Economics*, 8(2), pp.109–133.

Simula, M., Salmi, J. and Puustajarvi, E., 2002. *Forest Financing in Latin America: The Role of the Inter-American Development Bank*. Inter-American Development Bank, Washington DC.

Solow, R.M., 1971. The Economist's Approach to Pollution and Its Control. *Science*, 173, p.502.

Sterner, T., 2003. *Policy Instruments for Environmental and Natural Resource Management*, RFF Press, Washington DC.

Sullivan, J. and Amacher, G.S., 2009. The Social Costs of Mineland Restoration. *Land Economics*, 85(4), pp.712–726.

Uhlig, H., 1995. A Toolkit for Analyzing Nonlinear Stochastic Models Easily. Institute for Empirical Macroeconomics, Federal Reserve Bank of Minneapolis, 101.

Weitzman, M.L., 1974. Prices vs. Quantities. *The Review of Economic Studies*, 41(4), pp.477–491.

Wing, I.S. et al., 2009. *Absolute vs . Intensity Limits for CO2 Emission Control: Performance Under Uncertainty* R. Tulkens, H. Guesnerie, ed., MIT Press, Cambridge, MA.

Wooldridge, J.M., 2002. *Econometric Analysis of Cross Section and Panel Data*, MIT Press, Cambridge, MA.

Zhao, J., 2003. Irreversible Abatement Investment under Cost Uncertainties: Tradable Emission Permits and Emissions Charges. *Journal of Public Economics*, 87(12), pp.2765–2789.

APPENDIX A: COMPARATIVE STATICS

Agricultural land area:

Agricultural Produce Price Index:

$$\frac{dL_a}{dp_a} = k(q^*)\frac{W_{p_a}^* - A_{p_a}^*}{W_q^* - A_q^*} > 0$$

This can be established by noting that $W_{p_a}^* = 0$ and $A_{p_a}^* = r^{-1}G(l_a^*, q^*) > 0$. By assumption (4), $W_q^* - A_q^* < 0$, and the overall effect is therefore positive.

Timber Price:

$$\frac{dL_a}{dp_f} = k(q^*)\frac{W_{p_f}^* - A_{p_f}^*}{W_q^* - A_q^*} < 0$$

Note that $A_{p_f}^* = 0$ and $W_{p_f}^* = r^{-1}[1 - \rho_f(\psi)]F(l_f^*, q^*) > 0$. By assumption (4), $W_q^* - A_q^* < 0$, and the overall effect is therefore negative.

Labor Unit Price:

$$\frac{dL_a}{dw} = k(q^*)\frac{W_w^* - A_w^*}{W_q^* - A_q^*} \gtreqless 0$$

Note that $W_w^* = -r^{-1}[1 - \rho_f(\psi)]l_f^* < 0$ and $A_w^* = -r^{-1}l_a^* < 0$, and therefore the sign is ambiguous.

Regime Variable:

Define the following two expressions evaluated at q^*:

$$\Delta A = A^*(\psi_1) - A^*(\psi_0)$$

$$\Delta W = W^*(\psi_1) - W^*(\psi_0)$$

where ψ_1 stands for the presence of a new regime, and ψ_0 for the presence of status quo regime. The direction of the change in the agricultural margin depends on the sign of difference of the above two expressions:

$$\mathrm{J} = \Delta A - \Delta W$$

Since before the regime change the optimality condition was defined as

$$W^*(\psi_0) - A^*(\psi_0) = 0$$

we have

$$J = A^*(\psi_1) - W^*(\psi_1)$$

The sign of J determines whether the agricultural margin expands (+) or shrinks (-).

Roads Variable:

$$\frac{dL_a}{dR} = k(q^*)\frac{W_R^* - A_R^*}{W_q^* - A_q^*} \gtreqless 0$$

Since the C_f and C_a are both decreasing in road building, we have

$$W_R^* = -r^{-1}\left[1 - \rho_f(\psi)\right]\frac{\partial C_f(R,q)}{\partial R} > 0$$

$$A_R^* = -r^{-1}\frac{\partial C_a(R,q)}{\partial R} > 0$$

and therefore the sign is ambiguous.

<u>Virgin forest land area:</u>

Agricultural Produce Price Index:

$$\frac{dL_{vf}}{dp_a} = -k\left(q_f\right)\frac{W_{p_a}^*}{W_{q_f}^*} = 0$$

since $W_{p_a}^* = 0$.

Timber Price:

$$\frac{dL_{vf}}{dp_f} = -k\left(q_f\right)\frac{W_{p_f}^*}{W_{q_f}^*} < 0$$

since $W_{p_f}^* = r^{-1}\left[1 - \rho_f(\psi)\right]F\left(l_f^*, q^*\right) > 0$ and $W_{q_f}^* > 0$.

Labor Unit Price:

$$\frac{dL_{vf}}{dw} = -k\left(q_f\right)\frac{W_w^*}{W_{q_f}^*} > 0$$

since $W_w^* = -r^{-1}[1 - \rho_f(\psi)]l_f^* < 0$ and $W_{q_f}^* > 0$.

Regime Variable:

Define $J_f = W(\psi_1) - W(\psi_0)$. Since both terms on the right-hand side are evaluated at q_f, we have $J_f = W(\psi_1)$. If $J > 0$, then new regime leads to expansion of concession forestry until we reach a new point q_{ff} where $W(\psi_1) = 0$. Similarly, if $J_f < 0$, then virgin forests expand until the point where $W(\psi_1) = 0$.

Roads Variable:

$$\frac{dL_{vf}}{dR} = -k(q_f)\frac{W_R^*}{W_{q_f}^*} < 0$$

since

$$W_R^* = -r^{-1}[1 - \rho_f(\psi)]\frac{\partial C_f(R,q)}{\partial R} > 0$$

and $W_{q_f}^* > 0$.

APPENDIX B: BOND PROOFS

Proof of Proposition 2:

Let $B(x) = c(x_0) - c(x) + bx + a$ where $a > 0$ and $b > 0$. This function satisfies the condition in Proposition 1 and in effect generates a linear total cost of compliance function $T(x) \equiv B(x) + c(x)$. This can be seen clearly by substituting the proposed bond function into the definition for $T(x)$ which then becomes $T(x) \equiv c(x_0) + bx + a$. Our goal is to choose all the parameters in such a way to guarantee that x_0 then minimizes $T(x)$.

Using the condition $B(0) = B_0$ we have

$$B_0 = c(x_0) - c(0) + a$$

$$B_0 = c(x_0) + a$$

Using $B(x_0) = 0$ we get

$$c(x_0) - c(x_0) + bx_0 + a = 0$$

$$b = -\frac{a}{x_0}$$

Combining the above two conditions with $B(x) = c(x_0) - c(x) + bx + a$, we get the expression in (3) for $x \leq x_0$. For any RIL compliance level x such that $x_0 < x \leq 1$, we simply set the bond function to take value zero.

Proposition 3: We first prove two lemmas that establish the upper bound for feasible $x_0 \in (0,1)$.

Lemma 1:

If RIL compliance $x_0 \in (0,1)$ is a unique solution to the harvester's cost minimization problem, then the bond payment B_0 satisfies $B_0 > c(x_0)$. Conversely, if $B_0 < c(x_0)$, then x_0 cannot be a solution to the harvester's cost minimization problem.

Lemma 2:

The second-best bond, $\bar{B}$, can achieve any unique RIL compliance level $x_0 < \bar{x}$ where $\bar{x} = c^{-1}(\bar{B})$ and c^{-1} denotes the inverse mapping of the cost function. In other words, $\bar{x}$ denotes the upper bound for RIL compliance that can be achieved with the second-best bond.

Proof of Lemma 1 and Lemma 2:

Let $B_0 < c(x_0)$. For Lemma 1, then assume that the harvester chooses RIL level $x = 0$, that is, total noncompliance. At this point, the harvester's costs are $c(0) + B_0 = B_0$, and since $B_0 < c(x_0)$ by assumption, x_0 cannot minimize costs. For Lemma 2, notice that the case where $x_0 > \bar{x}$ is ruled out by Lemma 1. Now suppose that $x_0 = \bar{x}$. Then we can write the condition in Proposition 1 as

$$B(x;\bar{B}) > c(\bar{x}) - c(x)$$

which holds for any x. Since $\bar{B} = c(\bar{x})$ this becomes

$$B(x;\bar{B}) > \bar{B} - c(x)$$

Now evaluating this at $x = 0$ we have

$$B(0;\bar{B}) > \bar{B}$$

which cannot be true as the left hand side also equals $\bar{B}$. Therefore $x_0 = \bar{x}$ is not a unique solution. Finally, suppose that $x_0 < \bar{x}$. Then by applying Proposition 2, we can always devise a bond function $B(x;\bar{B})$ that guarantees a unique solution at x_0.

Proof of Proposition 3: Given the conditions in Lemma 1 and Lemma 2, the result follows from Proposition 2 by making the substitution $B_0 = \bar{B}$.

Proof of Proposition 5:

Let $B(x) = \frac{c(x_0) - c(x)}{1-r} + bx + a$ where $a > 0$ and $b > 0$. This function satisfies the condition in Proposition 4. Using the condition $B(0) = B_0$ we have

$$B_0 = \frac{c(x_0) - c(0)}{1-r} + a$$

$$\Rightarrow B_0 = \frac{c(x_0)}{1-r} + a$$

since $c(0) = 0$. Using $B(x_0) = 0$, it follows that

$$\frac{c(x_0) - c(x_0)}{1-r} + bx_0 + a = 0$$

$$b = -\frac{a}{x_0}$$

Combining the above to conditions, we have the expression in Proposition 5.

Proof of Proposition 8:

Proposition 8 follows from the requirement that

$$c(x) + \rho(x,e)B(x;B_0) > c(x_0) + \rho(x_0,e)B(x_0;B_0)$$

for all $x \neq x_0$ and where $B(x_0;B_0) = 0$. The left-hand side represents the expected cost of choosing any other RIL intensity, and the right-hand side captures the expected cost from choosing the target RIL level.

Proof of Proposition 9:

Let $B(x) = \frac{c(x_0)-c(x)}{\rho(x,e)} + bx + a$ where $a > 0$ and $b > 0$. This function satisfies the condition in Proposition 8. Using the conditions $B(0) = B_0$ and $\rho(1,e) = 1$, we have

$$B_0 = c(x_0) + a$$

Using $B(x_0) = 0$, it follows that

$$\frac{c(x_0) - c(x_0)}{\rho(x,e)} + bx_0 + a = 0$$

$$b = -\frac{a}{x_0}$$

The additional requirements on the parameters a and x_0 can be derived by taking the derivative of the bond function in the subset $x < x_0$ with respect to x:

$$B'(x;B_0) = \frac{\rho_x[c(x) - c(x_0)] - \rho(x,e)c'(x)}{[\rho(x,e)]^2} - \frac{a}{x_0} \qquad (78)$$

This expression has to be negative for all $x < x_0$ to guarantee a decreasing bond function. Combining the above to conditions, we get all the expressions in Proposition 8.

Simulations: Imperfect Enforcement

From Corollary 5, the first-best bond is given by $B_0 = c(1) + a$ where parameter a has to satisfy the following slope condition:

$$a > \frac{\rho_x[c(x) - c(1)] - \rho(x,e)c'(x)}{[\rho(x,e)]^2}$$

for all $x < 1$. Given the functional forms in our simulations, it can be shown that the right hand side in the above condition has a maximum point at $x^* = 0$ on the interval $x \in [0,1]$ and for $e > 1$. Therefore, using the assumed functional forms, the parameter a has to satisfy

$$a > \frac{k}{e}$$

Plugging in $k = 100$ and $e = 1.2$, we get $a > 83.33$. Hence the minimum bond payment that guarantees full RIL target is given by $B_0 = 100 + 83.33 = 183{,}33$.

APPENDIX C: FIRST ORDER CONDITIONS AND STEADY STATES

The Lagrangian of the constrained utility maximization problem can be written as

$$E_t \sum_{t=0}^{\infty} \{\beta^t U(C_t, 1-L_t) + \lambda_t [Y_t - C_t - K_{t+1} + (1-\delta)K_t - p_t M_t] + \mu_t [T(Y_t) - M_t]\} \quad (79)$$

The first order conditions are

$$\lambda_t = \beta^t U_C$$

$$\mathrm{z_t} F_L(K_t, L_t, M_t)(1 + \hat{\mu}_t T_Y) = -\frac{1}{\lambda_t} \beta^t U_L$$

$$\mathrm{z_t} F_K(K_t, L_t, M_t)(1 + \hat{\mu}_t T_Y) = E_t \left(\frac{\lambda_t}{\lambda_{t+1}} + \delta - 1 \right)$$

$$\mathrm{z_t} F_M(K_t, L_t, M_t)(1 + \hat{\mu}_t T_Y) = p_t + \hat{\mu}_t$$

$$z_t F(K_t, L_t, M_t) = K_{t+1} - (1-\delta)K_t + C_t + p_t M_t$$

$$M_t = T(Y_t)$$

where $\hat{\mu}_t = \mu_t / \lambda_t$, and functions with subscripts denote the derivative of the function with respect to the variable in the subscript. We can use the condition in the first line to substitute for λ_t and reduce the above system to the one in (45).

Fixed Permit Quota

With fixed quota, we have $T(Y_t) = \bar{M}$ and $T_Y = 0$. The necessary conditions in (45) become

$$\begin{aligned} &\mathrm{z_t} F_L(K_t, L_t, M_t) = -\frac{U_L}{U_C} \\ &\mathrm{z_t} F_K(K_t, L_t, M_t) = \beta^{-1} E_t \left(\frac{U_{C,t}}{U_{C,t+1}} + \delta - 1 \right) \\ &\mathrm{z_t} F_M(K_t, L_t, M_t) = p_t + \hat{\mu}_t \\ &z_t F(K_t, L_t, M_t) = K_{t+1} - (1-\delta)K_t + C_t + p_t M_t \\ &M_t = \bar{M} \end{aligned} \quad (80)$$

The steady state relationships in (46) can be written as

$$\begin{aligned} &F_L(K, L, M) = -\frac{U_L}{U_C} \\ &F_K(K, L, M) = \beta^{-1} \delta \\ &F_M(K, L, M) = 1 + \hat{\mu} \end{aligned} \quad (81)$$

$$F(K, L, M) = \delta K + C + M$$
$$M = \bar{M}$$

where all the variables are in a steady state.

Intensity Targeting

With intensity target, the permit allowance is adjusted periodically given the intensity target, s, and based on the rule $T(Y_t) = sY_t$. Therefore, $A_Y = s$, and the first-order conditions become

$$\begin{aligned} & z_t F_L(K_t, L_t, M_t)(1 + \hat{\mu}_t s) = -\frac{U_L}{U_C} \\ & z_t F_K(K_t, L_t, M_t)(1 + \hat{\mu}_t s) = \beta^{-1} E_t\left(\frac{U_{C,t}}{U_{C,t+1}} + \delta - 1\right) \\ & z_t F_M(K_t, L_t, M_t)(1 + \hat{\mu}_t s) = p_t + \hat{\mu}_t \\ & z_t F(K_t, L_t, M_t) = K_{t+1} - (1 - \delta)K_t + C_t + p_t M_t \\ & M_t = sY_t \end{aligned} \tag{82}$$

The steady state relationships are now:

$$\begin{aligned} & F_L(K, L, M)(1 + \hat{\mu}s) = -\frac{U_L}{U_C} \\ & F_K(K, L, M)(1 + \hat{\mu}s) = \beta^{-1}\delta \\ & F_M(K, L, M)(1 + \hat{\mu}s) = p_t + \hat{\mu}_t \\ & F(K, L, M) = \delta K + C + M \\ & M = sF(K, L, M) \end{aligned} \tag{83}$$

Log-linearization

For any variable, X_t, the following definitions hold

$$\begin{aligned} x_t &= \log(X_t) - \log(X) \\ X_t &= Xe^{x_t} \end{aligned} \tag{84}$$

where X denotes the steady state in levels. Assuming the functional forms in (65) and (66), the log-linearized equations under fixed allowances are

$$\begin{aligned} & (1 - \alpha - \gamma)Y(1 - L)y_t - [(1 - \alpha - \gamma)YL + \omega CL]l_t - \omega CLc_t = 0 \\ & E_t\{\beta^{-1}K\delta k_t + \beta^{-1}Kc_{t+1} - \beta^{-1}Kc_t - \alpha Y y_t\} = 0 \\ & \bar{M}\log p_t + \bar{M}\hat{\mu}\tilde{\mu}_t - \gamma Y y_t = 0 \end{aligned} \tag{85}$$

$$Kk_{t+1} - (1-\delta)Kk_t + Cc_t + \bar{M}\log p_t - Yy_t = 0$$
$$\log z_t + \alpha k_t + (1-\alpha-\gamma)l_t - y_t = 0$$

where $\tilde{\mu}_t = \log\hat{\mu}_t - \log\hat{\mu}$. Similarly, the log-linearized equations under intensity allowances are

$$\begin{aligned}
&(1-\alpha-\gamma)Y(1-L)(1+\hat{\mu}s)y_t - [(1-\alpha-\gamma)YL(1+\hat{\mu}s) + \omega CL]l_t \\
&\qquad + (1-\alpha-\gamma)Y(1-L)\hat{\mu}s\tilde{\mu}_t - \omega CLc_t = 0 \\
&E_t\{\beta^{-1}K\delta k_t + \beta^{-1}Kc_{t+1} - \beta^{-1}Kc_t - \alpha Y(1+\hat{\mu}s)y_t - \alpha Y\hat{\mu}s\tilde{\mu}_t\} = 0 \\
&M\log p_t - (\gamma Y\hat{\mu}s - M\hat{\mu})\tilde{\mu}_t + M(1-\hat{\mu})m_t - \gamma Y(1+\hat{\mu}s)y_t = 0 \\
&Kk_{t+1} - (1-\delta)Kk_t + Cc_t + M\log p_t + Mm_t - Yy_t = 0 \\
&\log z_t + \alpha k_t + \gamma m_t + (1-\alpha-\gamma)l_t - y_t = 0 \\
&sYy_t - Mm_t = 0
\end{aligned} \tag{86}$$

Define the following vectors: $v_t = [y_t, c_t, l_t, \tilde{\mu}_t]'$ and $w_t = [\log z_t, \log p_t]'$ where v_t collects the endogenous variables (jump variables) and w_t the exogenous variables. Collecting all the coefficients in their respective matrices, we can write (85) or (86) as

$$\begin{aligned}
E_t(Ak_t + Bv_{t+1} + Cv_t) &= 0 \\
Dk_{t+1} + Fk_t + Gv_t + Hw_t &= 0 \\
w_{t+1} &= Jw_t + \psi_{t+1}
\end{aligned} \tag{87}$$

APPENDIX D: PERMIT PRICE EXAMPLE

Let the energy price process, p_t, and the technology process, z_t, both take the following AR-1 forms:

$$\begin{aligned}\log p_t &= \pi \log p_{t-1} + \epsilon_t \\ \log z_t &= \eta \log z_{t-1} + \omega_t\end{aligned} \tag{88}$$

where ϵ_t and ω_t are independent white noise disturbances with mean zero and variance terms σ_ϵ^2 and σ_ω^2, respectively. Let the equation of motion for capital be given by

$$k_{t+1} = b_1 k_t + b_2 \log p_t + b_3 \log z_t \tag{89}$$

where k_t is defined as the log deviation from steady state and coefficients b_1, b_2, b_3 are known solutions to the log-linearized system. By applying recursive substitution, we can write (89) as a function of past shocks only:

$$k_{t+1} = b_3 \sum_{i=0}^{\infty} \sum_{j=0}^{i} \left({b_1}^j \eta^{i-j} \omega_{t-i} \right) + b_2 \sum_{i=0}^{\infty} \sum_{j=0}^{i} \left({b_1}^j \pi^{i-j} \epsilon_{t-i} \right) \tag{90}$$

Let the equation of motion for the permit price process, $\tilde{\mu}_t$, is given by

$$\tilde{\mu}_t = a_1 k_t + a_2 \log p_t + a_3 \log z_t \tag{91}$$

where coefficient a_1, a_2, a_3 are all known from the solution to the log-linearized system and $\tilde{\mu}_t = \log \hat{\mu}_t - \log \hat{\mu}$. Using the following expressions for the stochastic processes written in terms of lagged disturbances:

$$\begin{aligned}\log p_t &= \sum_{i=0}^{\infty} \pi^i \epsilon_{t-i} \\ \log z_t &= \sum_{i=0}^{\infty} \eta^i \omega_{t-i}\end{aligned} \tag{92}$$

and (90) lagged by one period, we can rewrite (91) as

$$\begin{aligned}\tilde{\mu}_t = {} & a_2 \sum_{i=0}^{\infty} \pi^i \epsilon_{t-i} + a_3 \sum_{i=0}^{\infty} \eta^i \omega_{t-i} \\ & + a_1 \left[b_3 \sum_{i=0}^{\infty} \sum_{j=0}^{i} \left({b_1}^j \eta^{i-j} \omega_{t-1-i} \right) + b_2 \sum_{i=0}^{\infty} \sum_{j=0}^{i} \left({b_1}^j \pi^{i-j} \epsilon_{t-1-i} \right) \right]\end{aligned} \tag{93}$$

This expression can furthermore be written as

$$\tilde{\mu}_t = a_2\epsilon_t + a_3\omega_t + \sum_{i=0}^{\infty}\left(a_1 b_3 \sum_{j=0}^{i}\left({b_1}^j \eta^{i-j} + a_3\eta^{i+1}\right)\right)\omega_{t-1-i} + \sum_{i=0}^{\infty}\left(a_1 b_2 \sum_{j=0}^{i}\left({b_1}^j \pi^{i-j} + a_2\pi^{i+1}\right)\right)\epsilon_{t-1-i} \tag{94}$$

From (94), we can derive the expected value:

$$E(\log\hat{\mu}_t) = \log\hat{\mu} \tag{95}$$

Since the ω_t and ϵ_t and independent processes, we can write the variance of the permit price process as

$$Var(\log\hat{\mu}_t) = \left[{a_2}^2 + \sum_{i=0}^{\infty}\left(a_1 b_2 \sum_{j=0}^{i}\left({b_1}^j \pi^{i-j} + a_2\pi^{i+1}\right)\right)^2\right]\sigma_\epsilon^2 + \left[{a_3}^2 + \sum_{i=0}^{\infty}\left(a_1 b_3 \sum_{j=0}^{i}\left({b_1}^j \eta^{i-j} + a_3\eta^{i+1}\right)\right)^2\right]\sigma_\omega^2 \tag{96}$$