ABSTRACT

Title of dissertation: SPATIAL EFFECTS OF LOCAL GOVERNANCE INSTITUTIONS ON ILLEGAL DEFORESTATION IN DEVELOPING COUNTRIES

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Deforestation worldwide is a major concern. In developing countries, it is a merciless and devastating reality. My thesis addresses how local governance institutions' strength influences this phenomenon, focusing on the Colombian Andes.

The theoretical analysis examines spatial patterns of illegal deforestation when enforcement is costly, and costs rise with distance from governmental centers. Those spatial patterns depend on the interaction between transportation costs incurred by farmers growing crops on deforested land and enforcement costs incurred by government officials conducting on-the-ground monitoring of deforestation. Areas closer to governmental centers can be monitored effectively and are thus less subject to illegal deforestation. Illegal deforestation is therefore more likely in areas where monitoring costs are high, but farmers' transportation costs are not. The calibration exercise then shows, that in this context, patches of deforestation might arise within the forest, causing unwanted forest fragmentation.

Based on these results I study empirically, first, if the effect of access difficulty on deforestation may be non-monotonic in accessibility, causing forest fragmentation; and second, if this fragmentation is more likely to occur when enforcement is more costly. I approach this question in two manners: (1) using a cubic function of access difficulty interacted with measures of enforcement capacity and (2) non-parametrically using indicators for discrete ranges of access difficulty, again interacted with measures of enforcement capacity.

I construct for this purpose a panel data set for the Colombian Andes from a variety of sources. Data on deforestation comes from satellite imaging at a 30mx30m resolution in two periods (2000-2005) and (2005-2010), this data was matched with biophysical variables such as, altitude, slope, precipitation, soil type, and roads using geographical information systems (GIS), as well as with socioeconomic variables which vary by municipality and time.

The regressions show a significant non-monotonic effect of access difficulty on deforestation. The evidence shows that deforestation probability first decreases with access difficulty, and it then increases in remoter places. This evidences forest fragmentation as one moves away from roads. Moreover, this pattern is affected by the fiscal performance index (a proxy for enforcement capacity) of the municipalities, showing that municipalities with lower enforcement capacity have a higher probability to present illegal deforestation at remote places. This research adds to the deforestation literature, by studying the spatial reach of governance capacity and how it affects deforestation patterns. The findings highlight the importance of taking enforcement and monitoring costs as well as their spatial variation into account, when designing land-use policies and defining the institutional arrangements, funding and monitoring processes to implement them.

Spatial effects of local governance institutions on illegal deforestation in developing countries

by

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Dedication

To Aurelio and Antonio, who fill my life with happiness.

To Jose, for his patience, tenacity and support.

To my parents for their resilience and love.

To Deb for her unconditional company.

To all my AREC colleagues, specially to Claudia Hitaj, Romina Ordonez and Rubaba Ali, for sharing this journey with me.

To my friends and family, who have seen me wrestle through the bad times and have helped me keep going.

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Chapter 1: Introduction

Facing a potential non-return point due to climate change, forests, their contribution to carbon storage and the prevention of deforestation are a prominent topic. The recent increases in deforestation in the Brazilian and Colombian Amazon foster a wealth of explanations, yet little agreement on the actions needed to address these spikes. Some argue that the increment in deforestation is due to lax governments and their alignments with economic development interests. [1] Others consider that governments have been too slow to react to confront these crises. [2] In practice, although forest conservation policies are in place, conservation is not strictly enforced, and there are few deterrent or consequences for land clearing. To address illegal deforestation conservation policies must be designed and implemented. For this purpose, one not only needs the political will, but this will must be backed up with resources. Unfortunately, this is still often not be sufficient. In Colombia, for example, the budget for the whole National Environment System (SINA), was decreased for 2019 to around 0.3 percent of government expenditures. [2]. Such reductions perpetuate the country's inability to enforce forest conservation policies.

In this thesis I consider the costs of implementing deforestation deterrence policies. Moreover, I recognize that policies' surveillance and enforcement costs vary with location. Results show that, in contexts with low institutional capacity (i.e. low budgets, lack of personnel, lack of human capacity, among others), these costs might render unintended harmful environmental effects, such as habitat fragmentation.[1] In the first part of the study, I model this process theoretically, showing how the steep increase of enforcement costs associated with low accessibility results in changes in the expected deforestation patterns. In the second part of the study, I explore this possibility empirically, finding a non-monotonic[2] pattern between accessibility and the probability of illegal deforestation in the Colombian Andes. I also find a significant change of this pattern when enforcement variables are added to the analysis. Based on these results I present recommendations to reduce illegal deforestation, in particular for Colombia, by improving local implementation capacity of local governments including: administrative capacity building, access to new resources, and improvements in optimizing present resource sources.

As global population continues to grow, the demand for food and agricultural products is simultaneously rising and is expected to continue this way. Since land is a fundamental input for agricultural production this growing demand is spurring the demand for productive land. On the other hand, ecosystem services provided by natural habitat are now well recognized and are becoming scarce, as land use change, from natural to productive, increases globally. [3] Therefore the land market faces a classic externalities problem; where land use change decisions are based solely on the benefits of agricultural production, but do not consider social and environmen-

[1] Fragmentation is defined as the degree to which habitat in a landscape exists as a single continuous unit versus smaller, isolated patches.

[2] Non-monotonic means neither constantly increasing not constantly decreasing

tal costs of deforestation. Land is becoming a scarce input and deforestation and fragmentation continue to rise, the rate of global forest loss is both rapid (125,000 km2/year between 2001 and 2012) and increasing (by 2,000 km2/year). [4]

Globally, although a few large patches of pristine forests still remain, there is an increasing need to manage *mosaic lands*[3] where both land covers (agriculture and natural habitat) are highly valuable simultaneously and thus the conflicts between them become more complex and intense. [6] There is a growing set of policies targeted at solving this problem: command and control, assignation property rights, economic incentives and voluntary agreements, among others. Some of these policies have been prolifically studied, in particular: protected areas, property rights designation and payments for environmental services (PES). [3, 7–9]

There is evidence that, although the policies are a necessary piece to effectively manage this problem, they are not enough. Policies need to be implemented, and in particular, in developing countries this is still a challenge. Often, local institutions are in charge of implementation, including surveillance and enforcement responsibilities. These local governments, are often overborne with these and other responsibilities, while their budgets are scarce, rendering them incapable of performing implementation duties effectively.

Land has a singular characteristic: location. This characteristic has been recognized as important for both, agricultural production (i.e. input and output transportation costs) and ecosystem service provision (e.g. recreation, water provi-

[3]Chomitz et. al 2006 define three types of forest: trans-frontier, frontier and mosaic lands [5]. He uses the term mosaic lands to refer to a mix of agriculture and forest patches, from dottings of trees between pastures to large forested islands surrounded by farming.

sion, biodiversity conservation). For agricultural production: distance to the market has a well recognized positive effect on deforestation [10–12]. For ecosystem services, tools like Systematic Conservation Planning (SCP) have been designed to organize land to spatially optimize their provision [13].

However, the spatial aspects of policy implementation have often been ignored. In particular, costs of surveillance and enforcement, will vary by location, as most of this work has to be done as in-person visits, either to make sure that policies are being followed or if not, to take the corresponding action. As a result, policy implementation close the administrative centers, where institutions are physically located, is much cheaper than in locations relatively away from administrative centers. In the latter, where the roads are scarce, terrain is difficult and mobility is restricted, these costs can become very high.

In consequence, land use policies might be implemented in places of easy access, but not as much at remoter places, where surveillance and enforcement is more costly. This generates an incentive for farmers to illegally deforest at places more remote, while leaving closer areas forested. A hiding process emerges, where deforestation increases at places less accessible, reversing the traditional *von Thunen* [4] pattern and fragmenting the forest.

My research recognizes the spatial variation of surveillance and enforcement costs, and its effect on illegal deforestation, first theoretically and then empirically. It focuses on areas where both agriculture and environmental benefits are positive

[4] von Thunen argues that land use activities will be organized in circular rings around the market, due to their different transportation costs. According to this model, farming will be done until a certain radius where it is not profitable anymore, and from there on natural land will prevail [14]

(i.e. mosaic lands). The theory presented shows how enforcement costs can end up reversing the expected positive effect of accessibility on deforestation.

This relation between illegal deforestation pattern and enforcement is then empirically studied in two different areas in the Colombian Andes: in forest reserves, where cutting the forest is prohibited, and in non-protected areas. In both cases, the empirical analysis shows that access difficulty (i.e. measured as slope-weighted distance to roads, to account for the effort of walking) is non-monotonically related to deforestation. Moreover, the enforcement proxies used, affect the obtained pattern showing that the better the enforcement capabilities, the lower the probability of deforestation at remote places.

Based on the theoretical and empirical results and to improve the local institutional capacity, and in particular reduce the probability of forest fragmentation, recommendations to reduce fragmentation within reserves, by strengthening the municipalities capacity to increase their budgets and manage their funds are presented.

Although drivers of deforestation have been prolifically studied, deforestation, and particularly illegal deforestation, continues to rise. The literature on drivers of deforestation has recognized the importance of understanding the spatial nature of these processes. The literature on policy evaluation recognizes that policies are not enough to stop deforestation, and that governance and in particular surveillance and enforcement capacities of the implementing institutions play a principal role on policy success. The research I undertake adds to this literature studying how governance variables, also depend on space, and as such, affect the expected spatial patterns of deforestation producing unwanted forest fragmentation.

This document continues as follows. In Chapter 2, I present a review of the related literature and in Chapter 3 I describe the empirical context. In Chapters 3 and 4, I introduce the theoretical model and a numerical calibration and sensitivity analysis. I continue explaining the data and methodology used for the econometric analysis (Chapter 6) and in Chapter 7, I present the results. I end with some policy implications and conclusion (Chapter 8).

Chapter 2: Literature Review

This literature reviews starts by describing the problem deforestation is still represents, particularly in developing countries. Then I introduce the literature on drivers of deforestation and summarize its general conclusions. I continue by describing the literature evaluating the effectiveness of deforestation prevention policies and strategies including protected areas, property right assignation and payments for ecosystem services. Then I address the literature of forest governance and focus on the results related to monitoring and enforcement. To finalize the chapter, I describe the studies most closely related to this research, which recognize conceptually, theoretically or empirically the spatial dimension of monitoring and enforcement of environmental policies.

While there is growing evidence, both in academic and non-academic literature, highlighting the importance of goods and services generated by forests, including carbon storage, biodiversity habitat, water filtration, storm mitigation, disease suppression, timber and non timber products, wild foods and medicines, and recreation; [15–17] forests continue to face high risks of degradation, fragmentation, conversion to other uses and unsustainable exploitation. [3, 4, 18] From the local provision of non-timber forest products to the regulation of climate, sustaining the biophysical properties of forests remains one of the most important goals for policymakers.

Moreover, the remaining natural forest continues to be distributed in smaller and more dispersed patches [19,20] Ineffective land conservation does not only allow for more deforestation, but it may also increase forest fragmentation. Fragmentation, as well as the reduction in total forest area, is identified as an essential determinant of the amount and quality environmental services produced in an area [21–26].

Mosaic forests include, as already mentioned, landscapes which range from dotting of trees between pastures, to large forested islands surrounded by farming. [5] Although this type of forests are often overlooked by environmental policy, mosaic lands are important because: 1) they contain a large proportion of forest dwellers, and consequently the interaction between forests and people is large, rendering trees there particularly important as source of economic income as well as ecosystem services, 2) although they may have more secure land tenure than forest frontier lands, they are also closer to markets and have higher land value for agricultural purposes, and 3) existing forest fragmentation places biodiversity in these areas under higher risk of extinction. [5]

Drivers of deforestation have been prolifically studied, from country wide comparisons to very detailed local panel data available from geographic information systems (GIS) and satellite images [3]. There are numerous previous reviews of the drivers of deforestation, some of the most cited include: Angelsen and Kaimowitz 1999; [27],Geist and Lambin 2002; [28] Chomitz 2007; [5], Rudel et al. 2009; [29], Angelsen and Rudel 2013 [30]; Pfaff, Amacher, and Sills 2013); [31].

Land users' decisions to convert land from forest to agriculture, pasture, or mining are influenced by a number of factors (i.e. indirect drivers [32]). The biophysical characteristics of land, such as slope, elevation, wetness, and soil suitability, influence the types of economic activity that different lands can support. The market demand for agricultural and timber commodities, reflected through prices, affects the revenues that can be gained from exploiting forests or converting them to agriculture. Characteristics of the built environment, such as roads and towns, influence the costs of transporting goods to market. The households or communities making land use decisions vary in their social, economic, cultural and demographic characteristics. [3, 32]

Recently a meta-analysis by Busch, Jonah and Ferreti. 2017, [3] found 121 studies of drivers between 1996 and 2013. Their results show that roads, urban areas, population, soil suitability, agricultural activity, and proximity to agriculture are consistently associated with higher deforestation, while slope, elevation, protected areas, and poverty are consistently associated with lower deforestation.

Variables related to access are among the first to be studied as drivers of deforestation. Dating back as far as Johann Heinrich *von Thunen*'s quantitative spatial model, in which economic returns determine how land is allocated between forests and agriculture. [14] *Von Thunen*'s model shows that since returns diminish as transportation costs increase, activities with relatively high transportation costs will be located closer to cities while activities with lower transportation costs will be located further away from populated centers or markets. Empirical evidence also shows that lands situated nearer to roads are associated with higher deforestation.

[10–12]

Drivers interact in complex ways. For example, fertile agricultural soil invites deforestation directly, and also encourages the construction of roads, which spurs further deforestation. [3] Moreover, the causality can run in both directions. For example, while growing populations can increase demand for deforestation, more deforested land can also support a greater population. [3, 33] Also, regarding income as a driver of deforestation, the existence of an "environmental Kuznets curve for deforestation", where deforestation first increases when countries are developing and the agricultural frontier is expanding and income increases, then it peaks, and starts falling when forests become scarce and recreation and environmental services are highly valued by the wealthier populations is also proposed. [34] Moreover, deforesting decisions are made within the context of varying ownership and management rights, ranging from protected public lands, to open access commons, to leased concessions, to privately owned land with varying degrees of tenure security and varying levels of war, violence, and corruption. [3]

While there is a general recognition of the importance of the forested areas and their ecosystem services, and despite the significant efforts from governments, *NGOs*, and multilateral agencies (among others) to stop deforestation, the latter remains rampant. Multiple strategies and policies for conserving forests have emerged to solve the deforestation problem. These include, among others, the declaration of protected areas through national or regional parks, the assignment of property and management rights to individuals or communities, and the design of economic incentives such as payments for ecosystem services (PES) to voluntarily protect forested land. Evaluating the effectiveness of these policies has been an important subject of the drivers of deforestation literature. [35, 36]

The expanding global protected area (PAs) network will likely meet its Aichi target of protecting 17% of the planet's surface by 2020 (CBD; http://www.cbd.int/sp/targets). In fact, protected areas have even been identified as the most important land-use on the planet [37]. The majority of the most recent PAs are located in developing countries, where biodiversity is greatest and there is substantial pressure on natural resources [38, 39]. In particular, Central America and South America are the regions with the highest percentage of protected terrestrial areas, where 28.2% and 25% of their territory respectively is under some kind of protection [40].

Assessments have demonstrated repeatedly that PAs experience significantly lower rates of forest clearing in comparison to their unprotected surroundings [3, 7, 36, 39]. Although well-managed PAs have been proved to reduce rates of habitat loss in terrestrial environments [41, 42] there are still major shortfalls in both coverage and effectiveness of PAs [43, 44]. Fragmentation has been recognized as a problem within PAs, even when it is reduced in comparison with their buffer zones for example [45].

Using matching as an empirical strategy to avoid selection bias, analyses determine that parks do lead to avoided deforestation. [9, 13, 46, 47] Most of these studies however, do not include variables of enforcement and management needed to deter deforestation. [36] Overall, these empirical assessments find that even the most effective PAs incur some deforestation within their boundaries.

The effect of PES on decreasing deforestation might also be affected by selection bias, where the mechanism for such payments are only implemented at areas which would in other cases also display high forest governance capabilities. Literature assessing the effectiveness of payments for ecosystem services in reducing deforestation initially find the effect on avoided deforestation to be small. [48, 49]

Assigning property rights and forest management to communities is a strategy that has also readily been evaluated. [50] The literature shows that in 81% of the cases these policies can be associated with a positive impact on forest cover. [36]. Spatial studies of community forest management find that smaller group size, higher secondary education, together with spatial distribution and the level of deforestation within the community, reduce deforestation rates. [51]

Clearly, policies are not enough to deter deforestation. Such policies must be accompanied by good quality governance and strong institutional capacity in the implementing organizations. This is particularly important if the policies are originated or designed from outside the forested area, but implemented locally.

Governance is a wide term that includes at least 3 levels:(i) decision making processes, (ii) rules and policies, and (iii) enforcement and monitoring. The variables used to measure governance vary widely as well, and include ownership rights, presence of environmental NGOs, and rule of law, and democracy. [8] These variables are harder to measure in micro settings, so much of the evidence linking these variables and deforestation is drawn from inter country comparisons. [52–55] A meta-analysis undertaken in 2018 shows, however, that the effect of governance on deforestation depends on which variable is used to represent governance. [8]

One of the important variables studied in forest governance literature is related to surveillance and enforcement capacity. Enforcement variables have been found related to lower deforestation, suggesting that law enforcement can play a key role in reducing deforestation. [3] For example, law enforcement prevented encroachment into a national park by coffee growers in Sumatra [56] and heightened monitoring of the forest code by police in Brazil also reduced deforestation. [57] Additionally, high scores in rule of law are found to increase the likelihood of reaching a tipping point in deforestation. [58]

One of the most important hurdles for implementing institutions is their financial budget and personnel deficiency, required to meet the high enforcement and surveillance costs of conservation policies. [13, 36, 41] For example, for protected areas, the costs of surveillance and enforcement have been found to be non-trivial and a cause for PAs ineffectiveness [59]. Additionally, many PAs face budget constraints, which inhibit them from performing the needed enforcement activities [60, 61]. Empirical analyses have also found that, in particular when PAs are under-funded, higher levels of enforcement improve conservation success, [41, 62, 63].

The law and economics literature demonstrates that costly enforcement typically implies that some illegal activity will optimally occur. This may be due to the greater marginal costs versus benefits of deterring all such activity, or due to enforcement budget constraints residing below the first-best level of enforcement. [64, 65] The theory on natural resource extraction analyses, building on Becker's [64] model of incomplete enforcement, centralized versus decentralized protected-area management and the role of penalties in a dynamic setting. [66]. In the lower income countries funding is typically insufficient to exclude people fully from the reserve. [67] This literature also explores costly enforcement of private property rights on remote areas [68].

A series of related papers focuses on spatially explicit theoretical models of resource extraction, where benefits vary with space for non-timber forest products (NTFP) in PAs in developing countries. [69] This literature uses spatial economic decision models of resource-dependent households to demonstrate how villagers react to a reserve depending on the institutional and socioeconomic setting [70–74]. According to this literature, it may be best to forgo patrols in very remote (to the extractor) areas, where villagers are unlikely to go, and to permit extraction in some outer "buffer zone", when facing a restrictive surveillance and enforcement budget. [70]

Enforcement costs in developing countries are particularly high because transportation infrastructure is frequently precarious [75]. These enforcement costs have been found to be so important, that some suggest legalizing resource extraction by selected groups or in selected locations, in exchange for enforcement private services in hopes to reduce forest overall degradation [76]. The costs of surveillance and enforcement have been found to be the bulk of the protected area budget in remote and inaccessible areas [61, 75]. For example, a study of Colombian Natural Parks, [61] found that, primarily because of limited accessibility, 67% of the studied parks contained areas that had not been visited by guards for years. In some of these parks, these unmonitored areas accounted for at least 50% of their territory.

Borner 2014 [77] develops a conceptual framework, and a spatially explicit model, to analyze regulatory enforcement in the Brazilian Amazon, finding that spatial patterns of both, deforestation and inspection costs, markedly influence enforcement patterns. In a related paper, building on elements of optimal enforcement theory, Borner 2015 [78] uses data collected from field-based forest law enforcement operations in the Amazon region to develop a spatially explicit simulation model for deforestation decisions in response to policy incentives and disincentives. The research finds there are trade-offs between the cost-effectiveness of forest conservation and landholder income. These papers however, do not look explicitly on how enforcement costs vary with space and how this might affect the location of deforestation. This study addresses this aspect.

In summary, drivers of deforestation have been prolifically studied, however deforestation, and particularly illegal deforestation, continues to rise. The literature on drivers of deforestation has recognized the importance of understanding the spatial nature of these processes. The literature on policy evaluation recognizes that policies are not enough to stop deforestation, and that governance and in particular surveillance and enforcement capacities of the implementing institutions play a principal role on policy success. The research I undertake adds to this literature by recognizing that governance variables, in particular surveillance and enforcement costs, also depend on space, and as such, the expected spatial patterns of deforestation may be changed due to this relationship. The research explores this effect first with a theoretical model and a numerical illustration, and then empirically, using the Andean Region of Colombia as subject.

Chapter 3: Colombian Context

I begin this chapter with a description of the Colombian institutional and policy context and some of its shortcomings. Then I tackle drivers of deforestation in the country. Finally, I explain the geographical delimitation of the study region.

3.1 Governance Structure of the Environmental Sector

Colombia is politically and geographically divided in 32 departments and 1101 municipalities. Each department elects its governor, likewise each municipality elects its mayor democratically. Most of the municipalities have only one urban center, which is called the "head" of the municipality, and where all the administrative activity is located.

The two legislative pillars of Colombia's current environmental management system are the Constitution of 1991 and Law 99 of 1993. [79] A National Environmental System (SINA, by its acronym in Spanish) was setup in the head of the Ministry of the Environment (MADs by its acronym in Spanish), who is in charge of generating and overseeing environmental policies. The whole country is geographically divided in Autonomous Regional Corporations (CARs), roughly corresponding to the departments, which are in charge of implementing environmental policies guided by the MADs. CARs must coordinate with the municipalities and departments to implement environmental norms. The responsibility of surveillance and enforcement of environmental rules and policies is then locally shared by the CARs, the departments and the municipalities. [80]

Funding for the municipalities comes principally from 3 sources, local taxes (about 30%), royalties (about 15%) and central government transfers (about 45%). Other funds include loans, co-financing projects and non-tributary income. The tributary income includes property taxes, commerce and industry taxes and tax on gasoline. Their spending/investment mostly falls into three categories: fixed capital expenditure, human capital expenditure, and operations expenditure. The central government's budget transfered to the municipalities is managed by General System of Participation (SGP, by its acronym in Spanish). The criteria for the allocation of the resources are complex and mostly based on the increase in coverage results of basic education and health services of the municipality. The environmental expenditures of the municipalities are not accounted separately, so it is not possible to know how much of their funds are destined to environmental purposes [81,82].

The funds of the CARs include: a percentage of the tax property collected by the municipalities, capital resources, taxes on energy generation and petroleum extraction, effluent fees, and inter-institutional agreements. [82] CARs and municipalities are supposed to cooperate to facilitate environmental management, but this is often not the case. Frictions exists between both of these institutions, since some municipalities resist making full payments of property taxes to their CARs as required under Law 99 of 1993. [79]

3.2 Forest Management

Colombia has different types of figures to declare regional or national conservation areas, including national parks, indigenous reserves, and forest reserves. The forests reserves are one of the oldest and largest conservation figures and were created by law 2 of 1954. These areas are subject to further zoning allowing for different low impact activities, which must preserve forest cover. These reserves however, do not fall only on public land and often property rights in these areas are not clear. Internal zoning of the largest of these reserves was not approved until after 2010. In the meantime, all productive activity in the forest reserves was banned.

Even though a Forestry Service is mentioned in several related policies since 1996, such service has been never designed or funded. This leaves forest reserves to be managed principally under the authority of CARs and municipalities, as the law 99 of 1993 designates.

Specifically, the municipalities have the function of designing and implementing the Territorial Planning Plans (POTs), in which the areas of conservation and protection of natural resources in rural areas are delimited. These must respect the declarations of regional or national conservation areas including forest reserves. The forest reserves are under CARs' and municipalities' responsibility.

Unfortunately, the wide variety of environmental and forestry policies and regulations in Colombia are not consistently enforced subject to factors including low levels of human and technical capacity, poor information systems, reliance on voluntary regulation, and inadequate regulations, among others. [79] Also municipalities, as well as several other government institutions, are underfunded for the large set of responsibilities assigned to them by the numerous environmental policies and regulations. [61, 80, 83]

According to estimates by Ucros 2008 [84], the area under forest reserves in Colombia is approximately 51,289,400 ha, equivalent to about 45% of Colombian terrestrial territory. However, according to the same source only 88.4% of the area within the reserves is forested and about 15,915,338 ha of the country's forested land is outside the reserves. Despite regulation deforestation has been occurring within and outside the reserves (see Figure 5.3 for a map of deforestation and forest reserves in Colombia). From the set of municipalities with reserves (about 354), more than 80% (288) are located in the Andean Region.

3.3 Environmental Information

Law 99 of 1993 designated the Hydrology, Meteorology, and Environmental Studies of Colombia (IDEAM) as the entity in charge of producing and managing environmental information. This system, although not perfect, compiles information on national and regional levels from many sources. However, the system is rather a compilation of systems still lacking comparability between data produced by the several institutions. [79] Methodological standards or protocols for data collection are lacking. Most of the deforestation information provided by the IDEAM was funded by the Moore Foundation and its sustainability depends to date on the success the IDEAM has at securing new funds for performing the classification process. Comparable environmental data or indicators at the municipality level are still lacking. [82, 85] Moreover, producing such environmental information and indicators is one of the many responsibilities assigned directly to municipalities.

3.4 Drivers of Deforestation

Deforestation rates in Colombia accelerated during the 2000s, particularly after 2007 [86]. It is in general agreed that most of the deforestation in Colombia has a proximate (direct) cause of agricultural expansion [32, 87–89]. Forest cover lost in the periods 2000 - 2005 and 2005 - 2010 was mainly transformed into pastures, 39.7% and 55.7% of deforestation was turned to pastures, respectively, followed in importance by regrowth vegetation, 41.2% and 32.8% respectively. Although pasture for livestock is the major direct cause of deforestation in Colombia [87], as in most of the developing world, other direct causes also include agriculture, illicit crops, mostly coca [90], mining, logging, natural fires, road construction, and urbanization. Deforestation dynamics also vary by region [88, 89].

A couple of studies have evaluated specific policies in the Colombian context. Land titling to Afro-Colombian communities was found to be a significant deterrent of deforestation when no illicit crops are present in the area, and was found to be stronger in places closer to roads. [91] Additionally, a study focused on communal land titling finds a reduction in deforestation only in the smaller areas, suggesting that titling is effective only when the community is capable of monitoring the area. [92]

One of the direct drivers of deforestation mentioned often for Colombia are illicit crops [89,93]. However, regional studies have found mixed evidence to support that claim. Conversion to coca is found to be more probable farther from other crops and from settlements. In contrast, proximity to other crops and to settlements increases conversion to pasture. [94, 95]

Colombia was also immersed in a perpetual rural civil war, which ended in 2016. Violent actions as well as the presence of armed groups deters any type of legal activity. Farming becomes more costly, since farmers are threatened and forced to pay fees to the insurgent groups to be able to perform their activities. Local institutions loose their authority as well, since insurgent groups only abide by their own law and threaten any organization or person who contradicts them. Studying the potential effect of civil war on deforestation, warnings were published predicting a spike in deforestation spurred by the peace accords. [86, 93, 96] The recent deforestation spike in Colombia is evidence that these warning were well in place.

3.5 Discussion of Political and Institutional Context

Colombian institutional and policy context displays some characteristics which are worth describing as context to the empirical sections.

First, the environmental institutional organization is different and parallel to the rest of the government arrangements. Although the municipality is the lowest institutional level in charge of environmental policy enforcement, in general it shares this responsibility with the CARs and/or the departments. The regulation does not clarify what the specific responsibility of each institution is, thus creating a gray area where each institution decides whether it is their responsibility to take action or not. Moreover, although forest and environmental policies often mention the creation of a Forest Management Service, such an entity has never been funded and does not exist. This void worsens the aforementioned situation particularly for forest management responsibilities.

Second, and aggravating the situation above mentioned, the municipalities do not receive funds specifically earmarked for environmental responsibilities, nor do they have to report any environmental indicators to the central government. For other sectors, such as education and health, the national budget allocated to the municipality depends on the report and performance of specific indicators.

Third, environmental and land use priorities are principally reflected in the Territorial Organization Plans (POTs) of the municipalities, which have to include geographic environmental criteria defined for each region. The forest reserves are one of several environmental restrictions and should be reflected in these plans. These plans have to be approved by the CARs. But CARs have no way to make sure these plans are respected. This is because CARs do not provide the municipality with any funds to either help develop the POTs, nor to implement the territorial organization reflected in the POT.

Fourth, although municipalities are the institutional unit closest to the ground, often environmental matters are perceived to be at another level, namely the CARs or the central government. Moreover, one of the CARs principal funding lines is a resource transfer from the property taxes in the municipalities in their region. Although CARs are tasked to help the municipality plan for and address the municipalities environmental matters, municipalities are not accountable to CARs in any of these matters and have ample leeway on whether to implement environmental policy or not.

Lastly, fiscal capacity in Colombia is, in general, low. Municipalities, who are in charge of collecting property taxes and maintaining property records perform this task poorly. Moreover, Colombia has a very low fiscal performance compared to other countries with large forest cover such as Brazil.

All of these situations are exacerbated by the presence of illegal groups, who displace the State and usurp many of its functions in remote areas, imposing their own law and order.

3.6 Geographical Delimitation of the Study Area

Colombia is recognized by its high biodiversity, following only by Brazil, in number total of species, and ranking first in birds and amphibians. More than half of the Colombian terrestrial territory is covered by forests (about 59 million hectares) and it ranks third in South America in terms of forest area (after Brazil and Peru). [97] These facts, combined with the multilevel decentralized management of the environmental sector [80] in the country, makes it a suitable country to study enforcement and deforestation patterns.

Due to the diversity of Colombian climates and reliefs, the country is divided into five geo-climatic regions: the Amazon, the Andean, the Pacific, the Orinoquia and the Caribbean regions. The Amazon region is the one with the largest forest area in the country. It is followed by the Andean Region with 18% of the country's natural forests. This region has the greatest variety of forest types due to the variety of climatic conditions that compose it. Many of the forests are fragmented forests, since this region is also the most densely populated. The Pacific Region, Orinoquia, and Caribbean Region each have less than 10% of the forest area of the country.

To study enforcement as an underlying driver of deforestation, one needs an area which is large enough to harbor diversity in institutional capacity, but also consistent enough, that the processes driving deforestation are similar (for example agricultural expansion). As noted in the literature review section, it is hard to find measures of governance at a micro level. The most detailed institutional measure available publicly in Colombia corresponds to municipalities.

I focus therefore this work on the Andean Region (see Figure 3.6), located in the middle of the country, since it has a large number of relatively small municipalities. Moreover, it is the only one that has data on enforcement proxies for the years corresponding to the deforestation data available. A large part of the country's population lives in this region, and agricultural land is in high demand. Its ecosystems and biodiversity, as well as the ecosystem services they provide are also highly diverse and valuable. The landscape is a mix between natural land, agricultural, urban and industrial development, corresponding to a "mosaic" area under Chomitz et. al 2006's classification [5].

About 25% of the countries' deforestation is occurring in the Andes Region.

This makes it, after the Amazon, the most endangered region for deforestation. [89] Deforestation in the Andes also happens mostly in patches between 1 and 3 hectares, hinting a fragmentation process, rather than the expansion of the forest frontier. Moreover, the remaining forests in the Andes are often of special interests, as are Mountain Cloud Forests or Dry Tropical Forests, which are in high risk of disappearing completely.

To be able to compare, I study both areas, within reserves, where deforestation is not permitted, and also outside reserves, where deforestation is allowed only after a cumbersome and sometimes impossible permit process.

Figures and Maps

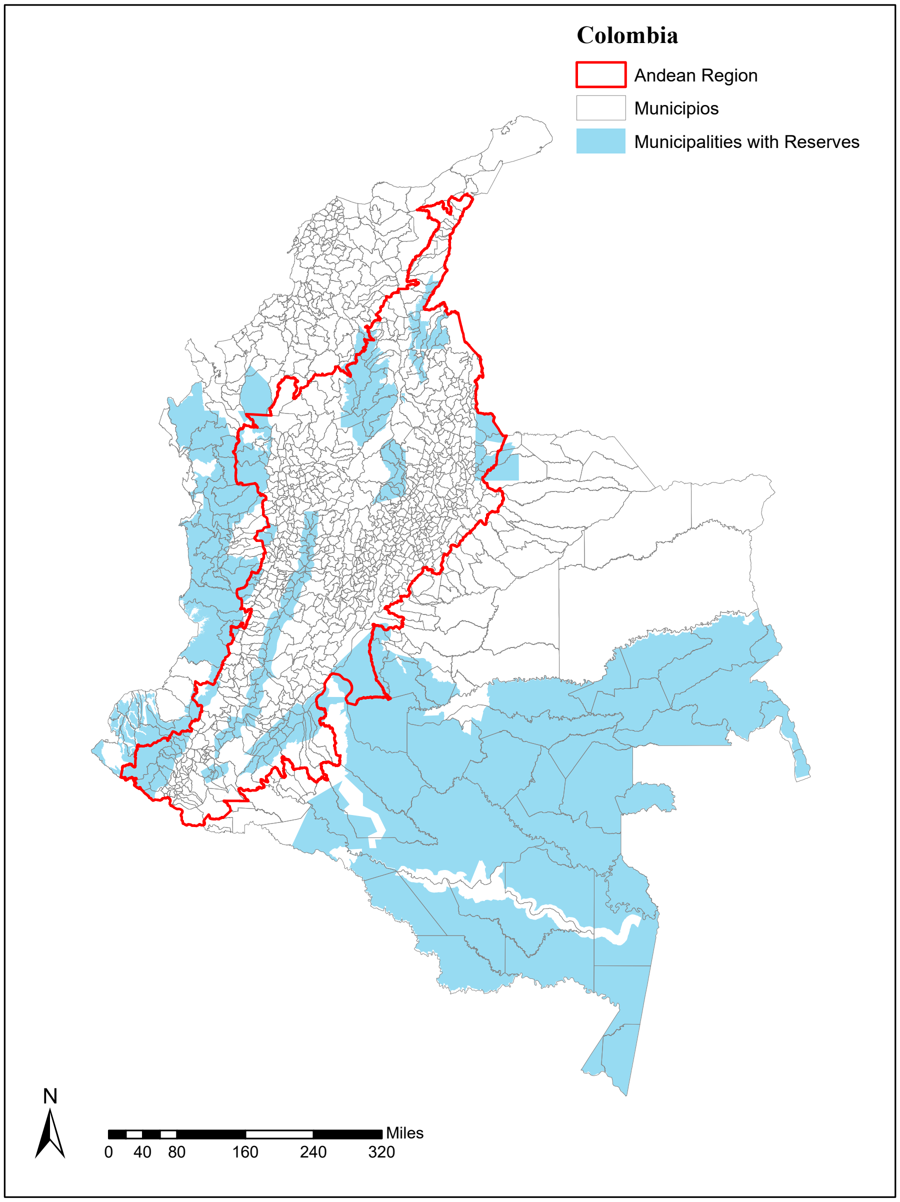


Figure 3.1: Municipalities, Reserves and Andean Region

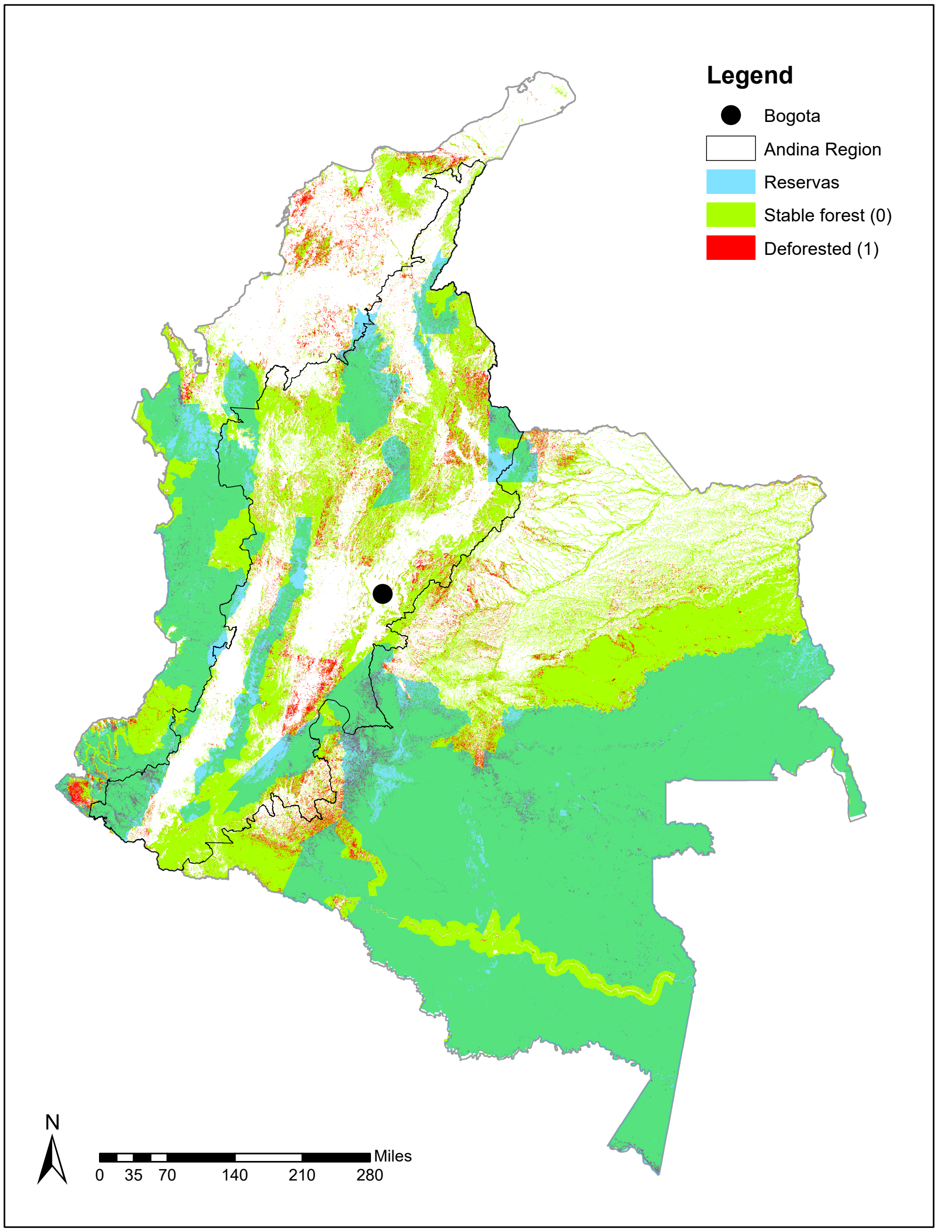


Figure 3.2: Deforestation 2005-2010 (Source: IDEAM)

Chapter 4: Theoretical Chapter

This section develops a theoretical model to study the spatial relationship between enforcement and surveillance costs, opportunity costs of conservation in the form of forgone agricultural revenues, and land accessibility; and the effect that such relation has on conservation outcomes. Its starts by describing the concept of accessibility nd the framework of the model. Then it considers the benefits to farming and how they vary with access difficulty, solving the problem from the perspective of the farmer in a land lacking social policies. The next subsection introduces ecosystem services and "costless" conservation policies, and solves the problem from the perspective of the central government representing society as a whole. The last section recognizes that social policies have surveillance and enforcement costs, which vary with space, and solves the problem from the implementation agency's perspective, showing how farmers react to such settings to produce different land use patterns.

4.1 Accessibility Framework

The model represents a town and the area around it - neighborhood. We define s as the "access difficulty" or distance of any point in the neighborhood (of the town) to the town. The concept of *accessibility* here takes into account not only the simple distance measurement, but also the added travel time due to existence and quality of roads and roughness and slope of the terrain. The larger the distance, the steeper the terrain, and the fewer or rougher the roads are, the lower the accessibility or the higher the access difficulty, and thus the higher the s.

The town is defined as the principal market for the agricultural production and also the administrative center of the neighborhood and is located at $s = 0$, which is completely accessible. The furthest distance in the model, or the least accessible land, is defined as S and any point further would correspond to another market or administrative center. In the model a *policy center*, is also defined. This *policy center* corresponds to a major city in the region, from where policies are dictated, such center is assumed to be outside the region and outside the neighborhood $[0, S]$ (i.e. accessible area).

The land around the town has two principal uses: farming and conservation[1]. Define $l(s)$ as the total land (in hectares) at location (access difficulty) s from the town. Let $a(s)$ be the total farmed land (in hectares) at s and let $n(s)$ be the land (in hectares) with natural cover or in conservation at that same location. Since there are only two possible uses for the land we have that $l(s) = a(s) + n(s) \forall s \in [0, S]$. The whole area under consideration can be written as $L = \int_0^S l(s)ds$.[2]

[1] Although it could be any other land use which provides local profits and entails a transport cost to the market

[2] This function could be normalized to 1 and would correspond to a density function representing the proportion of the total land located at each *accessibility* point.

4.2 Agricultural Profit: the Farmer's Perspective

When farmed, the land in the neighborhood has an *in situ* revenue r per hectare, and *in situ* production cost c per hectare. The cost and the revenue per hectare do not vary at different locations, because the land productivity in the region is assumed to be similar.

Accessibility however, affects transportation costs. Define τ as output transportation costs (per hectare at s). The total profit per hectare (π) at s would then be $\pi(s) = r - c - \tau(s)$. We assume $r - c > 0$ in the neighborhood, such that there is always profit from farming, not taking into account the transport costs.

As stated above, transport costs vary with accessibility, in particular, they are higher for longer and more difficult trips to the market, therefore we have $\tau_s > 0$. Transport costs are always non-negative, reaching zero at the town ($\tau(0) = 0$). Also, $\tau(s)_{s \to \infty} = \infty$, meaning that if access difficulty increases, i.e. s increases indefinitely, transportation costs increase indefinitely as well.

Without any applicable policies or enforcement, the farmers would decide how much land $a(s)$ to farm at each location s maximizing their total profit $\pi(s)a(s)$. Define $\hat{a}$ as the area the farmer decides to convert to farming in each location, such that: $\hat{a}(s) = max_{a(s)}\pi(s)a(s)$. The solution to this maximization problem is the farmer's decision function that depends on s, with the following cases:

1. If $\pi(s) = r - c - \tau(s) > 0$ or $r - c > \tau(s)$ then $\hat{a}(s) = l(s)$, the farmers will convert everything at location s.

2. If $\pi(s) = r - c - \tau(s) = 0$ or $r - c = \tau(s)$ then the farmer is indifferent between converting and not converting and he may farm anything between 0 and $l(s)$. We assume here that the farmers will not farm in this case.

3. If $\pi(s) = r - c - \tau(s) < 0$ or $r - c < \tau(s)$ then $\hat{a}(s) = 0$, the farmers will not convert land because costs are larger than benefits.

The above conditions mean that, the farmer will farm all the area, if accessibility is easy enough that transportation costs can be covered by revenues.

Since $\tau_s > 0$ for all s, there exists only one distance $s = \hat{s}$ such that: if $s \leq \hat{s}$ then $\hat{a}(s) = 0$ and if $s < \hat{s}$ then $\hat{a}(s) = l(s)$. This is the farmers' switching distance and would correspond to the forest fringe. This location $\hat{s}$ is the point at which $\tau(s) = r - c$, and we will assume that $\hat{s} \in [0, S]$, such that the switching distance for the farmer is inside the region S. A graph of the area that the farmer would farm if left alone is presented in Figure 4.4, with value per hectare in the y-axis and access difficulty in the x-axis. Profit is the dashed line and the area farmed would correspond to all the area where profits are positive $s < \hat{s}$. At $s = \hat{s}$ there are no profits from farming, so it is assumed that at this point the farmer will not farm.

4.3 Ecosystem Services: the Social Problem

It is widely recognized that ecosystems provide benefits for society. These benefits are for example: water-flow regulation (i.e prevention of droughts and floods), and water purification (i.e. water quality), erosion and landslide prevention, carbon sequestration, biodiversity conservation, among many others. While it is difficult to measure the value of these services, it is generally agreed that land under conservation produces more of these services than land in other uses, such as farming.

Thus, in the model, the land under conservation is assumed to produce ecosystems services for the town, as well as for the *policy center*, in a higher degree than farmland. For clarity, in this model we assume that the ecosystem benefits provided are only received only by the town and the *policy center* and not directly by the farmers.

The additional ecosystem services provided by one hectare of conserved land as compared to the farmland is defined ϕ. To clarify this concept, take for example the water provision service. The natural land stores water and delivers a constant flow of ξ on average per hectare, this water can be used in the town and potentially also at the policy center. The farmland, on the other hand, would extract water for irrigation, for a value ι per hectare. Therefore, comparatively, the water provided by the land would be $\phi = \xi + \iota$. The same calculation can potentially be done for all other ecosystem services with ϕ reflecting the value per hectare of the aggregation of all of them. We assume $\phi > 0$ for all the land in the region, so there is no change in their value corresponding to the accessibility from the town, so $\phi_s = 0$.[3]

The individual decision made by the farmers does not take into account the ecosystem's benefits produced by the land when left in a natural state. If all the land at location s is left natural (conserved) it would produce $\phi l(s)$ ecosystem benefits

[3]Ecosystem services are very hard to measure and value and it is difficult to define how they would vary with location [98]. Some argue that their value is higher the closer they are to the people who enjoy them [99]; while others argue that the value is higher the more pristine, untouched and therefore inaccessible the land is. Therefore, this model assumes that the value of ecosystem services does not change with distance or access difficulty.

as compared to the farmed alternative. So the benefits from not farming $n(s)$ land are $\phi n(s)$. The decision makers at the policy site take the profits into account when designing the conservation policies, in the form of protected area, but ignore the enforcement and surveillance costs of such policy. Therefore, for each town and neighborhood, policy makers maximize the benefits of farming and conserving delimiting the protected area such that:

$\max_{a(s)} \int_0^S \pi(s)a(s) + \phi[l(s) - a(s)]ds.$

Because there is no interaction between the benefits and costs at different accessibility points, and denoting the optimum or central conservation policy as $a^*(s)$ - land allowed to be farmed at s- we would have that the solution is again a decision function, but for society, with:

1. If $\pi(s) = r - c - \tau(s) > \phi$ or $r - c > \tau(s) + \phi$ then $a^*(s) = l(s)$, the farmers are allowed to farm everything at distance s.

2. If $\pi(s) = r - c - \tau(s) = \phi$ or $r - c = \tau(s) + \phi$ society is indifferent to the farmer farming or not farming at s. Here we assume that farmers would be allowed to farm here, since society is indifferent between farming and not farming, while the farmers have a direct benefits from farming.

3. If $\pi(s) = r - c - \tau(s) < \phi$ or $r - c < \tau(s) + \phi$ then $a^*(s) = 0$, the farmers are not allowed to farm, because farming benefits do not outweigh the environmental costs.

Since $\tau_s > 0$ for all s, there exists one distance $s = s^*$ such that: if $s > s^*$ then $a^*(s) = 0$ and if $s \leq s^*$ then $a^*(s) = l(s)$. This is the conservation policy switch location. Conservation would be then located away from the town in a continuous area. A picture showing the area to be conserved under the central policy is presented $s \leq s^*$ in Figure 4.4 together with the profits from the farmer's profit and the ecosystem services line (dotted).

The amount of land in farming under the central conservation policy, is less than without the policy. This is due to the positive transportation costs $\tau_s > 0$ as well as the positive ecosystem services $\phi > 0$ such that $s^* < \hat{s}$. Note that exactly at $s = \hat{s}$ we assume that farmer farms, since he has profits from farming, while society is indifferent between farming and conserving.

4.4 Surveillance and Enforcement Costs: the Implementation Agency's Problem

Now we assume that we are between $\hat{s}$ and s^*, here the farmer's optimum is different than the optimal social policy. In this region the farmer has an incentive to farm at locations not permitted by the social policy $\hat{a}(s) \geq 0 = a^*(s)$. This is illustrated in Figure 4.4 $s \in [s^*, \hat{s}]$.

The farmers' decision changes in this case, when confronted with a protection policy and its corresponding surveillance and enforcement activities. Importantly however, protecting natural land from land conversion to farming, is costly to the local administrative institution in charge of implementing such policy.

Let's define $\tilde{a}(s)$ as the policy implemented under costly surveillance and enforcement costs. Also define $e(s)$ as the probability that the farmer is caught farming at a non-permitted location s. If the farmer is caught, at least he looses his investment per hectare (c). While facing this risk the farmer has to choose between complying and not complying with the policy. If the farmer complies he will just get the benefits of farming what is allowed $\pi(s)\tilde{a}(s)$. If he does not comply and farms the profitable area at location s he will gain $\pi(s)l(s)$, if he is not caught, and he will loose his investment $cl(s)$ if he is caught. As is typical in developing countries the model assumes not only enforcement costs are relatively high, but that fines are relatively low [75].

The benefits for the farmer are for derivation):

- **Comply:** $\pi(s)\tilde{a}(s)$
- **Not Comply:** $\Big[(1 - e(s))\pi(s) - e(s)c\Big]l(s)$

To assure compliance it, the policy has to make complying have larger benefits than not complying[4], therefore the policy and enforcement frequency have to meet the following condition :

$$\frac{\pi(s)[l(s) - \tilde{a}(s)]}{[\pi(s) + c]l(s)} \leq e(s) \tag{4.1}$$

Note that $\pi(s)[l(s) - \tilde{a}(s)]$ is the opportunity cost to the farmer if he complies with policy $\tilde{a}$, while $[\pi(s) + c]l(s)$ is the opportunity cost to the farmer

Although the conservation policy $a^*(s)$, defined by the center, it internalizes the ecosystem service benefits provided by the natural land, it does not take into account the enforcement costs that the local agencies in the town have to incur to

[4] Comply>Not comply, such that $\pi\tilde{a} \geq (1 - e)\pi l - ecl$, and $e\pi l + ec \geq \pi l - \pi - \tilde{a}$

implement the policy. At the town however, the enforcement agency does not only care about the ecosystem services but also recognizes the cost of enforcing the policy. The enforcement effort has a positive cost $k(s) > 0$ at each location and the total cost is also proportional to the size of the area to be monitored at each location $l(s)$. Since it is harder to get to locations further away, the surveillance and enforcement cost is higher the more difficult it is to access the location $k_s > 0$.

The implementing agency chooses the effort spent on enforcement $e(s)$, together with the policy $\tilde{a}(s)$ it is willing to enforce. This effort (monitoring frequency) can also be interpreted as probability to find the unlawful farming $e(s)$. Assuming that the implementation agency chooses enforcement at a level that ensures compliance of its chosen policy level $\tilde{a}(s)$, and taking into account the enforcement cost, the problem is to maximize:

$$\max_{a(s),e(s)} \int_0^S \pi(s)a(s) + \phi[l(s) - a(s)] - k(s)e(s)l(s)ds \tag{4.2}$$

s.t. Equation 4.1.

The solution to this problem is again a decision function for $\tilde{a}(s)$ - area conserved under costly enforcement and surveillance (as is shown in the Appendix A and noting that $\pi(s) + c = r - \tau(s)$):

1. If $\pi(s) > \phi - k(s)\pi(s)/[r - \tau(s)]$,then $\tilde{a}(s) = l(s)$, and the farmers should farm everything at location s. And the enforcement is $\tilde{e}(s) = 0$.

2. If $\pi(s) = \phi - k(s)\pi(s)/[r - \tau(s)]$ society is indifferent to the farmer farming or not farming at s. And enforcement is $\tilde{e}(s) = \pi(s)[l(s) - \tilde{a}(s)]/[r - \tau(s)]l(s)$,

depending on the area enforced.

3. If $\pi(s) < \phi - k(s)\pi(s)/[r - \tau(s)]$, then $\tilde{a}(s) = 0$, and the farmers should not farm because farming benefits do not outweigh the environmental costs. And enforcement is $\tilde{e}(s) = \pi(s)/[r - \tau(s)]$.

Enforcement effort is chosen then to comply with Equation 4.1.

$$\tilde{e}(s) = \frac{\pi(s)[l(s) - \tilde{a}(s)]}{[\pi(s) + c]l(s)} \tag{4.3}$$

Note that we assume that farmers do farm at $\tilde{s}$, since the implementation agency is indifferent there between farming and conserving, while farmers have positive profit.

From this condition Equation 4.3 we can see that $\tilde{e}(s) = 0$ when farming is allowed (i.e $\tilde{a}(s) = l(s)$). Also the enforcement and surveillance effort $\tilde{e}(s)$ has to be higher at places with lower input costs c, because farmers have less to loose when caught farming. Additionally, surveillance and enforcement effort is inversely related to the total available area at s, since the larger the area the costlier the total effort.

According to the decision functions above, a sufficient condition for the area to be truly protected and conservation effectively enforced is to allow farming only where:

$$Q(s) = \pi(s)\Big[1 + \frac{k(s)}{[\pi(s) + c]}\Big] \geq \phi \tag{4.4}$$

and in other areas enforce conservation with: $\tilde{e}(s) = \pi(s)/[\pi(s) + c]$.

The area effectively conserved under costly enforcement would always be less than the area than the central policy would would optimally seek to conserve. This is because $K(s) = \frac{k(s)}{[\pi(s)+c]} > 0$ for all $s \in [s^*, \hat{s}]$. Additionally, when adhering to the above conditions, the area where policy is not enforced is equal or less than the area that would be privately farmed, since enforcement will be done at places between s^* and $\hat{s}$ in which $\phi - \frac{k(s)}{[\pi(s)+c]} > \pi(s)$ (compared to the previously conserved areas where only $\phi > \pi(s)$). The land strip between s^* and $\hat{s}$, i.e. the land which should be conserved in the social perspective, but is lost to farming when taking into account costly surveillance and enforcement costs, depends on $K(s)$. The strip is wider the higher the surveillance costs $k(s)$. The strip is also wider when c (i.e. the fine) is lower, since the there is less to lose when caught farming.

An illustration of the scenario described above is presented in Figure 4.4, above $s*$ would de the area conserved under the social policy, but the area above $\tilde{s}$ (decision function 1) is the area effectively conserved under local enforcement and surveillance equilibrium.

Importantly in this case, the decision function $Q(s)$ is non-monotonic in s because $Q'(s) = \pi(s)K'(s) + \pi'(s)(1+K(s))$ can be positive or negative depending on the relative sizes of its two terms. This happens because $K'(s) = \frac{k'(\pi(s)+c)+k\pi'(s)}{(\pi(s)+c)^2} > 0$ in our area of interest, since $\pi(s)$ is decreasing in access difficulty and $k(s)$ is increasing in access difficulty. Then the first term in $Q'(s)$ always positive and the second always negative. Replacing terms, and dropping the dependence on s for ease of notation, we get (See Appendix B for derivation):

$$Q' = \left[1 - \frac{c}{r-\tau}\right]k' - \left[1 + \frac{ck}{(r-\tau)^2}\right]\tau' \tag{4.5}$$

For the non-monotonicity of Q to occur $Q(s)' > 0$ for some s and $Q(s)' < 0$ for others. Equating $Q(s)' = 0$ and rearranging the term in the equation above we get condition:

$$\frac{k'}{\tau'} > \frac{(r-\tau)^2 + ck}{(r-\tau)^2 - c(r-\tau)} \tag{4.6}$$

This shows that the likelihood of a reversal depends on the relation of the rates of change of the transportation (profits) and the enforcement costs.

Because of the possible mon-monotonicity of the decision function, $Q(s) = \phi$ could happen at more than one $\tilde{s} \in [s^*, \hat{s}]$. This means, that a point in space could exist within the socially optimal protected area, where the value of ecosystem services does not outweigh the cost of enforcement plus the farming benefits, and conservation will not be enforced anymore, allowing farming in remoter areas and causing natural habitat fragmentation. This will be likelier at places where the enforcement costs rise steeper than transportation costs with access difficulty. An illustration the scenario described above is also shown in Figure 4.4, with the second decision function, where there is a strip of land, above $\tilde{s}$ that again would be left to farming by the enforcement agency, due to the non-monotonicity of $Q(s)$.

There are several simplifying assumptions made in the analysis, which are worth discussing before turning into the numerical simulation of the model. They include: (1) the form of ecosystem services and (2) the form of farming revenues and costs.

If the ecosystem services were increasing instead of stable in space, leapfrogging would be less probable. This because higher enforcement costs would be justifiable, when higher ecosystem services values should be protected. The opposite would happen if they were decreasing, such that leapfrogging would be more probable, since enforcement costs might not the worth it in further distances, since there are lower ecosystem services values to outweigh them.

The assumption of constant land productivity ($r-c$ constant) is made here only for convenience. The critical assumption is that $\pi(s)$ is monotonically decreasing in s. This could be the case not only if transportation costs increase with space but also if revenues decrease with space or input costs increase with space. For decreasing agriculture revenues in space, leapfrogging would be less probable, since there would be less incentives to farmers to farm remotely. If the opposite would occur, and revenues would be increasing in space (although hard to envision), the leapfrogging would be more likely, since farmers would have more incentive to farm far away, and te implementation agency might find it not worth it to protect these areas anymore. Production costs change with space would mirror the effect of revenues.

Theory shows that in areas were deforestation is illegal, and competing opportunity costs are positive, unwanted fragmentation can occur. Therefore in reality, following this model, either were land is protected or where the agricultural crop (or alternative land use) is prohibited.

Within protected areas land fragmentation then could be more possible if protected areas were delimited either a long time ago and the neighboring areas have faced development and population growth, or when the delimitation is made not taking into account any of the local benefits the local population derive from the use of these lands. Therefore, unrealistic or outdated protected area delimitation, where forest does not exist anymore or other highly profitable activities are present might render unwanted deforestation more likely. Fragmentation might happen outside reserves when the forest depletion activity is outlawed, for example illegal crops and or illegal mining. These activities, for their mere nature, are highly profitable, again resulting in higher likelihoods of fragmentation. In the context of Colombia we have both cases, in particular in the Andean Region (as noted in the context chapter): forest reserves and coca and poppy crops.

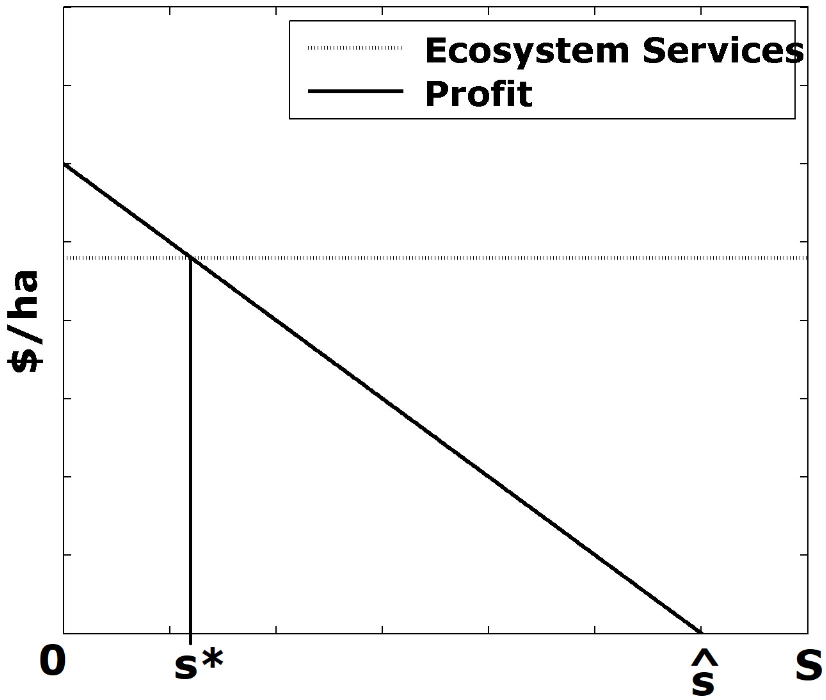


Figure 4.1: Unregulated equilibrium ($s*$) vs social equilibrium ($\hat{s}$)

Figures

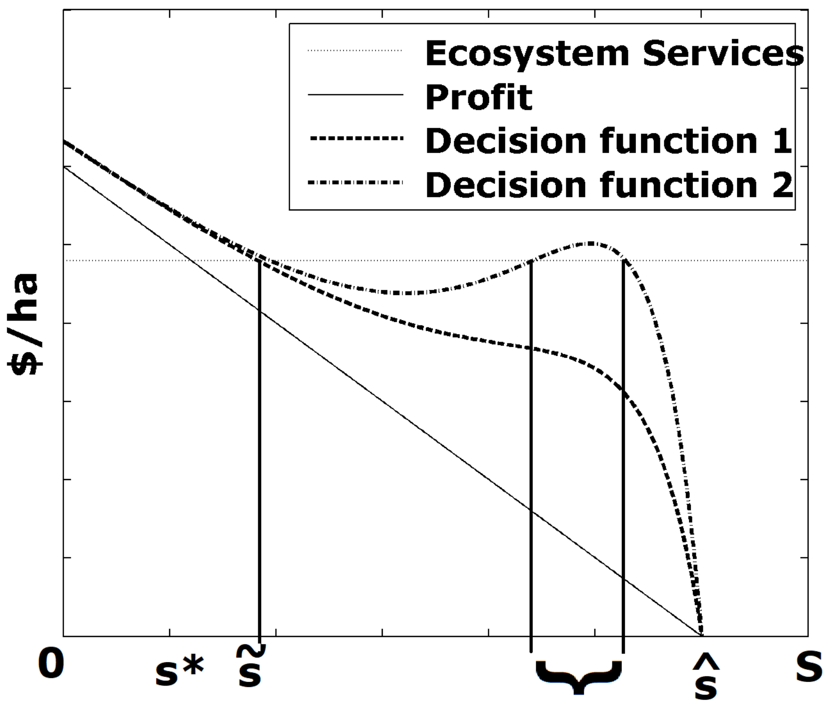


Figure 4.2: Costly enforcement equilibrium, potential forest fragmentation

Chapter 5: Parametrization: Potato Farming in the Colombian Andes

5.1 Model Calibration

Although the theoretical model in Chapter 4 is applicable to any situation where the implementation of land use policy is threatened by land conversion to other illegal productive uses by local population, the case of potato cultivation areas, in Antioquia and Narino departments of Colombia, is here presented to explore the spatial patterns arising from costly surveillance and enforcement and to simulate the features of the afore described theoretical model[1].

The Colombian case fits the theoretical model well because environmental policy in Colombia is dictated from the central Ministry of the Environment and most of its enforcement is delegated to Departmental Autonomous Environmental Corporations and municipalities. Additionally the most present threats to Colombia's PAs and highly valuable ecosystem like the *paramo* are linked to agricultural and pastoral uses [61]. Antioquia and Narino (see map 5.3) are two of the largest departments in the Andean region of Colombia, characterized by broken landscapes

[1]Potato farming in the Andes Region in outlawed for paramo ecosystems as well as for many of the remaining cloud forests

and difficult accessibility it particular away from the roads grid. Additionally, these departments are important for agricultural production. They are two of the four departments that account for more than 90% of the potato production in Colombia. Both of these departments also have presence of protected areas, and specifically also areas above 3000 meters over sea level, altitudes protected by law in the whole country.

The following theoretical functions were calibrated using the available data from these two departments. The details of estimation for the parametrization can be found in the Appendix B. The base year used is 2005, since most of the sparse information found for calibration is close to this year. All monetary units are presented in US dollars.

The two principal components of the theoretical model which need to be parametrized are: (1) the enforcement costs, (2) the profit function and the simpler ecosystem services level. The theoretical and calibrated functions, parameters, and corresponding values are shown in Table 5.1 and explained in the following paragraphs.

The enforcement and surveillance costs, aggregate 4 components: transportation costs (of the inspector), wages (of the inspector), hotel and food costs. All these costs depend on the distance (or time) spent by the enforcement personnel surveying each location. After estimating these costs, several (quadratic, cubic and exponential) regressions were run using the distance from the administrative center to all municipalities in Antioquia and Narino (estimated in Google maps) and obtaining an enforcement function depending on distance[2]. The quadratic option was chosen for ease of computation, since it shows the same general behavior than the others. Detail of this calibration process can be found in Appendix B. The best fit was obtained with a constant $k_0 = 38$ and a quadratic coefficient of $k_1 = 0.0025$ over the distance.

The potato profit calculation has 3 major components: the revenue (r), the input costs (c), and the output transport costs ($\tau(s)$). The revenue was calculated as price p times yield y available for Antioquia and Narino in Agronet, the Colombia agricultural information system. The weekly potato prices reported, needed to be averaged taking into account production varieties and seasonality, to reflect the prices for the producer. A commercialization margin (M) also was deducted from the profits, since the intermediaries in Colombia are reported to take a significant share of the revenues [100–102]. The per ton input costs (γ) were estimated using data from a detailed costs survey undertaken in 2009. The output transport costs were calculated matching data produced by the Ministry of Agriculture on agricultural transportation costs per ton between the principal cities of Colombia and Google map distance. A regression was run to estimate the relationship between cost and distance. The obtained fixed (F) and variable (t) transportation costs are also shown in table 5.1 above. Further estimation details are included in the Appendix B.

The value of local ecosystem services is difficult to estimate and depends on many geographical and biological characteristics of the area. Ecosystem services

[2]Google map can only calculate distances on the roads grid, so municipality centers were used, the costs of surveillance should increase much more steeply when parcels are located away from roads and surveillance has to be done by foot or other transportation method

could theoretically be either increasing or decreasing in distance [98, 99]. Given the characteristics of the area studied the most prevailing ecosystem services are: water provision and regulation, carbon sequestration, flood prevention, erosion prevention, and biodiversity habitat support [103]. Estimates for these services in the areas of interest are scarce, and are very variable [104–106]. Based of the estimates from the study on protected areas by [106], and taking into account only potable water, tourism, and carbon sequestration, the per hectare value of ecosystem services could vary between 320 US$/ha and 560 US$/ha. This ranges only take 3 ecosystem services into account, such that they are likely underestimating the value. Moreover, information on how these ecosystem services values vary with distance is almost inexistent. Therefore, and consistent with the theoretical framework, a constant value of ecosystem services is used here. In this simulation therefore, values around 500 US$/ha are used.

The profit, decision function, and ecosystem services are shown in Figure 5.3 for the base case values in Table 5.1. Here the policy is effectively enforced in most of the area where it is socially optimal too do so, and only a small strip near the PA's border is allowed to be farmed due to costly enforcement costs which outweigh the benefits to society of preserving that strip. Therefore, the switch between agricultural and natural land, does not occur because farming is not profitable anymore at that distances, but because for the enforcement agency it is optimal to preserve this land for their ecosystem services, given the enforcement costs. As can be observed Figure 5.3 these calibrated values do not initially show a fragmented conservation land use pattern. However, as will be shown later in this chapter, the fragmented (leapfrogging) conservation pattern may arise under plausible contexts with different parameters for agricultural transportation and surveillance and enforcement costs.

5.2 Sensitivity Analysis

Although the base case parametrization in the last section shows a classic pattern, where farming happens close to the center and natural land is effectively conserved far away from the center, similar to the case where the social optimal policy is perfectly enforced, a sensitivity analysis was performed to characterize cases where a fragmented pattern could occur. The analysis focuses on the parameters accompanying the variable enforcement costs (k_1) and transport costs (t), as they are the ones more closely connected to the distance (access difficulty) variable. The parametrized decision function (Q) in terms of these two variables is the following:

$$Q(k_1, t, s) = \frac{k_1 s^2(st - 29) - 20s^2t^2 + 4099st - 102051}{st - 174} \tag{5.1}$$

And its derivative is:

$$\frac{dQ(k_1, t, s)}{ds} = \frac{k_1 s\left(2s^2t^2 - 551st + 10092\right) + t\left(-20s^2t^2 + 6960st - 611175\right)}{(st - 174)^2} \tag{5.2}$$

With second derivative:

$$\frac{d^2Q(k_1, t, s)}{ds^2} = \frac{k_1\left(2s^3t^3 - 1044s^2t^2 + 181656st - 1.75601 \times 10^6\right) + 11310t^2}{(st - 174)^3} \tag{5.3}$$

By replacing different values for t and $k1$ different forms of the decision function and its derivative arise. In figure 5.3 the decision function for different values of k_1 and t is presented. Figures B.3 and B.4 in Appendix B show the corresponding derivatives of Q. The patterns arising depend on three parameters t and $k1$, but also the maximum distance $S = 500$, since we only care about the form of Q within the neighborhood around the administrative center.

To ease the discussion, I label s_1 and s_2, with $0 < s_1 < s_2$ as the points, if existing, where $Q'(s) = 0$. They correspond to the extreme points in the decision function. I also label s_0 the positive point at which $Q''(s) = 0$, if it exists. This is the point at which the derivative of the decision function reaches its maximum.

Figure 5.5 summarizes the results from the sensitivity analysis on t and k_1. Four different areas are differentiated:

Let farm (A), when $t << k_1$, here enforcement costs are high and transportation costs rise very slowly. For these areas the decision function, although it starts decreasing $Q' < 0$, it quickly shifts upward $Q' > 0$ and does not come back down. Only s_1 is an element of $[0, 500]$. Here, farming is profitable even in the most remote areas, while enforcement is impossible due to its large and increasing costs. Unless ecosystem services increase with distance, the optimal enforcement policy here would result in conserving close to the town and letting farm away from the town.

Simple fragmentation (B), when $t < k_1$, here enforcement costs are high and transportation costs are close below them. For these areas the decision function also starts decreasing $Q' < 0$ and later shifts upward $Q' > 0$. As in (A) s_1 is an element of $[0, 500]$, but also s_0 is within the area. More importantly, these cases also display larger s_1, allowing the decision function to decrease closer to the town for longer. Therefore, these cases start similar to the *Fragmentation (C)* case. The farmers might be left to farm close to the town, at least for a little part, then enforcement of protection could come in place. Further away though, and for all the rest of the region, farming would be allowed again, because of the sharper increase of the enforcement costs with distance, as compared to the slow increase in the transportation costs. Here, the decision function, as in case (A) does not come back down within the area of interest. Both cases (A) and (B) could happen at municipalities with very high agricultural productivity, or with transportation costs that are slowly increasing or independent of space, for example illicit crops, and with highly increasing enforcement costs, for example if these areas also have violent conflict present.

Complex Fragmentation (C), when $k_1 > t$ but $k_1 \approx t$, here enforcement costs are high, but do not increase as sharply as in (A) or (B). This means that the decision function starts decreasing $Q' < 0$ for a substantive portion of the area, later shifts upward $Q' > 0$, but within the area of interest it shifts back down, $Q' < 0$. This means that s_1 and s_2 are both elements of $[0, 500]$, as well as s_0. Farming is then profitable enough to be done close to the town, then conservation becomes important, but enforcement costs render enforcement impossible in remoter places, and fragmentation occurs. However, as opposed to the cases in (B), in this case, at the furthest distances, farming becomes nearly unprofitable and ecosystem services are so high that it becomes again important to conserve. Therefore the furthest areas are again forested.

Classic (D), when $t >> k_1$, here enforcement costs are not high enough to outweigh the increase in transportation costs so the driving force for the decision function is the agricultural profits. This case corresponds to the base case, where only a strip of land of socially optimal land to conserve (and adjunct to the agricultural land) is lost due to enforcement costs. Here $Q' < 0$ throughout the area of interest. In these cases, there is a large connected area of natural land conserved by the policies and effectively enforced by local institutions and far away from the town.

I also calculate condition in equation 4.6 in terms of t and k_1:

$$\frac{k'}{\tau'} \leq ? \geq \frac{(r-\tau)^2 + ck}{(r-\tau)^2 - c(r-\tau)} \tag{5.4}$$

$$\frac{k_1 s}{10t} \leq ? \geq \frac{8.3k_1 s^2 + s^2t^2 - 390st + 383404}{s^2t^2 - 224st + 5655} \tag{5.5}$$

Results of the sensitivity on the condition are presented in Figure 5.4. For fragmentation to occur one needs k'/τ' the red line, to be higher than the blue line, within $[0, S]$. If this does not happen, we are in the classic case (D), where we only loose a strip of land due to enforcement costs. However, in all the rest of the cases, illegal deforestation could be allowed in remote places, because if the high enforcement costs related to preventing it.

From Figure 5.3 it is clear that the non-monotonicity of the decision function and its behaviour within the area of the neighborhood, is not the only determinant of fragmentation. The Ecosystem Services level has to be comparable to the level where the non-monotonicity of the decision function.[3] To explore conditions needed for the level of ecosystem services (ES) to fall within the range where the non-monotonicity of the decision function curve occurs, Descartes Rule was applied to $SF - ES = 0$ (see Appendix B).

Using the calibrated parameters this means that ES need to be below 568 US$/ha approximately for a leapfrogging pattern to occur.

5.3 Discussion

The model shows that where agriculture is profitable, but illegal, and because enforcement costs also depend on difficulty of access, forest fragmentation (i.e.non-monotonic effect of accessibility on deforestation) might occur. The analysis shows that fragmentation is more likely at places which high or steeply incrementing enforcement costs or high or slowly decreasing profits (i.e. high or slowly increasing transportation costs). Here I present some discussion about the factors which might affect both of these costs.

First, it is important to note that the calibration here presented only included Google Map"accessible" locations, and most of these locations are relatively easy to access, since they are on the roads network. In reality, remote areas are much less accessible: steep slopes and dirt roads or absence of roads make surveillance

[3]Not that here the ecosystem services are the ones determining the policy decision from the central government, however, there are many other ways to decide what areas should and should not be protected. The enforcement costs affect the pattern of deforestation of any type of protection policies, which need to be locally enforced.

and enforcement activities harder to undertake. The terrain conditions require high performance all-wheel drive vehicles, mule or donkey trains, or sometimes even foot. The time, and therefore the costs to access these locations, are therefore likely much higher than estimated in the calibration model.

Additionally, between the 2000 and 2010 Colombia was immersed in civil war. The guerrillas took over large peaces of the territory and maintained their governance through violent actions. These places were generally hard to access, and away from roads. Monitoring places where the guerrillas were present could potentially be prohibitively high, since nobody dares to go into these locations. Moreover, insurgent groups were also recognized drug dealers, and illicit crops were present in their territories. Transportations costs in these areas would be higher than the calibrated ones in this section.

Those two factors however, might increase both transportation and enforcement costs in reality. Deficient or inexistent road infrastructure, geographical or ecological hurdles like broken terrain or dense forests, hard to transverse and with low visibility, and violent conflict, make moving in general harder.

However, the following are some factors which might result in higher or more steeply increasing enforcement costs as compared to transportation costs. First, the over use of precarious conservation policies as are protected areas, which focus on keeping the local people out of these areas render enforcement costs very high, as compared to less extreme land uses, like silvo-pastoral alternatives, non-timber forest product extraction, or any mixed use landscape. Second, the low knowledge of the terrain by enforcement officers, which make it much more difficult to transverse as opposed to the common dwellers. Third, precarious local monitoring technologies, which rely on personal revisions. Forth, disorganized ad-hoc local implementation agencies, with untrained personnel. Fifth, lack of environmental information in local institutions making them prone to regulatory capture and corruption.

Additionally, this model can also be applied to areas were most farming is unprofitable but illegal crops still represent high benefits. In particular, for farmer of illegal crops, often the transportation costs is taken over by the commercialization agent, who picks the product up at the farm gate. In these areas, the policies outlaw this type of farming, and local agencies are in charge of enforcing these policies. However, illegal farming profits might outweigh the costs of being caught, given the probability of enforcement implementation is areas far away from the administrative center.

In summary I find that (1) land fragmentation might occur (i.e.the effect of accessibility on deforestation may be non-monotonic spatially) when enforcement is costly and (2) fragmentation is more likely to occur when enforcement is more costly. Both of these questions are explored empirically in the next chapters.

Figures and Maps

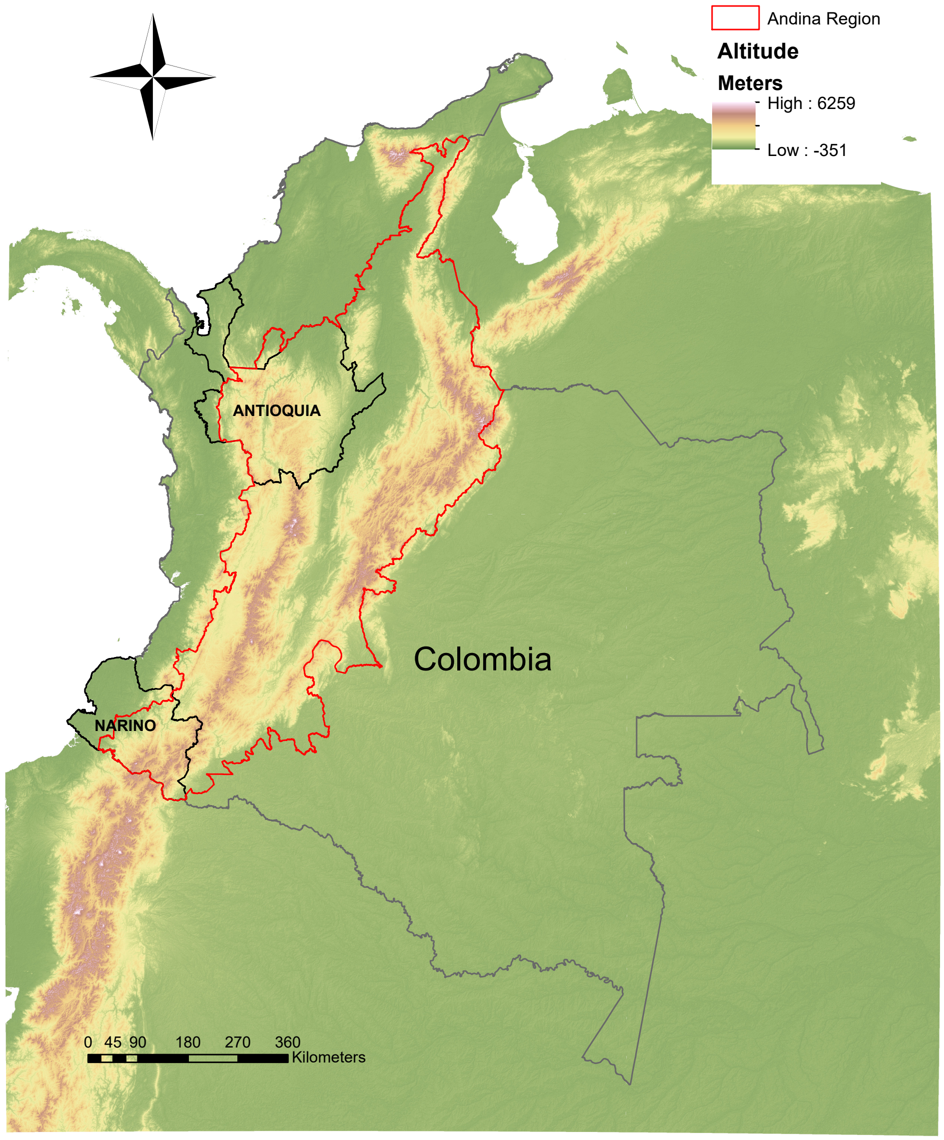


Figure 5.1: Map of selected departments in Colombia

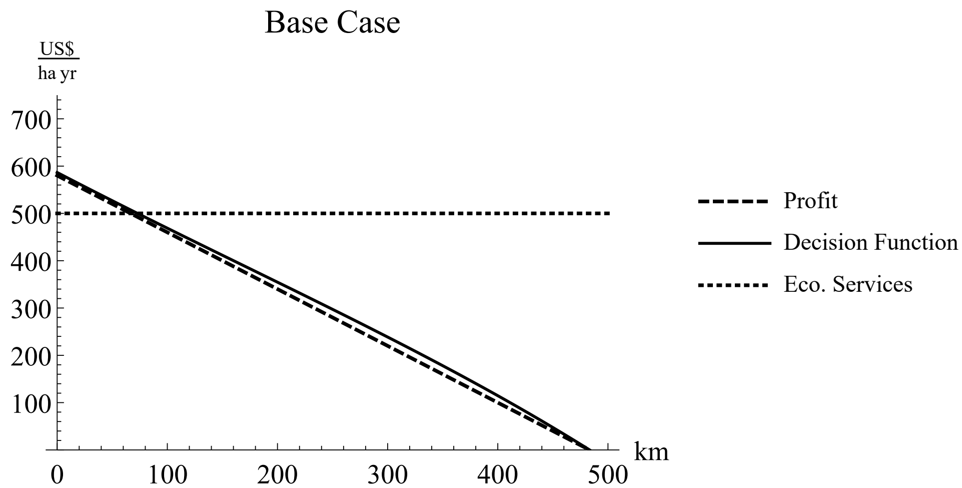


Figure 5.2: Base case: profit (π) decision function (Q) and ecosystem services (ϕ)

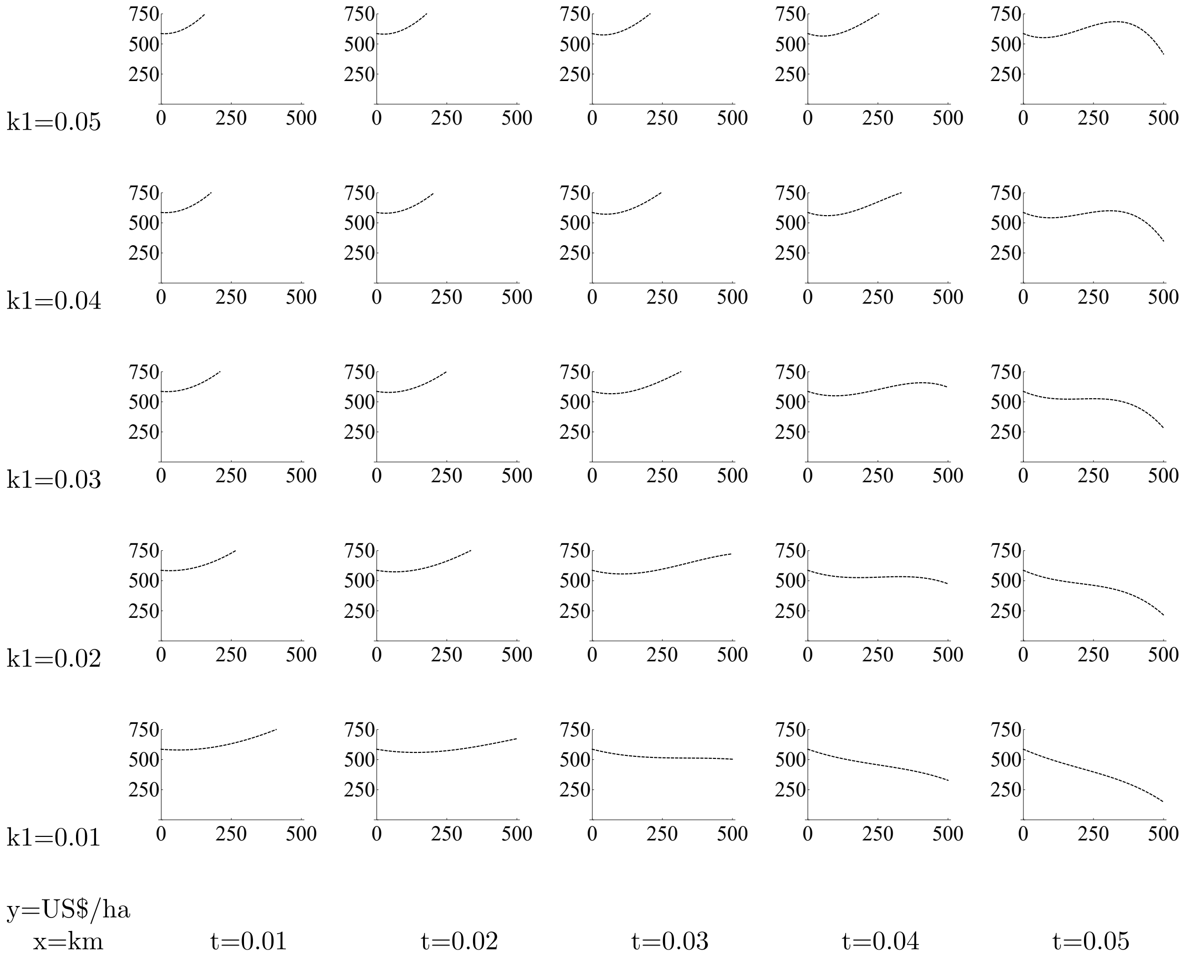


Figure 5.3: Decision function

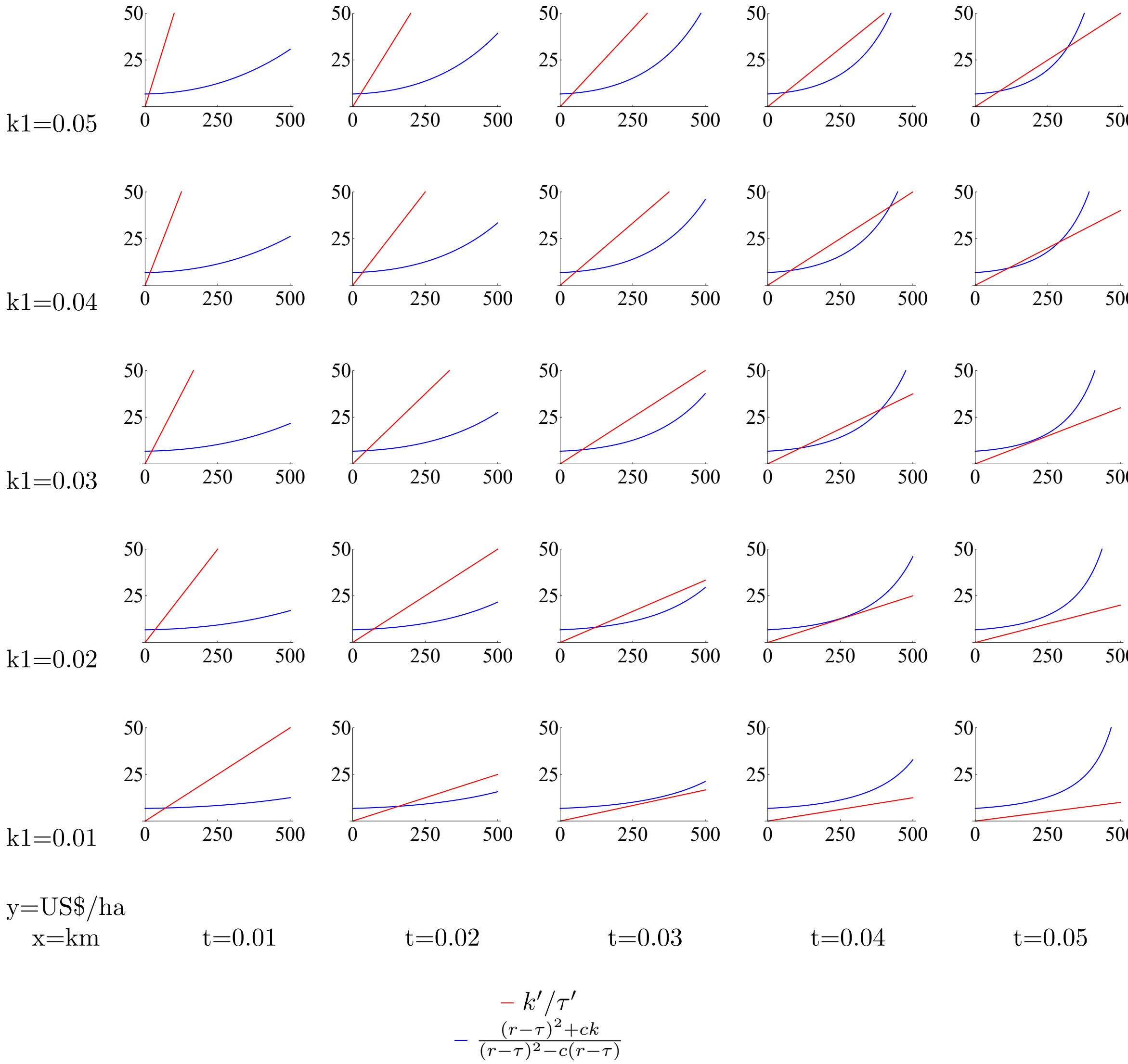
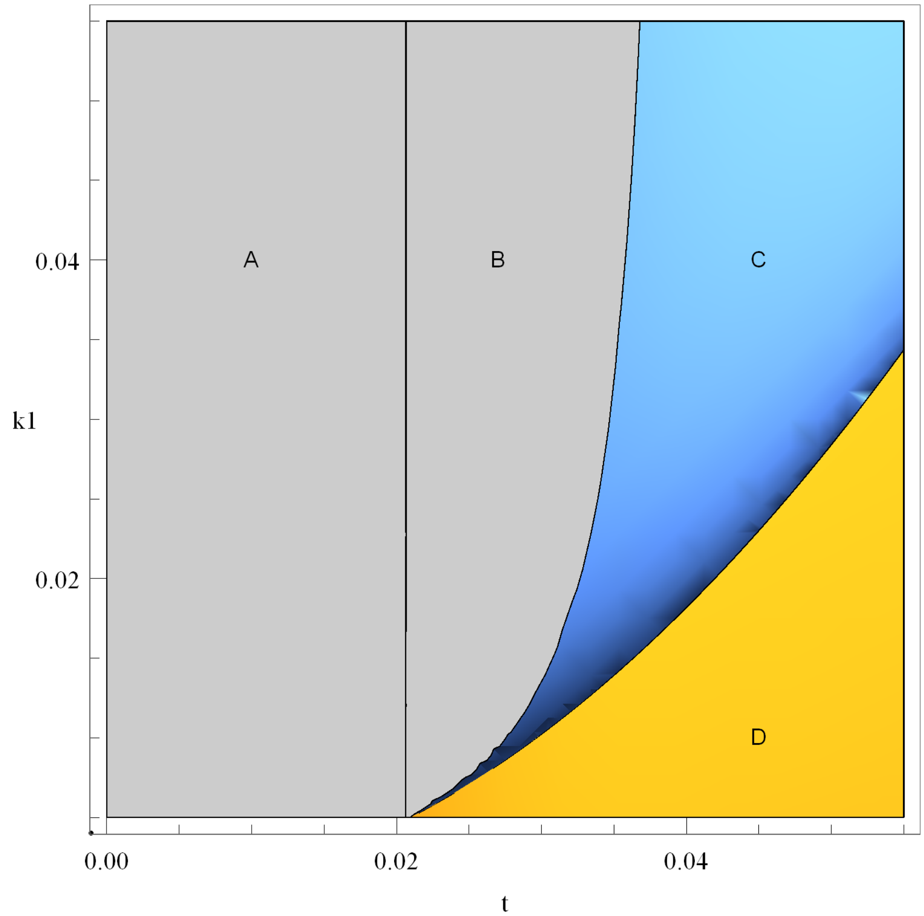


Figure 5.4: Sensitivity on the condition (eq. 4.6) for the slope of the derivative of the decision function



A: Let Farm $Q' < 0, Q' > 0; s_1 \in [0, S]$
B: Simple Fragmentation $Q' < 0, Q' > 0$ *and* $Q'' = 0$; s_1 *and* $s_0 \in [0, S]$
C: Complex Fragmentation $Q' < 0, Q' > 0, Q' < 0$ *and* $Q'' = 0$; s_1, s_2 *and* $s_0 \in [0, S]$
D: Strip lost to farming $Q' < 0$

Figure 5.5: Sensitivity to transport costs (t) and enforcement costs (k_1)

Tables

Table 5.1: Calibration Summary

Theoretical Component	**Functional Form**	**Parameter**	**Value**	**Units**
Enforcement Cost ($k(s)$)	$k_0 + k_1 s^2$			
Linear component		k_0	38	US$
Quadratic component		k_1	0.0025	US$/$km^2$
Revenue (r)	$p(1 - M)y$			
Yield		y	20	Ton/ha
Output price		p	210	US$/Ton
Commercial margin		M	10	%
Input Cost (c)	$\gamma * y$			
Input per unit cost		γ	145	US$/Ton
Output Transport Cost ($\tau(s)$)	$(F + ts)y$			
Variable		t	0.06	US$/Ton/$km$
Fixed		F	15	US$/Ton
Ecosystem Services (ϕ)	ES	ES	500	US$/ha
Neighborhood (S)	S	S	500	km

Chapter 6: Empirical Methodology and Data Description

In the theory section (Chapter 4), I model the possibility of forest fragmentation (a reversal o break in the *von Thunen* pattern of illegal deforestation) and propose that this phenomenon could be explained by high or steeply rising costs of the monitoring and enforcement activities. Therefore, in this chapter I empirically investigate, first, if access difficulty may produce forest fragmentation; and second, if this fragmentation is more likely to occur where enforcement is more costly. I propose to investigate both of these questions using two approaches: (1) a cubic function of access difficulty interacted with a measure of enforcement capacity and (2) non-parametrically using indicators for discrete ranges of access difficulty, again interacted with a measure of enforcement capacity.

In the first part of this chapter I present the deforestation data obtained and the sampling methods used. Then I describe the access difficulty variable constructed and the enforcement proxy utilized. I continue describing the econometric model, non-parametric approach, and explain the control variables included. Finally, I go over the robustness checks performed. At the end of the chapter I provide the descriptive statistics tables. I include more detailed comparative statistics tables in Appendix C.

6.1 Deforestation and Sampling

Official data on forest and non-forest areas were estimated by the Institute of Hydrology, Meteorology, and Environmental Studies of Colombia (IDEAM) and are available at pixel level for the whole country at Landsat scale (i.e.30mx30m) for the years: 2000, 2005 and 2010. These maps are calculated based on satellite images following the "Digital Image Processing Protocol for the Quantification of Deforestation in Colombia at National level - Thick and Fine Scale" protocol. The forest and non-forest data comes classified as: 1 (forest), 2 (non-forest) and NA (clouds), for each of the available years. This allowed me to calculate a deforestation panel dataset at that same resolution, with two deforestation periods: from 2000 to 2005 and from 2005 to 2010. I constructed a two period binary pixel level deforestation dataset, with 0 representing stable forested land for each period and 1 representing a deforestation event, NA is assigned to all other pixels.

The Andean Region in Colombia has an area of approximately 310,000 km^2, covering about 30% of the country. At the resolution of the deforestation data, this would be about 350 million pixels. In this region about 30% is forest, and average deforestation was 5% and 6% in the periods of 2000 to 2005 and 2005 to 2010 respectively, see table 6.2.

Running a regression for the whole deforestation dataset would be computationally non-viable, so I followed the most recent literature on drivers [3] and policy evaluation [35] and worked with samples. I drew two samples on a rectangle area covering the Andes Region: a grid sample, every 1 km, resulting in a total of 867,776 pixels and a random sample with 1 million pixels. Within these rectangles the pixels corresponding to the Andean Region were 319,770 for the grid sample, and 368,522 for the random sample. Moreover, I included only pixels which where forested in year 2000, reducing the samples to 104,543 for the grid sample and 120,323 for the random sample. These samples can be further split into pixels within reserves, and pixels in non-protected to perform the analyses.[1]

In table 6.2, I present statistics of the average illegal deforestation calculated for reserves and unprotected areas, for each of the samples (i.e. random and grid) in each of the available periods. We can observe that deforestation is between 5% (2000 to 2005) and 4% (2005 to 2010) in the reserves, and about 8% in non-protected areas. While the sampling procedure is different in the two samples, the deforestation statistics are almost exact between the grid and the random samples.[2]

6.2 Econometric Specification

The econometric model uses pixel/parcel level deforestation as dependent variable, controlling for the effect of different deforestation "drivers"[3]. The principal regression run is a linear probability model (LP).

The dependent variable I use for deforestation, y_{ijt}, is binary, showing 0 when forest is constant on pixel i and 1 if that pixel is deforested, in municipality j in period t. I run a two period fixed effects linear probability model, with the following

[1]The final sample is less than these numbers because of missing values for some of the other variables in the regressions.

[2]This is true for all the other variables as well

[3]See [35] or Chapter 3 for a description of the pertaining literature.

form:[4]

$$
\begin{aligned}
y_{ijt} = \alpha + x_{jt}\beta + d_{ij}\delta_1 + d_{ij}^2\delta_2 + d_{ij}^3\delta_3 \\
+x_{jt}d_{ij}\gamma_1 + x_{jt}d_{ij}^2\gamma_2 + x_{jt}d_{ij}^3\gamma_3 \\
+z_i'\eta' + w_{jt}'\kappa' + a_j + b_t + u_{ijt}
\end{aligned} \tag{6.1}
$$

The independent variables will be explained in detail in the following paragraphs.

6.3 Access Difficulty

Variable d_{ij} denotes difficulty of access to roads for pixel i in municipality j. Access to roads is identified in the literature as an important underlying driver of deforestation, [12, 107, 108] mainly because it affects agricultural profit through transportations costs. Here, according to the theory in Chapter 4, I use it to also explore the possibility of a reversal on this *von Thunen* effect, potentially related to enforcement and surveillance costs.

The access difficulty measure was calculated based on the roads' map available from the National Geographical Institution (IGAC) and the slope calculated from the digital elevation data DMI. For each pixel, I calculated access difficulty to roads with ArcGis software and its tool *least cost path*[5]. This tool uses a costs' surface,

[4] $'$ is used to denote the vectors.

[5] https://pro.arcgis.com/es/pro-app/help/data/imagery/least-cost-path-global-function.htm

in this case the slope layer, because it proxies the effort a person has to make when walking through it (i.e. the steeper the slope, the harder the effort to traverse the pixel walking). Thus, the cost of a route between each pixel and the road consists of the sum of all the cost values of the consequent pixels of the route one would have to transverse to travel from the pixel to the road. The tool is able to pick from all the possible routes, the shortest one (minimum value), and assigns this value to the pixel. This value was then divided by the largest value in the dataset to obtain a 0-1 measure of access difficulty, since values were extremely large (since it is a sum through all pixels in the route of distance km times slope degrees) and would render very small coefficients. To show the variability of the calculated measure in the datasets histograms for access difficulty in each of the samples are presented in Figure 6.7 where 1 is the less accessible land and 0 would be the point at the road. Thus, access difficulty is interpreted similar to distance (i.e. it is a weighted distance), where the high values mean the most remote unapproachable lands.

This variable is included in the regressions in squared and cubic form, to allow for the nonlinear relationship with deforestation. If these coefficients are significant in the regressions there may be a non-linear pattern of deforestation over the access difficulty measure.

An alternative access difficulty measure used as robustness check is simply the shortest linear distance from each pixel to the road. This distance is also calculated by the ArgGis software with the tool *shortest distance*. The averages of these two access measures can also be found for each sample in each period in table 6.2. Other linear distances were also calculated using ArcGis software and included as controls in the robustness checks: distance to CAR (environmental administrative center, see Chapter 3) distance to principal road, and distance to municipality center, since they could affect both deforestation and enforcement measures.

6.4 Enforcement Capacity

The term x_{jt} represents the enforcement capacity of municipality j in period t. In this analysis the Municipal Fiscal Performance Index (FPI) was used as a proxy of enforcement capacity. This variable varies with time, but is the same for all the pixels within a municipality.

Law 617 of 2000 establishes to the National Planning Department (DNP)[6] the task of evaluating the fiscal performance of the municipalities. This entity started calculating the Fiscal Performance Index in 2000 and has been performing it yearly ever since. The Fiscal Performance Index is mostly based on a self reported budget information and complemented with data reported to the Office of the General Comptroller of the Republic. The index is then used by the DNP in municipal evaluations and is taken into account in the decision to assign central resources to the different municipalities.

The measure is a yearly municipality level index. Its purpose is to measure the capacity of the municipalities to manage their funds in a productive and transparent manner. The FPI ranges from zero to one hundred points, where zero is the lowest and one hundred is the highest, taking into account the following factors:

[6] https://www.dnp.gov.co/programas/desarrollo-territorial/Estudios-Territoriales/Indicadores-y-Mediciones/Paginas/desempeno-fiscal.aspx

- *Capacity to self-finance their operation:* The self-financing of the operating expenses indicator measures what part of the general payroll and operating expenses of the municipality is covered by the resources of free destination. The information is obtained from the budgetary executions reported to the DNP.

- *Debt support:* The debt support indicator is obtained as the proportion of total debt over disposable income. It is expected that the total debt does not compromise the municipality's liquidity.

- *Degree of dependence on government transfers and royalties:* It measures the importance of central government's resources, in relation to the total income of the municipality. Their magnitude reflects the degree to which transfers are the fundamental resources to finance municipal government activities.

- *Effort to strengthen fiscal resources, generation of own resources:* Reflects the relative weight of local tax revenues in total current income. This is a measure of the fiscal effort made by the municipality and reflects the importance of local tax management resources against other external sources of current expenditure financing.

- *Magnitude of public investment:* Quantifies the degree of investment made by the municipality, with respect to total expenditure (including operational and administrative personnel costs). For the calculation of this indicator, investment is understood as not only the gross formation of fixed capital, but also as what is called social investment, which includes the salaries of doctors and teachers, training, subsidies, and school endowments, regardless of funding sources.

- *Savings capacity:* Is the balance between current income and current expenses and it is equal to current savings as a percentage of current income. This indicator is a measure of the solvency of the territorial entity to generate own surpluses that are can be destined for investment.

All these indicators are aggregated by the technique of principal components analysis and the value of the first component is defined as the FPI.[7] A high measure for the municipalities in FPI means: 1) enough resources to sustain their operation, 2) adequate capacity to support debt, 3) important level of own resources (tax solvency) as counterpart to government transfers, 4) effective fiscal effort for financing their development plans, 5) high levels of investment as compared to operating costs, and 7) adequate saving capacity to assure future solvency.

The overall FPI measure, which accounts for the factors listed above, proxies then the ability of the municipality to manage their budget. In this sense, it also proxies the general capacity of the municipality to perform its responsibilities. One such responsibility is to monitor illegal deforestation and enforce conservation policies. Moreover, if the municipality is able to efficiently manage its resources, it may

[7] Principal component analysis is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of orthogonal variables called principal components. This transformation is defined in such a way that the first principal component has the largest possible variance, that is, it accounts for as much of the variability in the data as possible. This first component is then chosen to represent most of the information in the set of variables

also have the leeway to assign more resources (personnel and working capital) to environmental monitoring and enforcement activities.

The fiscal performance index is available yearly, I chose observations from 2000 and 2005 to match with the deforestation data, to help avoid inverse causality. See table 6.2 for means of these variables in each sample and year.

To study the effect that municipal enforcement might have on the pattern of deforestation, interactions between the access difficulty measures d_{ij}, d_{ij}^2 and d_{ij}^3 and the enforcement measure x_{jt} are included in the regressions. If these terms are significant, there would be evidence to say that the pattern of deforestation changes with enforcement level, as the theory in Chapter 4 suggests.

To better visualize the effects of enforcement, the predictive margins for the prediction along the access difficulty measure, and their 95% confidence intervals for different levels of the enforcement proxy, are graphed. Although I do not directly have a variable of enforcement costs changing with access difficulty, with this interactions analysis, I am able to assess if municipalities which have higher enforcement capabilities are also less likely to present the reversal in the pattern of deforestation. I am also able to compare this effect within reserves and in non-protected areas, expecting the effect of enforcement capacity to be stronger inside the reserves.

6.5 Non-parametric Analysis

To address the possibility that the results are driven by the selection of the polynomial functional form, I also perform a non-parametric approach constructing sets of indicators for discrete ranges of access difficulty and running the regressions with these indicators and their interactions with the enforcement proxy. Thus, instead of the terms $d_{ij}\delta_1 + d_{ij}^2\delta_2 + d_{ij}^3\delta_3$ in the regressions, I use the terms $D'_{ij} * \Delta' + D'_{ij} * x_{jt}\Gamma'$, where D'_{ij} is the a vector for each observation, with length equal to the number of discrete ranges (bins) of access difficulty chosen, displaying 1 only for the range in which the distance of this specific observation falls into and 0 for the rest of the vector. Δ'_I and Γ'_I are the corresponding coefficients for the indicators and their interactions with the enforcement proxy variable respectively. To visualize the results, again the predictive margins and their 90% confidence intervals are calculated at each of the dummies for each different level of the enforcement proxy.

6.6 Controls

To control for other underlying drivers of deforestation, [3,32] geographical and municipality level data, were matched to the deforestation data. Most of these variables affect the costs of farming and therefore deforestation. In the next subsections, I describe each of the factors included in the regressions and their sources.

6.6.1 Geophysical Controls

Some of the most important indirect drivers of deforestation, as they are factors which affect agricultural productivity, correspond to geological (i.e. altitude and slope) and climatic (i.e.temperature and precipitation) variables. [12, 32, 109] I matched these variables, a vector (z'_i) of geophysical characteristics, which vary by pixel/parcel but not with time, including: slope, elevation, temperature, precipitation and soil type, geographically to the deforestation samples.

The elevation variable is available from DEM SRTM (CIAT) at a 1km resolution. From these data, I also calculated with ArcGis Software the slope measure in degrees, statistics are shown in table 6.2.

The data for climatic variables were available from the IDEAM in the form of geographical polygons corresponding to precipitation and temperature ranges. Additionally, data on soil types, in geographical shape format, were available also from IGAC. The IGAC classifies soils according to their geomorphological characteristics and their physical, chemical and mineralogical properties. These data were geographically matched to the deforestation panel and later included as categorical variables in the econometric work. Frequency statistics are presented in tables 6.3, 6.4 and 6.5.

6.6.2 Municipality Controls

To account for unobservable cross sectional variation that might affect deforestation and the enforcement proxies simultaneously, I include a municipality fixed effect a_j. I also include a time effect b_t to capture the general time trend. My identification assumption is the nonexistence of unobservable effects that vary both over time and by municipality, and that are simultaneously associated with the enforcement proxies. However, there may be many other phenomenon which could affect the enforcement capacity of the municipality and deforestation simultaneously, in particular at municipal level. I included some of them to check the robustness of the results. All these control variables, w'_{jt}, are available at municipal level j, but not at pixel level and vary with time t. Their means are included for the two samples and the two years in table 6.2.

Population is one of the most studied variables in relation with deforestation [3,28,33]. However, it is still not completely understood if deforestation permits new settlers to come to places they could not come to before, or more people moving in means higher demand for land, thus more deforestation. Importantly, population growth can also affect enforcement capacity in several ways, if there are more people under the jurisdiction of the same institutions, the institutions personnel may not be enough, to manage, and avoid, the (negative) effects of a larger population. On the other side, more people also means more "eyes", and they could also help to monitor the municipality area even if not hired. Rural population is available from the National Statistics Department (DANE) institute as well as the official area, so rural population density was calculated.

Colombia faced a more that 50 year-long civil war, until 2016, when President Juan Manuel Santos and the Revolutionary Armed Forces of Colombia (FARC-EP) signed a peace agreement that officially ended the armed conflict. The armed conflict relationship with deforestation has been studied, and in Colombia, the conflict may reduce deforestation probability [86]. It is not clear if this effect is due to the violent groups directly protecting the forest or if it is a secondary effect of people and farmers fleeing or avoiding the areas where conflict is more prone. Additionally, areas directly affected by armed conflict might also have less institutional capacity. The guerrillas often overtook power in the municipalities and did not allow the municipal authorities to perform their duties. Moreover, remoter areas of the municipality could loose municipal government control altogether. Number of Conflicts per municipality per year is available from the IGAC and was used to control for these effects.

Deforestation might be driven by private farmers or companies in need for productive land, as well as by small settlers, who might be pushed off the better land and driven to cut forest to survive [6]. Inequality in land distribution, could proxy any of these phenomena. Inequality however, also might affect municipalities' enforcement capacity. Wealthy players can influence the municipal government, if they are not members of the government themselves. This influence might render the government institutions: either more capable, once money and royalties are received, or, inadequate, when bribes and corruption are present. Inequality in rural land distribution was calculated yearly per municipality between 2000 and 2009, by Ibanez et. al. [110] and pasted geographically to the dataset for the years 2000 and 2005.

To avoid inverse causality, for the variables that are fixed over time, I used measures at the beginning or before 2000 only, and for the time varying variables, I picked the measures closest to the start of the period (i.e. 2000 and 2005).

The random error is denoted by u_{ijt} and α is the intercept.

6.7 Robustness

The effect of enforcement on the deforestation pattern was explored for areas within forest reserves and in non-protected areas, to observe if the effect of the enforcement proxy varies. The regressions were also run for both samples (i.e. grid and random), to make sure the effect is not observable only on a specific set of observations. Regressions are also presented with and without municipal level time varying controls and with and without other linear distance controls.

The linear probability regressions were run with robust standard errors to account for possible heteroskedasticity. After running the LP regressions, logit regressions, their average marginal effects, and the standards errors are calculated for the models with the full set of controls, as comparison.

Figures

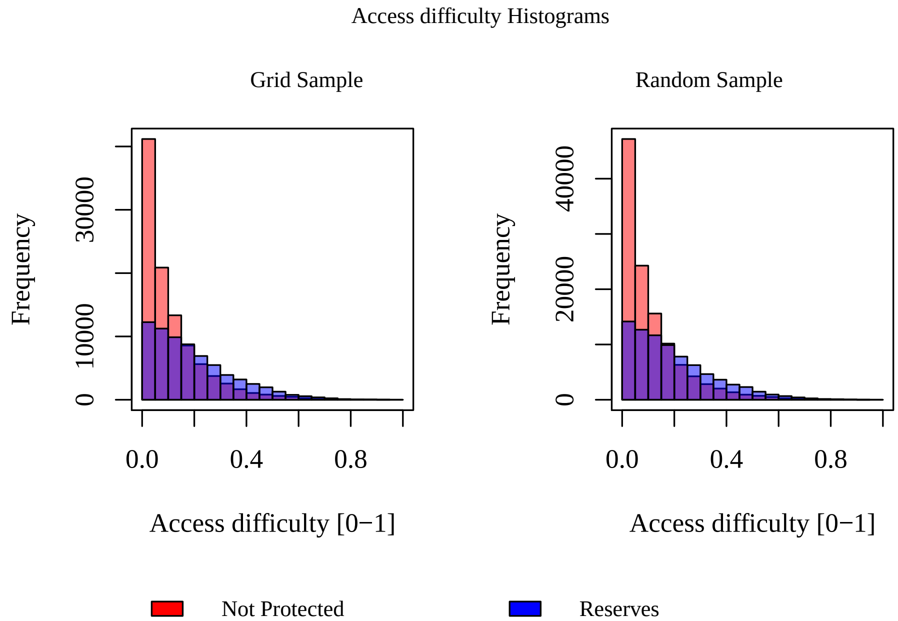


Figure 6.1: Access difficulty histograms, grid and random samples, reserves and not protected areas

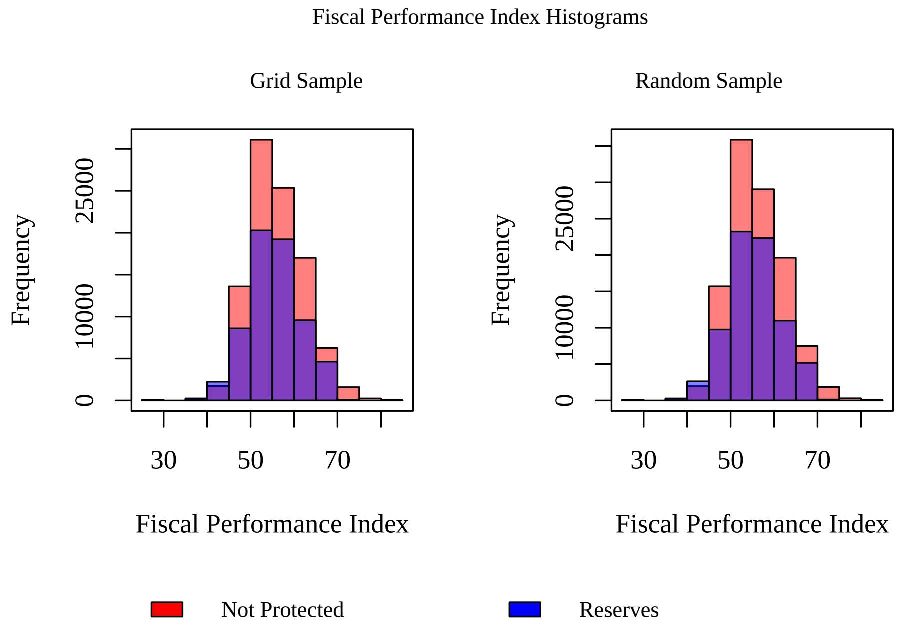


Figure 6.2: Fiscal performance index histogram

Tables

Table 6.1: Regional Deforestation Statistics

	Total Area		**Forested Area within Region** beginning of the period		**Deforested Area within Region** per period		
Area	(km2)	(th. pixels)	(% or area)	(th. pixels)	(% forested)	(th. pixels)	(km2)
Period	**2000-2005**						
Andina Region	313,510	348,345	33%	113,693	5%	6,140	5,636
Not Protected	237,788	264,209	25%	65,078	6%	4,127	3,788
Reserves	75,723	84,136	58%	48,615	4%	2,013	1,848
Period	**2005-2010**						
Andina Region	313,510	348,345	29%	100,236	6%	5,915	5,430
Not Protected	237,788	264,209	22%	56,848	7%	4,167	3,826
Reserves	75,723	84,136	52%	43,388	4%	1,747	1,604

Note: Calculated from IDEAM data

Table 6.2: Sample averages of the dependent variables and the controls

	Not Protected				Reserves			
Year	2000-2005		2005-2010		2000-2005		2005-2010	
Sample	Grid	Random	Grid	Random	Grid	Random	Grid	Random
Deforestation (0-1)	0.07	0.07	0.08	0.08	0.04	0.05	0.04	0.04
Access difficulty/Remoteness								
Walking effort (0-1)	0.11	0.11	0.11	0.11	0.19	0.19	0.19	0.19
Distance to Road (km)	4.37	4.38	4.32	4.31	9.11	9.12	9.17	9.19
Fiscal Performance Index (%)	53.60	53.61	58.54	58.58	52.80	52.82	57.99	57.96
Number of Violent Conflicts	3.51	3.55	5.52	5.55	2.92	2.93	6.60	6.54
Land Owner GINI (0-1)	0.68	0.68	0.68	0.68	0.67	0.67	0.67	0.67
Rural Population								
Density (#persons/km2)	18.63	18.70	18.46	18.62	13.16	13.10	12.92	12.97
Linear Distance to Municipality's								
Urban Center (km)	14.58	14.57	14.62	14.59	23.34	23.40	23.41	23.42
Linear Distance to								
Principal Road (km)	17.85	17.93	17.98	18.00	28.61	28.62	29.20	29.16
Slope (degrees)	17.65	17.69	17.61	17.62	17.11	17.08	17.00	16.97
Elevation (m)	1515	1515	1490	1485	1407	1406	1376	1377
Observations	54001	62245	47029	54448	36615	41992	32933	37823

Table 6.3: Precipitation sample frequencies (%) for average yearly precipitation ranges

Sample	Not Protected Grid	Not Protected Random	Reserves Grid	Reserves Random
500 to 1000 mm	1.03	1.04	0.02	0.03
1000 to 1500 mm	11.78	11.53	10.21	9.99
1500 to 2000 mm	21.91	22.06	19.6	19.76
2000 to 2500 mm	18.22	18.21	17.7	18.03
2500 to 3000 mm	17.1	17.23	19.78	19.92
3000 to 3500 mm	19.28	19.31	16.85	16.78
3500 to 4000 mm	9.95	9.84	10.74	10.43
4000 to 4500 mm	0.52	0.57	4.54	4.53
4500 to 5000 mm	0.1	0.11	0.52	0.53
5000 to 7000 mm	0.03	0.02	0	0

Table 6.4: Temperature sample frequencies (%) for average yearly temperatures ranges

Sample	Not Protected Grid	Not Protected Random	Reserves Grid	Reserves Random
Less than 12 Deg. Celsius	10.56	10.49	12.04	12.08
12 to 18 Deg. Celsius	30.55	30.69	20.49	20.37
18 to 24 Deg. Celsius	27.95	27.71	28.76	28.79
More than 24 Deg. Celsius	30.94	31.1	38.7	38.75

Table 6.5: Type of soil: frequencies (%) IGAC classification

Sample	Not Protected Grid	Not Protected Random	Reserves Grid	Reserves Random
Aa	2.45	2.4	0.96	0.95
Ab	0.01	0.01	0	0.01
Ac	0	0	0	0
Ae	0.26	0.27	0.03	0.02
Af	1.38	1.39	2.33	2.34
Ag	0.01	0.01	0	0
Ah	0.1	0.07	0.79	0.86
Aj	0	0	0	0
Ak	0.14	0.14	0	0
Ca	0.25	0.24	0.03	0.02
Cb	0.01	0	0	0
Cf	0.28	0.32	0.08	0.1
Cg	0.08	0.09	0	0.01
Ch	5.39	5.58	1.45	1.46
Cj	0.36	0.31	0.13	0.14
Ck	0.13	0.16	0	0
Cm	0.04	0.02	0.12	0.12
Cn	0.02	0.01	0.66	0.69
Dd	0.04	0.04	0	0
De	1.6	1.58	0.1	0.12
Df	0.51	0.47	0	0
Na	0	0.01	0	0
Nb	0.01	0.02	0	0
Nc	0.02	0.02	0	0
Nd	0.35	0.31	0.01	0.02
Ne	0.15	0.18	0	0
Nf	0.01	0.03	0	0
Ng	0.03	0.02	0	0
Pb	0.03	0.02	0	0
Pe	0.04	0.02	0	0
Pf	0.08	0.08	0.13	0.13
Pg	1.78	1.74	0.39	0.39

Table 6.6: Type of soil: frequencies (%) IGAC classification - Cont.

	Reserves		Not Protected	
Sample	Grid	Random	Grid	Random
Va	1.58	1.59	0.16	0.18
Vb	1.63	1.61	0.77	0.83
Vc	14.34	14.21	20.05	19.89
Vd	0.35	0.32	0.04	0.06
Ve	1.63	1.76	0.13	0.11
Vf	14.97	14.85	10.09	10.09
Vg	4.38	4.44	3.36	3.42
Vh	3.09	3.13	2.21	2.35
Vj	0.5	0.45	0.01	0.01
Vk	10.19	9.91	4.81	4.9
Vm	12.26	12.27	12.47	12.29
Vn	1.76	1.84	2.5	2.4
Vo	6.09	6.01	7.95	8.03
Vp	0	0	0.02	0.02
Vq	0.42	0.42	0.11	0.13
Vr	10.8	11.2	28.09	27.9
Vs	0.23	0.21	0	0

Chapter 7: Results

In this chapter I present the results from applying the methodology described in Chapter 6. I start by describing the results on the effect of access difficulty on deforestation showing that forest fragmentation might occur (i.e. the deforestation pattern may be non-monotonic spatially). Then I explore how this forest fragmentation is affected by governance capacity (i.e. the costs of enforcement). The results are presented for two approaches, (1) using a cubic function of access difficulty interacted with measures of enforcement capacity and (2) non-parametrically using indicators for discrete ranges of access difficulty, again interacted with measures of enforcement capacity. The analysis compares results inside reserves and in non-protected areas and the differences are discussed.

7.1 Spatial Non-monotonicity of Deforestation Probability

7.1.1 Exploratory Analysis

To start the analyses an exploratory assessment was performed to see if any non-monotonic pattern over the access difficulty measure would be observable on average indicating the potential presence of forest fragmentation. Figure 7.3 shows the deforestation averages for the both samples inside and outside the reserves, for access difficulty divided in 20 access difficulty bins. Deforestation seems to start very high close to the roads and falls steeply until a measure of 0.3 of access difficulty. after that it levels out, disperses and in particular for the reserves climbs back up. A non-linear pattern is therefore observable, particularly for the data corresponding to the reserves, encouraging further analyses. Figures for several other numbers of bins can be found in the Appendix D.

Additionally, to make sure the approach of splitting the datasets in reserves and not reserves was pertinent, a Chow test was run to test if all coefficients between the two groups were equal, The test rejected the null hypothesis with an F(799,194990)=2.06 for the grid sample and an F(797,224920)=2.16 for the random sample. Additionally tests to check if the access difficulty and the fiscal performance index variables and their interactions are equal between reserves and not protected areas ,[1] were different between reserves and not protected were also run resulting in F(7,154383)=23.34 for the grid sample and F(7,178044)=19.21 for the random sample, rejecting again the null hypothesis for these coefficients being equal between the groups. Therefore the results here presented are calculated separately for reserves and not protected areas.

[1]The tests here reported were performed using the cubic interacted models. A similar results was obtained for the tests without interactions between access difficulty and fiscal performance index

7.1.2 Cubic Function of Access Difficulty

The results for the regressions including the cubic form of access difficulty, but without the enforcement variable are shown in column (1) the tables 7.1 and 7.2 for the grid and random sample within reserves and in tables 7.3 and 7.4 for the not protected areas. The non-linear access difficulty coefficients are significant at a 0.01 significance level. The linear coefficient is negative, the squared one is positive and the cubic one is negative again. These coefficients correspond to a initially decreasing deforestation probability, closer to roads, then it becomes increasing and then it falls back again as land become more inaccessible. There is statistical evidence that the pattern of deforestation as one moves away from the road is non-monotonic indicating the presence of forest fragmentation. Figure 7.3 shows the predictive margins for and their 95% confidence intervals for access difficulty within reserves and in not protected areas, for both the grid and the random sample. Both lines initially show a decreasing probability of deforestation as one moves away from the roads until about 0.2 measure of access difficulty. Then it the curve levels out for the observations within reserves and it increases steeply for non-protected areas, reaching a maximum at about 0.6 on the access difficulty scale. This shows that fragmentation is possible in both areas, but likelier in non-protected areas.

7.1.3 Non-parametric Analysis

To check if this potential fragmentation is driven by the cubic functional form selected, a non-parametric approach was also performed, where the access difficulty measure was replaced by dummies for different numbers of bins. The coefficients resulting from this analysis are graphed in figure 7.3 for 20 bins[2] and shown on table 7.5, for reserves and not protected areas and in both samples. The coefficients on all the indicators are significantly different from zero, and significantly different for estimates within and outside reserves. The arising pattern is potentially non-linear, particularly for the areas outside reserves. These same results, for different numbers of bins, are included in Appendix D.

7.2 Effect of Enforcement Capacity

The FPI variable individually, see columns (3) and (4) in tables 7.1 and 7.2 for the grid and random sample within reserves and in tables 7.3 and 7.4 for the not protected areas, shows that the higher this index, the lower the probability of deforestation within reserves. However, the contrary seems to be true for areas outside reserves. This indicates that the municipality may be targeting reserves for deforestation reduction measures, and leaving the rest of its territory unprotected. This effect might seem small, but it means that a 1% increase in the deforestation index would reduce deforestation in 0.1%. The total average deforestation per period within reserves is about 4%, so a 0.1% change in deforestation attributable to a 1% increase in the index, is important.

[2] bins after 0.9 are grouped together since they have too little observations

7.2.1 Cubic Function of Access Difficulty and Enforcement Capacity

The evidence supports the existence of forest fragmentation on the Colombian Andes, since deforestation probability remains constant or grows as the measure for access difficulty increases (i.e. land becomes more remote). The purpose of this section is to further explore if this pattern is affected by municipal enforcement capacity.

The first approach to investigate the relationship between access difficulty, enforcement capacity and deforestation is to interact the continuous access difficulty polynomial with the enforcement proxy. The results of this analysis are presented in column (5) and (6) of the tables 7.1 and 7.2 for the grid and random sample within reserves and in tables 7.3 and 7.4 for the not protected areas. Column (5) does not include controls for other municipal characteristics or distances and column (6) does. The coefficients for both, the individual access difficulty terms and interactions remain significant within reserves, showing that the pattern arising within reserves is significantly affected by the enforcement capacity. For not protected areas however the results are not so clear, the coefficients change signs and become insignificant, when interacted with the enforcement variable. The significance of the effect of the enforcement variable in non-protected areas is therefore not clear.

To be able to visualize these results, the predicted deforestation probabilities are graphed in Figure 7.3 along the difficulty of access measure, for the results in column (6), for three different levels of the FPI (the mean, percentile 5 and percentile 95). The right column corresponds to calculations within reserves and the left column for the calculations outside reserves. Although the non-monotonic pattern for the not protected area looks stronger, the effect of the enforcement variable is less discernible. Moreover, recall that the coefficients graphed for non-protected areas are not consistently significant.

In opposition, for the results inside reserves, higher enforcement capacity (p95=63.49/100 FPI), the green line flattens, signaling lower probabilities of deforestation appearing in middle areas. However, when the enforcement variable has a low value (p5=48.74/100 FPI), the pattern becomes steeper, reaching a maximum around 0.6 on the access difficulty axis. This means that increased enforcement capacity is related to a decrease in the probability of finding forest fragmentation.

The magnitude of this effect is small but not insignificant, since a change from low (5th percentile) and high (95th percentile) enforcement capacity changes on average the deforestation probability from about 3% to about 5-6%, as illustrated by the difference between the green and blue lines. Off coarse this effect is only observed at the maximum difference location and with a substantive change in the FPI (about 15 points).

7.2.2 Non-parametric Analysis and Enforcement Capacity

To investigate if the above results are driven only by the functional form chosen, a non-parametric approach was also performed, where the access difficulty measure was replaced by a vector of dummies, corresponding to indicators of different access difficulty bins. The coefficients accompanying these indicators and their interactions with enforcement capacity measure, are shown in table 7.6 and graphed in figure 7.3. In reserves, the higher levels of enforcement capacity (green) take lower values than the lower enforcement capacity measures (in blue). Although harder to see, enforcement capacity does not decrease the probability of deforestation in non-protected areas, rather the opposite.

These non-parametric results echo the polynomial form results, particularly in the effect that the enforcement capacity proxy has on the pattern within reserves, as compared to outside them. It shows, as with the polynomial, that the likelihood of finding deforestation in less accessible areas can increase when and if enforcement decreases.

7.2.3 Robustness

The polynomial results show that enforcement capacity reduces illegal (in reserves) deforestation, more so in places less accessible from the roads. This effect is not observable or significant in non-protected areas. Non-parametric analysis agrees with not finding a positive effect of enforcement in non-protected areas, and supports the result for reserves at medium levels of access difficulty. As robustness checks, all the results were performed on two different samples, the grid and the random one showing consistency between the estimates. The results were also calculated for regressions with and without additional time, varying municipality and other linear distances controls, and the signs and the magnitudes of the effects are robust to all these changes.

The regressions with all the controls and all the interactions, column (6) in tables 7.1, 7.2, 7.3 and 7.4 were also run in logit form. And the average marginal affects and their standard errors are shown in table D.5 in appendix D. The signs are consistent with the LP models but significance varies.

7.3 Discussion

I find evidence for forest fragmentation inside and outside the reserves. This result is backed up not only by the significant coefficients on the cubic polynomial but also by the non-parametric analysis which confirms the increase in deforestation probability as one moves away from roads. Since deforestation is in general not allowed in Colombia, this could be evidence of a hiding behaviour from the farmer's point of view.

For the non-protected areas, this effect however, is not attributable directly to lack of enforcement capacity at the municipal level. This seems reasonable since deforestation outside reserves is not a municipal level responsibility, but a responsibility of the CARs only. The municipalities, since they benefit directly from local taxes on income, could even be aligned with deforestation outside reserves. The non-monotonicity of deforestation outside reserves could be due also to illegal crops, which have very low transportation costs for the farmers, even at remote places. Normally these products are picked up at the farm gate and taken directly to processing stations distant from the roads and administrative centers. In this sense the transportation costs for illegal crops might be close to 0 for the farmer. Therefore, it is more likely that illegal crops appear in remote places.

Inside the reserves I find that forest fragmentation is affected by enforcement capacity. This could mean that the forest reserves are being included, at least for the municipalities that have better capacity to generate and manage funds, not only in the territorial organization plans (POTs) but also in their monitoring and enforcement activities. In general, I find that, all along the access difficulty gradient, enforcement capacity reduces deforestation probability within reserves. Importantly however, this effect is larger at medium distance places, where deforestation probability is increased about 4% with a change in the fiscal performance index of 15 points.

Figures

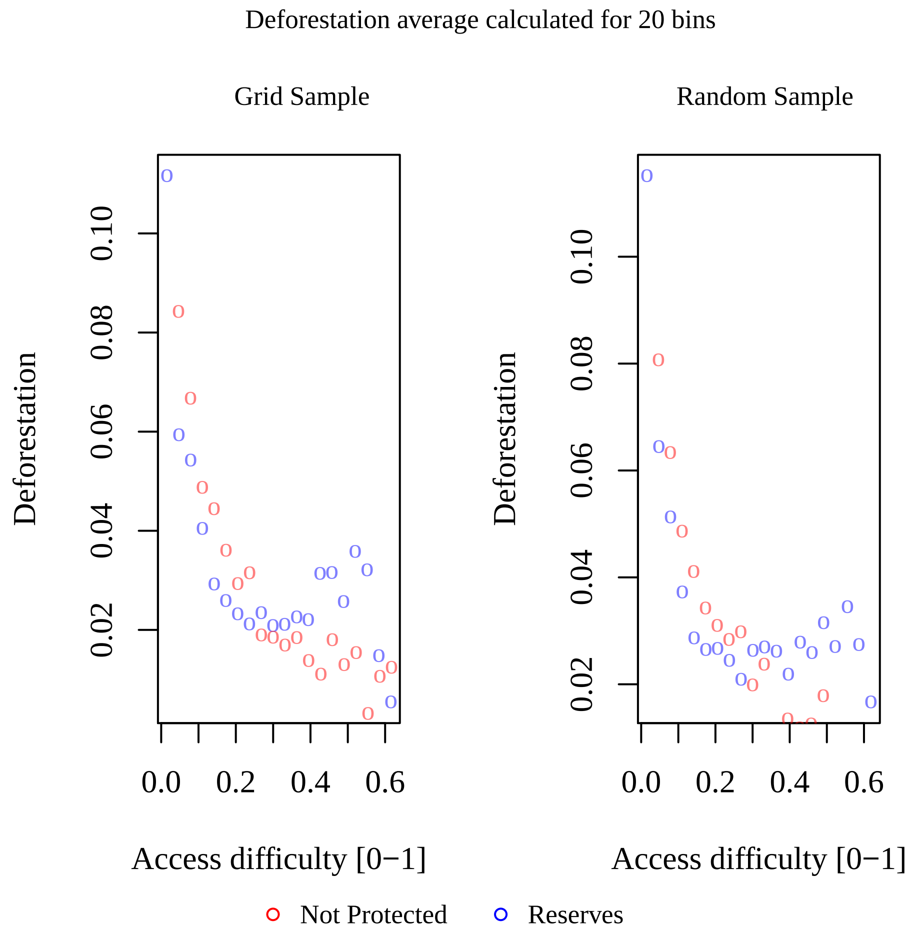


Figure 7.1: Deforestation average for 20 difficulty of access bins

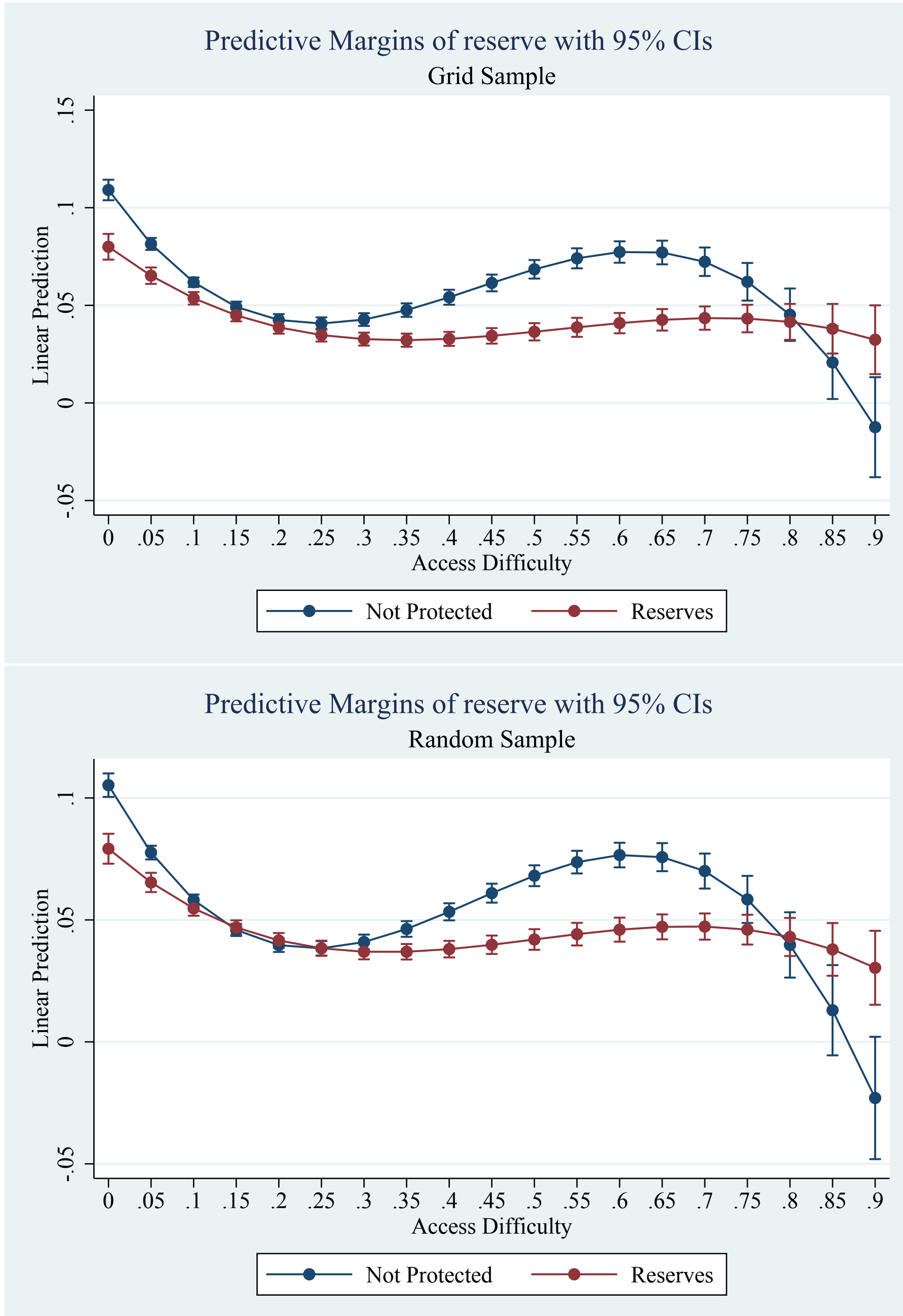


Figure 7.2: Effect of access difficulty on deforestation w/o enforcement interactions

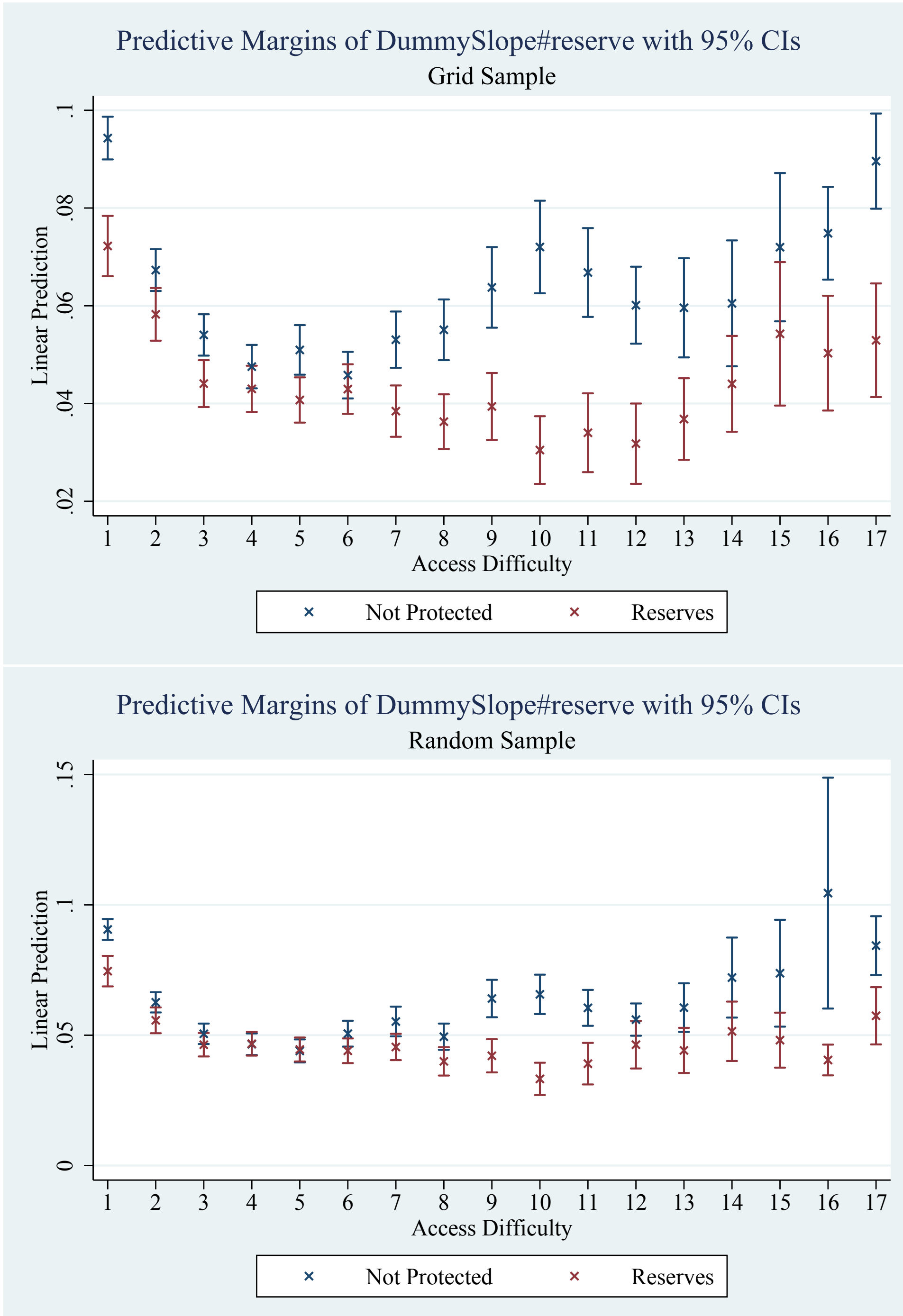


Figure 7.3: Effect of access difficulty on deforestation w/o enforcement interactions (20 bins)

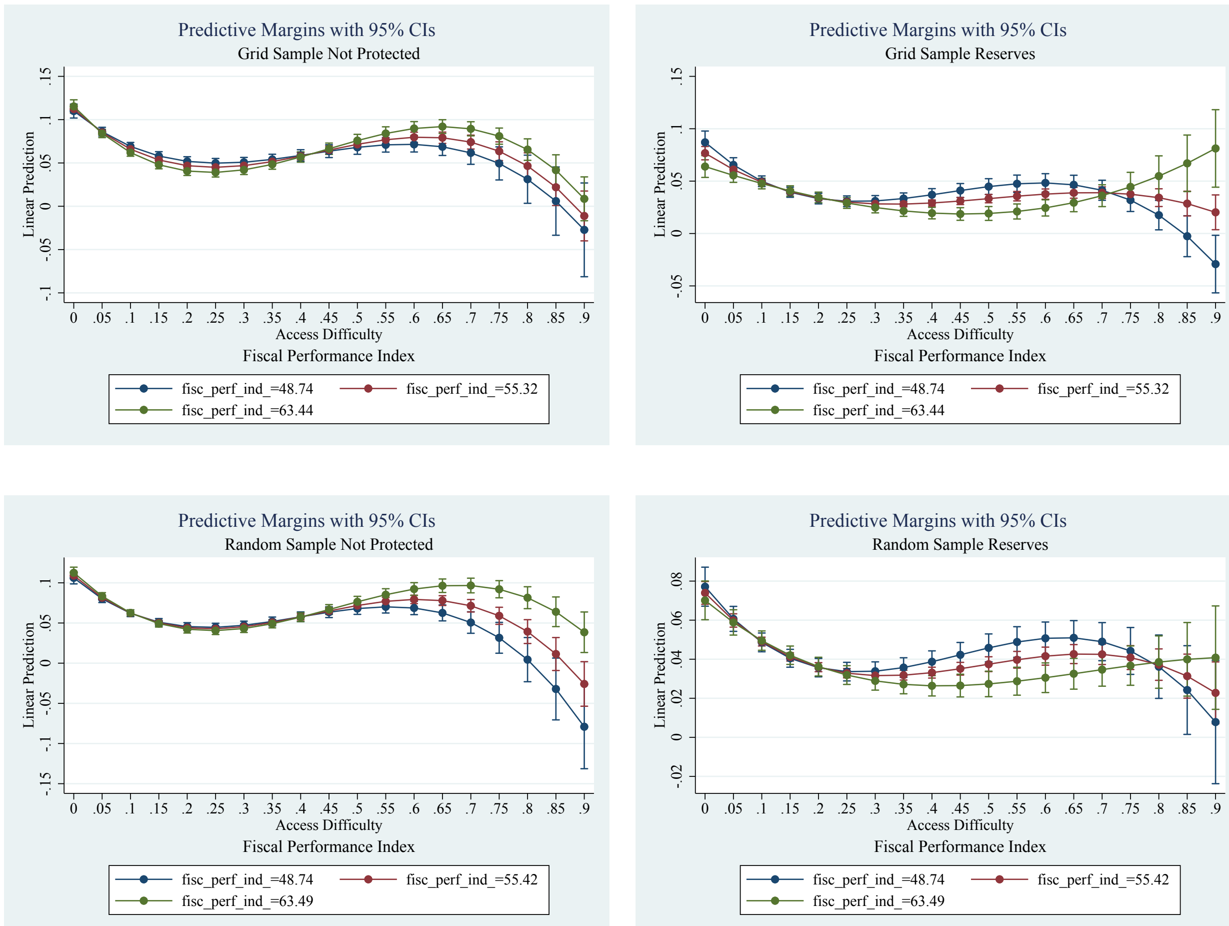


Figure 7.4: Effect of access difficulty and fiscal performance index on deforestation probability

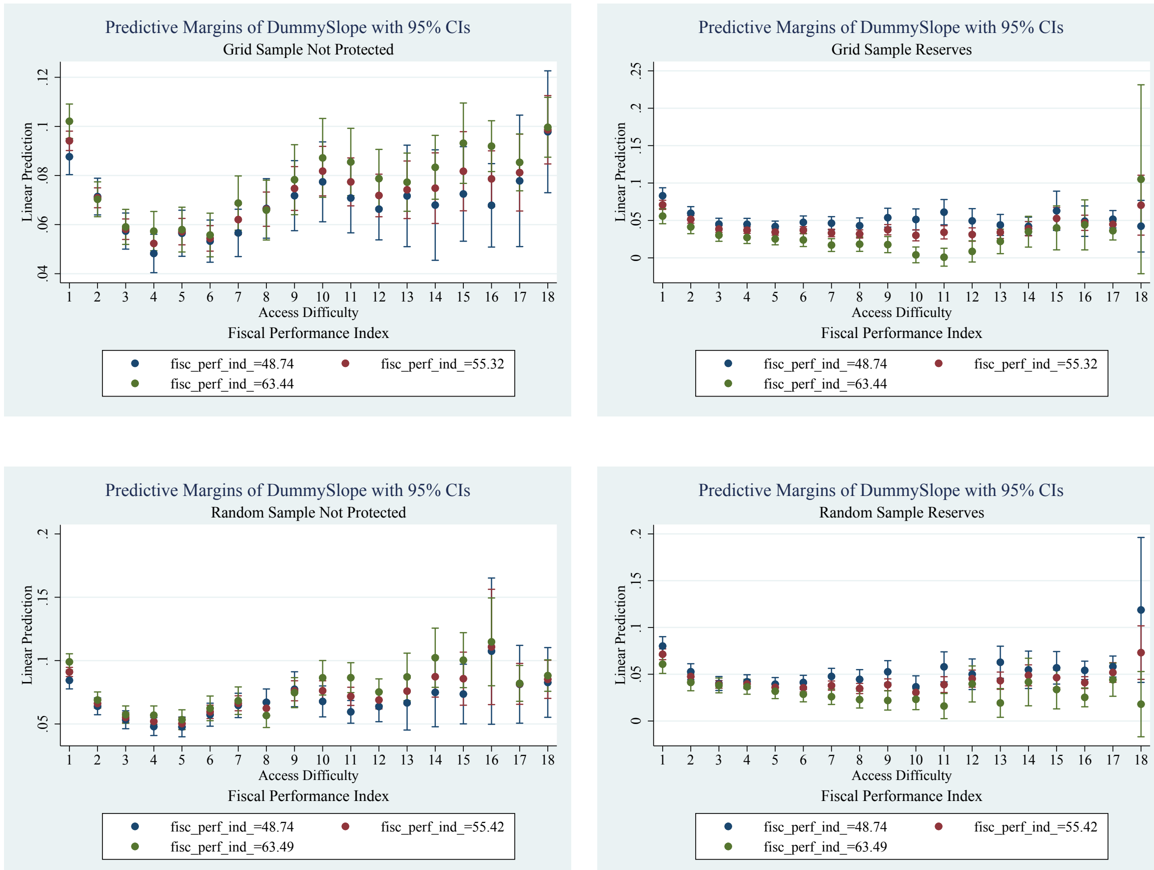


Figure 7.5: Non parametric analysis results, coefficients for 20 bins

Tables

Table 7.1: Effect of enforcement and access difficulty on deforestation in reserves - grid sample

	Dependent Variable: Deforestation in Reserves					
	(1)	(2)	(3)	(4)	(5)	(6)
Access difficulty linear	-0.466^{***}	-0.398^{***}	-0.471^{***}	-0.412^{***}	-1.254^{***}	-1.340^{***}
	(0.037)	(0.042)	(0.038)	(0.043)	(0.341)	(0.388)
Access difficulty squared	1.014^{***}	0.884^{***}	1.017^{***}	0.906^{***}	4.709^{***}	4.740^{***}
	(0.118)	(0.129)	(0.120)	(0.132)	(1.106)	(1.236)
Access difficulty cubic	-0.714^{***}	-0.606^{***}	-0.713^{***}	-0.620^{***}	-4.142^{***}	-4.027^{***}
	(0.102)	(0.110)	(0.103)	(0.112)	(0.992)	(1.089)
Fiscal Performance Index			-0.002^{***}	-0.002^{***}	-0.002^{***}	-0.002^{***}
			(0.0003)	(0.0004)	(0.001)	(0.001)
Acc. dif.linear Interaction					0.014^{**}	0.016^{**}
					(0.006)	(0.007)
Acc. dif. squared Interaction					-0.066^{***}	-0.068^{***}
					(0.020)	(0.022)
Acc. dif. cubic Interaction					0.061^{***}	0.060^{***}
					(0.018)	(0.019)
Number of Conflicts		0.003^{***}		0.003^{***}		0.003^{**}
		(0.001)		(0.001)		(0.001)
Rural Pop. Dens.		0.173^{***}		0.143^{*}		0.150^{**}
		(0.062)		(0.074)		(0.074)
Land Owner GINI		-0.001^{***}		-0.001^{***}		-0.001^{***}
		(0.0001)		(0.0002)		(0.0002)
Dist. Municipio		-0.001^{***}		-0.001^{***}		-0.001^{***}
		(0.0001)		(0.0002)		(0.0002)
Dist. Principal Road		-0.002^{***}		-0.001^{***}		-0.001^{***}
		(0.0003)		(0.0003)		(0.0003)
Observations	69,548	57,961	64,869	53,431	64,869	53,431
F Statistic	15.846^{***}	14.336^{***}	16.100^{***}	14.410^{***}	16.031^{***}	14.312^{***}

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Table 7.2: Effect of enforcement and access difficulty on deforestation in reserves - random sample

	Dependent Variable: Deforestation in Reserves					
	(1)	(2)	(3)	(4)	(5)	(6)
Access difficulty linear	-0.453^{***}	-0.350^{***}	-0.466^{***}	-0.372^{***}	-0.992^{***}	-1.184^{***}
	(0.035)	(0.039)	(0.036)	(0.041)	(0.322)	(0.365)
Access difficulty squared	0.996^{***}	0.793^{***}	1.019^{***}	0.829^{***}	3.563^{***}	3.879^{***}
	(0.113)	(0.123)	(0.116)	(0.127)	(1.062)	(1.188)
Access difficulty cubic	-0.694^{***}	-0.523^{***}	-0.706^{***}	-0.544^{***}	-2.838^{***}	-2.883^{***}
	(0.100)	(0.107)	(0.102)	(0.110)	(0.970)	(1.068)
Fiscal Performance Index			-0.001^{***}	-0.001^{***}	-0.001^{**}	-0.002^{**}
			(0.0003)	(0.0003)	(0.001)	(0.001)
Acc. dif.linear Interaction					0.009	0.014^{**}
					(0.006)	(0.006)
Acc. dif. squared Interaction					-0.045^{**}	-0.054^{**}
					(0.019)	(0.021)
Acc. dif. cubic Interaction					0.038^{**}	0.041^{**}
					(0.017)	(0.019)
Number of Conflicts		0.004^{***}		0.004^{***}		0.004^{***}
		(0.001)		(0.001)		(0.001)
Rural Pop. Dens.		0.162^{***}		0.115		0.123^{*}
		(0.062)		(0.072)		(0.072)
Land Owner GINI		-0.001^{***}		-0.001^{***}		-0.001^{***}
		(0.0001)		(0.0001)		(0.0001)
Dist. Municipio		-0.001^{***}		-0.001^{***}		-0.001^{***}
		(0.0001)		(0.0001)		(0.0001)
Dist. Principal Road		-0.002^{***}		-0.002^{***}		-0.002^{***}
		(0.0003)		(0.0003)		(0.0003)
Observations	79,815	66,570	74,529	61,446	74,529	61,446
F Statistic	17.345^{***}	15.906^{***}	18.226^{***}	16.454^{***}	18.128^{***}	16.340^{***}

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Table 7.3: Effect of enforcement and access difficulty on deforestation in not protected area - grid sample

	Dependent Variable: Deforestation in Not Protected Area					
	(1)	(2)	(3)	(4)	(5)	(6)
Access difficulty linear	-0.531^{***}	-0.561^{***}	-0.542^{***}	-0.577^{***}	0.876^{***}	0.380
	(0.035)	(0.040)	(0.036)	(0.041)	(0.321)	(0.377)
Access difficulty squared	1.501^{***}	1.651^{***}	1.533^{***}	1.699^{***}	-2.610^{**}	-1.673
	(0.126)	(0.141)	(0.130)	(0.146)	(1.312)	(1.557)
Access difficulty cubic	-1.119^{***}	-1.218^{***}	-1.160^{***}	-1.273^{***}	2.133	1.875
	(0.125)	(0.137)	(0.130)	(0.143)	(1.471)	(1.754)
Fiscal Performance Index			0.001^{***}	0.001^{**}	0.002^{***}	0.002^{***}
			(0.0003)	(0.0004)	(0.0004)	(0.001)
Acc. dif.linear Interaction					-0.025^{***}	-0.017^{***}
					(0.006)	(0.006)
Acc. dif. squared Interaction					0.073^{***}	0.058^{**}
					(0.022)	(0.026)
Acc. dif. cubic Interaction					-0.058^{**}	-0.054^{*}
					(0.024)	(0.028)
Number of Conflicts		0.003^{***}		0.003^{***}		0.003^{***}
		(0.001)		(0.001)		(0.001)
Rural Pop. Dens.		-0.106^{*}		-0.249^{***}		-0.248^{***}
		(0.063)		(0.067)		(0.067)
Land Owner GINI		-0.001^{***}		-0.001^{***}		-0.001^{***}
		(0.0002)		(0.0002)		(0.0002)
Dist. Municipio		-0.001^{***}		-0.001^{***}		-0.001^{***}
		(0.0002)		(0.0002)		(0.0002)
Dist. Principal Road		-0.001^{**}		-0.001^{***}		-0.001^{***}
		(0.0003)		(0.0003)		(0.0003)
Observations	101,030	82,968	97,112	79,502	97,112	79,502
F Statistic	12.784^{***}	12.498^{***}	12.521^{***}	12.241^{***}	12.518^{***}	12.205^{***}

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Table 7.4: Effect of enforcement and access difficulty on deforestation in not protected area - random sample

	Dependent Variable: Deforestation in Not Protected Area					
	(1)	(2)	(3)	(4)	(5)	(6)
Access difficulty linear	-0.603^{***}	-0.614^{***}	-0.601^{***}	-0.617^{***}	0.336	-0.156
	(0.032)	(0.036)	(0.033)	(0.037)	(0.269)	(0.310)
Access difficulty squared	1.803^{***}	1.938^{***}	1.783^{***}	1.929^{***}	-0.029	1.209
	(0.113)	(0.125)	(0.117)	(0.129)	(0.973)	(1.101)
Access difficulty cubic	-1.440^{***}	-1.545^{***}	-1.428^{***}	-1.543^{***}	-0.836	-1.628
	(0.110)	(0.118)	(0.114)	(0.123)	(0.972)	(1.051)
Fiscal Performance Index			0.001^{***}	0.001^{**}	0.002^{***}	0.001^{***}
			(0.0003)	(0.0003)	(0.0004)	(0.0005)
Acc. dif.linear Interaction					-0.017^{***}	-0.008
					(0.005)	(0.005)
Acc. dif. squared Interaction					0.034^{**}	0.014
					(0.017)	(0.019)
Acc. dif. cubic Interaction					-0.012	-0.0000
					(0.016)	(0.018)
Number of Conflicts		0.005^{***}		0.004^{***}		0.004^{***}
		(0.001)		(0.001)		(0.001)
Rural Pop. Dens.		-0.021		-0.194^{***}		-0.194^{***}
		(0.057)		(0.060)		(0.060)
Land Owner GINI		-0.001^{***}		-0.001^{***}		-0.001^{***}
		(0.0002)		(0.0002)		(0.0002)
Dist. Municipio		-0.001^{***}		-0.001^{***}		-0.001^{***}
		(0.0002)		(0.0002)		(0.0002)
Dist. Principal Road		-0.001^{**}		-0.001^{***}		-0.001^{***}
		(0.0002)		(0.0002)		(0.0002)
Observations	116,693	95,798	112,161	91,773	112,161	91,773
F Statistic	14.319^{***}	13.976^{***}	14.029^{***}	13.658^{***}	14.016^{***}	13.615^{***}

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Table 7.5: Non-parametric effect of access difficulty on deforestation (20 bins)

	Dependent Variable: Deforestation			
	Reserves Random	Not Protect Random	Reserves Grid	No Protect Grid
	(1)	(2)	(3)	(4)
Acc. Diff. bin 2	-0.028^{***}	-0.026^{***}	-0.030^{***}	-0.021^{***}
Acc. Diff. bin 3	-0.027^{***}	-0.034^{***}	-0.027^{***}	-0.027^{***}
Acc. Diff. bin 4	-0.039^{***}	-0.044^{***}	-0.035^{***}	-0.040^{***}
Acc. Diff. bin 5	-0.041^{***}	-0.046^{***}	-0.044^{***}	-0.035^{***}
Acc. Diff. bin 6	-0.043^{***}	-0.046^{***}	-0.044^{***}	-0.042^{***}
Acc. Diff. bin 7	-0.043^{***}	-0.047^{***}	-0.047^{***}	-0.044^{***}
Acc. Diff. bin 8	-0.046^{***}	-0.045^{***}	-0.048^{***}	-0.035^{***}
Acc. Diff. bin 9	-0.049^{***}	-0.036^{***}	-0.045^{***}	-0.043^{***}
Acc. Diff. bin 10	-0.041^{***}	-0.041^{***}	-0.050^{***}	-0.037^{***}
Acc. Diff. bin 11	-0.044^{***}	-0.028^{***}	-0.052^{***}	-0.033^{***}
Acc. Diff. bin 12	-0.045^{***}	-0.040^{***}	-0.053^{***}	-0.033^{***}
Acc. Diff. bin 13	-0.054^{***}	-0.032^{***}	-0.057^{***}	-0.028^{***}
Acc. Diff. bin 14	-0.049^{***}	-0.030^{***}	-0.053^{***}	-0.028^{***}
Acc. Diff. bin 15	-0.057^{***}	-0.025^{***}	-0.058^{***}	-0.017^{**}
Acc. Diff. bin 16	-0.055^{***}	-0.012	-0.068^{***}	-0.022^{***}
Acc. Diff. bin 17	-0.058^{***}	-0.021^{***}	-0.057^{***}	-0.009
Acc. Diff. bin 18	-0.044^{***}	-0.026^{***}	-0.056^{***}	-0.026^{***}
Acc. Diff. bin 19	-0.037^{***}	-0.030^{***}	-0.063^{***}	-0.015^{*}
Acc. Diff. bin 20	-0.050^{***}	-0.028^{***}	-0.068^{***}	-0.015
Dist.Mun.	-0.001^{***}	-0.001^{***}	-0.001^{***}	-0.001^{***}
Observations	65,156	94,377	56,732	81,792
F Statistic	14.892^{***}	13.511^{***}	13.321^{***}	12.093^{***}

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Table 7.6: Non-parametric effect of enforcement and access difficulty on deforestation

	Dependent Variable: Deforestation			
	Res Random	Not Prot. Random	Res Grid	Not Prot. Grid
	(1)	(2)	(3)	(4)
Acc. Diff. bin 2	−0.052	0.003	−0.084*	0.061**
Acc. Diff. bin 3	−0.041	0.037	−0.078*	0.061**
Acc. Diff. bin 4	−0.084**	0.045*	−0.069	0.066**
Acc. Diff. bin 5	−0.116***	0.029	−0.116***	0.060**
Acc. Diff. bin 6	−0.068*	0.037	−0.082*	0.057*
Acc. Diff. bin 7	−0.106***	0.038	−0.127***	0.052
Acc. Diff. bin 8	−0.064	0.016	−0.058	0.088**
Acc. Diff. bin 9	−0.050	0.104***	−0.094**	0.068*
Acc. Diff. bin 10	−0.057	0.077**	−0.082*	0.050
Acc. Diff. bin 11	0.005	0.050	−0.049	0.092**
Acc. Diff. bin 12	0.015	0.051	−0.055	0.042
Acc. Diff. bin 13	−0.024	0.076*	−0.080	0.045
Acc. Diff. bin 14	0.0000	0.034	0.0001	0.030
Acc. Diff. bin 15	−0.062	−0.008	0.021	0.148**
Acc. Diff. bin 16	−0.011	0.067	0.071	0.014
Acc. Diff. bin 17	0.092	0.035	0.079	0.096*
Acc. Diff. bin 18	0.033	0.057	0.083	0.102
Acc. Diff. bin 19	−0.158*	0.036	0.042	0.135*
Acc. Diff. bin 20	0.023	0.111	−0.091	0.037
Fisc.Perf.Ind.	−0.001**	0.002***	−0.002***	0.002***
Acc. Diff. bin 2:Fisc.Perf.Ind.	0.0004	−0.0005	0.001	−0.001***
Acc. Diff. bin 3:Fisc.Perf.Ind.	0.0000	−0.001***	0.001	−0.002***
Acc. Diff. bin 4:Fisc.Perf.Ind.	0.001	−0.002***	0.001	−0.002***
Acc. Diff. bin 5:Fisc.Perf.Ind.	0.001	−0.001***	0.001	−0.002***
Acc. Diff. bin 6:Fisc.Perf.Ind.	0.0002	−0.002***	0.0005	−0.002***
Acc. Diff. bin 7:Fisc.Perf.Ind.	0.001	−0.002***	0.001*	−0.002***
Acc. Diff. bin 8:Fisc.Perf.Ind.	0.0000	−0.001*	0.0000	−0.002***
Acc. Diff. bin 9:Fisc.Perf.Ind.	−0.0003	−0.003***	0.001	−0.002***
Acc. Diff. bin 10:Fisc.Perf.Ind.	−0.0001	−0.002***	0.0004	−0.002**
Acc. Diff. bin 11:Fisc.Perf.Ind.	−0.001	−0.002*	−0.0003	−0.002***
Acc. Diff. bin 12:Fisc.Perf.Ind.	−0.001*	−0.002***	−0.0002	−0.001*
Acc. Diff. bin 13:Fisc.Perf.Ind.	−0.001	−0.002***	0.0002	−0.001*
Acc. Diff. bin 14:Fisc.Perf.Ind.	−0.001	−0.001*	−0.001	−0.001**
Acc. Diff. bin 15:Fisc.Perf.Ind.	−0.0003	−0.001	−0.002	−0.003***
Acc. Diff. bin 16:Fisc.Perf.Ind.	−0.001	−0.002**	−0.003**	−0.001
Acc. Diff. bin 17:Fisc.Perf.Ind.	−0.003***	−0.001**	−0.003**	−0.002**
Acc. Diff. bin 18:Fisc.Perf.Ind.	−0.002	−0.002**	−0.003*	−0.003**
Acc. Diff. bin 19:Fisc.Perf.Ind.	0.002	−0.002***	−0.002*	−0.003**
Acc. Diff. bin 20:Fisc.Perf.Ind.	−0.002	−0.003**	0.0001	−0.001

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Chapter 8: Discussion and Public Policy Implications

Theoretical results presented in Chapter 4 show how illegal farming, either in an area reserved for forestry uses and, or because the crop is illegal (i.e. coca and poppy plantations), may result in forest fragmentation (i.e deforested patches may appear inside the forest). The empirical results from the Colombian Andes support this idea. Chapter 7 shows that such fragmentation appears away from roads, both in reserves and also in non-protected areas.

Within reserves, land fragmentation may be exacerbated because these areas were designed in the 50's and the neighboring areas have faced development and population growth. Therefore, potential profitable activities are now present in these regions. In contrast, fragmentation outside reserves might be due to illegal crops and or illegal mining. These activities, by their mere nature, are highly profitable, again resulting in higher likelihoods of fragmentation.

Updating the delimitation of reserves to reflect current ecosystem services values as well as development priorities, might reduce the deforestation pressure and unwanted fragmentation. Moreover, recognizing the dynamics of the territories and updating these delimitations accordingly, should help prevent further fragmentation. On the other hand, legalizing and regulating illicit crops, would likely also reduce forest fragmentation. However, the policies and enforcement needed against illegal crops falls outside the topic of this research, since it is a matter of national security and military action.

The model also shows that where agriculture is profitable, but illegal, forest fragmentation might occur due to enforcement costs. The analysis in Chapters 4 and 5 shows that fragmentation is more likely at places with high or steeply incrementing enforcement costs, or high with high with slowly or non-decreasing profits (i.e. high with slowly or non-increasing transportation costs). These enforcement costs are affected by many factors. Therefore, with the objective to reduce unwanted forest fragmentation, one might recommend actions to reduce implementation agencies' enforcement costs in several ways, some of the them are described in the following paragraphs.

First, the over-use of protected areas as the flagship conservation policy, focusing principally on keeping the local people out of these areas, renders enforcement costs very high, as compared to less extreme land use management policies. Protected areas, in which no other economic activity is permitted are the costliest to enforce, and for which the implementation agency will likely face higher threats of non-compliance. Alternative softer policies could reduce the enforcement costs and would likely produce comparative conservation benefits. Some of these policies include: mixed used landscapes, with natural vegetation corridors and low impact agriculture, non-timber forest product extraction, silvo-pastoril practices, and even sustainable forestry. All of these policies have a lower impact on local income, dissuading and reducing the likelihood of braking the law, even in less monitored areas.

Second, as opposed to the local communities, enforcement agencies personnel often do not know the terrain well, resulting in much higher monitoring and enforcement costs. These costs might be reduced by engaging the local communities to help with the monitoring and enforcement activities. Hiring local people as field supervisors would be a straight forward alternative. Additionally, educating communities about pertaining conservation policies, as well as on the existing alternatives to denounce violations of such policies, might also reduce the enforcement agencies' costs.

Third, local enforcement agencies often rely on precarious monitoring technologies, which are very costly, and these costs increase with access difficulty. New technologies could decrease the costs of monitoring in remote areas. For example, remote sensing and drones. Remote sensing images together with geographic information systems (GIS) technology could be made available to the enforcement agencies in charge of implementing deforestation prevention. This type of technology can be used to identify illegal land use change almost in simultaneous time, and it has the same cost independent of locations. Alternatively, the central government could use such technologies to prioritize municipalities with high deforestation and reach out to them and advise targeted personal surveillance. Another option useful in particular where the road network ends, is drone technology. This technology allows to take videos or pictures standing on the road network, without having to reach unaccessible areas personally.

Fourth, enforcement costs are high when implementation agencies are disorganized and work with untrained personnel. Recognizing the improvisation and precariousness of some of these institutions, local capacity building of officials should be a priority. Periodic training workshops and distributing material in environmental policies and regulation, as well as the local government responsibilities would be ideal. More on this later in this chapter.

Fifth, enforcement costs where information is lacking may become prohibitively high. The meager information systems in local institutions makes them prone to regulatory capture[1] and corruption. Promoting the construction of environmental indicators, at the local level, as well as other transparency information, regarding funds sources and destinations, could help keep enforcement costs low.

The empirical chapter shows that fragmentation is linked to the fiscal performance index as a measure of enforcement capacity through budget management capacity. The analysis shows that forest fragmentation within reserves is less likely when the fiscal performance index is high. Governments of municipalities with high fiscal performance index exhibit higher budgetary independence from the central government's transfers, better proficiency at managing their operating costs, as well as better competence at collecting local taxes.

The empirical analysis suggests that improving FPI would result in less forest fragmentation within reserves. To improve FPI one could help the municipality to get better at managing the resources they already have, or augmenting the funds they already receive, as well as finding new ways to gain access to resources.

[1] Regulatory capture means here undue influence of powerful grups on regulation or compliance with it.

Previous investigations [79, 82] have found that municipalities in Colombia present deficient human capacity to handle their responsibilities. Not only do they have too little workers, but workers often are not capable of doing their assignments, either because they ignore their specific tasks or they do not have the knowledge needed to perform such tasks correctly. Several types of capacity building activities including workshops and summarized easy accessible reference material (i.e websites designed to work well on cellphones) should be performed at least at the beginning of each government period. The topics for these training activities should range from: knowledge of the responsibilities of the municipality, to bookkeeping, environmental law and regulation (including available tools for land management), and potential new sources of income.

Municipalities have also been described as lacking information, [79] making them prone to regulatory capture and corruption, particularly in land use matters. Designing a simple yet effective municipality level indicator system, in particular for environmental matters, and promoting its implementation should help improve transparency. The information produced by such a system should be publicly available such that NGOs as well as the community could help keep the authorities accountable and liable for their land use decisions and their implementation.

Promoting environmental education for the community, including the value of local forests and ecosystems as well as recognizing the benefits of such forests, not only for the global population in term of climate change, but for the more local ecosystem services, such as water provision and regulation and landslide prevention, should help raise awareness and provide support for local governments with such concerns as well as better accountability.

To improve the amount of resources that municipalities already have access to, it is important to note that Colombia is not efficient at collecting taxes. One of the reasons for a low fiscal return is because of outdated and faulty or non-existent land property records. General efforts to improve this information could increase the municipal property tax base, giving the municipalities (and the CARs) more funds.

The central government has several funds which are available for projects presented by municipalities. Such funds more than often are not exhausted, because the process to access them involves unsurmountable steps for municipal governments. Even if there is capacity building to access such funds, municipalities would benefit from a two stage process to access such funds, including a first step with a project idea and the related support for the development of the project, before the full grant is assigned to the fully developed project proposal.

Municipalities should also have access to new types of funding sources. Funds, for example from the National Royalty Fund, could be prioritized for conservation or land management projects presented in alliance between CARs and municipalities. This would give the municipality additional funds and should improve the relationships between CARs and municipalities and strengthen the municipalities' environmental administration capacity.

Moreover, environmental projects jointly designed by the municipality and the CARs, should be funded by the share of the property tax which is assigned to the CARs. Therefore, the municipalities would not feel so resented towards the CARs and their lack of attention to municipalities' issues and at the same time the CARs would have some of their environmental duties truly shared by the municipalities' governments.

Another potential source of funding for municipalities is the development of payments for ecosystem services projects. The regulation in Colombia already gives municipalities the authority to set up such payments for ecosystem services schemes, in particular for water regulation and carbon sequestration purposes. Municipalities together with the CARs could also propose zoning within forest reserves, including areas for sustainable forestry, and therefore gain access to forest concession fees.

Given Colombia's importance in terms of biodiversity and forest cover, international funds could be levied to fund some of the capacity building activities, environmental education, as well as information and technology applications described above. Specifically, for such projects which are designed to be sustainable, but only lack initial investment.

Lastly if additional levied funds are used to improve the capacity of administrative personnel a self-enforcing cycle could be created, because better management should also be able to access more funds.

While the fiscal performance index affects fragmentation in reserves, it does not in non-protected areas. This could be because the municipalities might not have the resources to cover all the area under their authority, and chose to protect the reserves, while allowing hidden deforestation for illegal crops outside them. The recommendations above, to help increase the municipalities budget, in particular for environmental matters, and improve their management capacity should also help them reduce fragmentation outside protected areas. Nevertheless it is important to note, that for illicit crops legalization would also render a decrease in fragmentation, while further recommendations on the control and management of illicit crops exceed the limits of this dissertation.

8.1 Conclusion

This work shows how the expected effect of deforestation deterrence policies can be spatially changed by surveillance and enforcement capacity. In particular, it recognizes that surveillance and enforcement costs vary with space, such that for an implementing agency, short in capacity or budget, there is incentive to enforce selectively in more accessible places, while leaving the less accessible areas unwatched. The theory shows that in places where the surveillance and enforcement costs increase steeply as compared to the agricultural transport costs, this interaction can result in a broken deforestation pattern, where deforestation appears again in remoter less monitored places. This fragmented deforestation pattern, as one moves away from roads, is also found empirically, in the Colombian Andes. The empirical work also shows, that within reserves fragmentation is reduced as institutional capacity improves. To reduce fragmentation, strengthening the municipalities capacity to obtain more resources and manage their funds would be beneficial.

Appendix A: Mathematical Derivations

A.1 Derivation of decision function for costly enforcement problem

The problem can be solved, as before, separately for each point in space. So for a particular s the problem is as follows (dropping the dependence on s):

$$\max_{a,e} \pi a + \phi[l - a] - kel \tag{A.1}$$

s.t.

$$\frac{\pi[l - a]}{[r - \tau]l} \leq e \tag{A.2}$$

Since e is linear in the objective function, the condition will be met with equality, so we can replace e in the objective function and have a linear problem with one variable a:

$$\max_{a} \pi a + \phi[l - a] - \frac{k\pi[l - a]}{[r - \tau]} \tag{A.3}$$

Taking the derivative with respect to a we obtain:

$$\pi[1 + \frac{k}{[r - \tau]}] - \phi \tag{A.4}$$

A.2 Decision Function Derivatives

First derivative of Q with respect to s Recall the decision function:

$$Q(s) = \pi(s)\Big[1 + \frac{k(s)}{[r - \tau(s)]}\Big] = \pi(s)\big[1 + K(s)\big] \tag{A.5}$$

with

$$K(s) = \frac{k(s)}{[r - \tau(s)]} > 0 \tag{A.6}$$

such that:

$$Q'(s) = \pi(s)K'(s) + \pi'(s)(1 + K(s)) \tag{A.7}$$

Taking the derivative of K with respect to s and dropping the dependence on s for ease of notation, we have:

$$K' = \frac{k'(r - \tau) + k\tau'}{(r - \tau)^2} > 0 \tag{A.8}$$

Remembering that $\pi(s) = (r - \tau(s) - c)$

$$Q' = (r - \tau - c)\Big[\frac{k'(r - \tau) + k\tau'}{(r - \tau)^2}\Big] - \tau'\Big[1 + \frac{k}{r - \tau}\Big] \tag{A.9}$$

Distributing:

$$Q' = \frac{(r - \tau - c)k'}{(r - \tau)} + \frac{(r - \tau - c)k\tau'}{(r - \tau)^2} - \tau'\Big[1 + \frac{k}{r - \tau}\Big] \tag{A.10}$$

Rearranging:

$$Q' = \Big[\frac{(r-\tau-c)}{(r-\tau)}\Big]k' - \Big[1 + \frac{k(r-\tau)-(r-\tau-c)k}{(r-\tau)^2}\Big]\tau' \tag{A.11}$$

And adding terms:

$$Q' = \Big[1 - \frac{c}{r-\tau}\Big]k' - \Big[1 + \frac{ck}{(r-\tau)^2}\Big]\tau' \tag{A.12}$$

Remembering that $(\pi(s)+c) = (r-\tau(s))$, this is equivalent to:

$$Q' = \Big[1 - \frac{c}{\pi+c}\Big]k' + \Big[1 + \frac{ck}{(\pi+c)^2}\Big]\pi' \tag{A.13}$$

Second derivative of Q with respect to s

$$Q'(s) = \pi(s)K'(s) + \pi'(s)(1+K(s)) \tag{A.14}$$

Taking the derivative w.r.t. S gives:

$$Q''(s) = \pi(s)'K'(s) + \pi(s)K''(s) + \pi''(s)(1+K(s)) + \pi'(s)K'(s) \tag{A.15}$$

$$Q''(s) = \pi(s)K''(s) + 2\pi'(s)K'(s) + \pi''(s)(1+K(s)) \tag{A.16}$$

Now taking the second derivative of K w.r.t. s, we have:

$$K'' = \frac{(k'' - 2\tau'^2 k)(r - \tau) - k\tau''}{(r - \tau)^2} \tag{A.17}$$

Replacing and recalling $\pi' = -\tau'$:

$$Q'' = (r - c - \tau)\Big[\frac{(k'' - 2\tau'^2 k)(r - \tau) - \tau'' k}{(r - \tau)^2}\Big] - 2\tau'\Big[\frac{k'(r - \tau) + k\tau'}{(r - \tau)^2}\Big] + \tau''\Big[\frac{r}{(r - \tau)}\Big] \tag{A.18}$$

Appendix B: Numerical Calibration Details

B.1 Potato in Antioquia and Narino

This appendix summarizes the principal characteristics of potato cultivation in Colombia, as background for the numerical simulation estimates presented in the main text. Potato in Colombia is one of the principal transitory agricultural products accounting for more than 30% of the Colombian transitory agricultural production. Most of the national potato production is centered in 4 departments: Cundinamarca, Boyaca, Narino, and Antioquia. Also, most of the potato produced in Colombia is consumed fresh and within the country. From the potato production in the country, only 8% goes to industry (to produce chips or frozen French fries), 10% is self-consumption, 64% is commercialized domestically, and the remaining is used as seeds.

Although more than 30 varieties of potato are produced in Colombia, 90% of the production consists of only three varieties: *Diacol Capiro (R12)*, *Parda pastusa*, and *Parda Suprema*. The next table shows by area cultivated, the principal varieties and departments.

Department	Total Area Cultivated with Potato (ha) 2009	Principal Potato Varieties		
		Pastusa Suprema	*Parda Pastusa*	*Diacol Capiro*
Antioquia	13,070	0	0	10,450
Boyaca	36,820	12,887	7,364	7,732
Cundinamarca	52,825	27,369	11,552	9,509
Narino	20,505	4,511	2,871	6,972
Others	11,420	1,350	5,800	1,713
Total	134,640	46,117	27,587	36,376

Table B.1: Area of potato variety by department 2009. Source: National Potato Council (CNP, 2010)

Most of potato agriculture in Colombia is done on higher altitudes, on slopes, with low mechanization, and is rain-fed. Therefore production depends on rain seasonality. There are only precarious storage facilities. Prices therefore generally reflect the variability in production.

Potato producers are usually classified in small (less than 3 ha), medium (between 3 and 10 ha) and large producers (more than 10 ha). About 85% of the production is done by smallholders. The intermediaries between the producers and the consumers, who are in charge of gathering the production of many smallholders, sorting it, washing it, packing it, and taking it to the market, have strong market power. Some analysis argue that intermediaries charge unfair margins reporting the producer's margin as low as 51% to 59%.

For the calibration we picked two states which in addition to being significant producers of potato, also exhibit deforestation in the period from 2005 to 2010 and also have forest reserves: Antioquia and Narino.

We used the base year 2005 and all monetary units are presented in US dollars. The exchange rate used is based on Bank of the Republic of Colombia data.[1] The inflation calculations were made by using the Consumer Price Index (CPI-U) which is compiled by the U.S. Bureau of Labor Statistics.

The next sections describe in detail the calibration estimates for agricultural profits in Antioquia and Narino, starting with the direct and transportation costs.

[1] http://www.banrep.gov.co/es/series-estadisticas/see_tas_cam_otrasmonedas_dia.htm (Accessed November 2015)

B.1.1 Cost of Potato Farming

A detailed survey of potato producers that included, both, Antioquia and Narino producers, and specified small, medium and large producer costs was undertaken in 2009 and the results are available online from Agronet Colombia, Costs Structures Survey.[2] The costs were adjusted to exclude land rent (which was included as a cost) and converted to 2005. A summary of the estimates are shown in the next table. There are two potato production cycles per year, depending on rain seasons.

Table B.2: Potato production costs

Department	**Narino**		**Antioquia**		
Size	**Small**	**Medium**	**Small**	**Medium**	**Large**
Annual Cost (US$/ha) - 2005	$ 4,888	$ 8,512	$ 7,264	$ 6,130	$ 4,918
Yield per cycle (Ton/ha)	14	29	19	17	17
Yield per year (Ton/ha)	29	59	38	33	34
US$/ton - 2005	$ 171	$ 145	$ 189	$ 186	$ 146

Note that the yield per cycle here was estimated from the data reported in the survey using the costs per ton and the total costs.[3]

The input transport costs, when reported, only amounted to 0.1 %, so they are dropped from the calibration making. The input costs per ton then (c) would range from: 145 to 189 US$/ Ton.

[2] http://www.agronet.gov.co/www/htm3b/public/boletines/Costos2009trim4/Costos2009T4_archivos/frame.htm (Accessed December 2015)

[3] Yield data, however is available from better sources (not focused on costs) and this more reliable yield data is used for the revenue calculation.

B.1.2 Potato Transport Costs

A survey on agricultural transport costs between all principal cities was done in 2006 and 2008 and cost estimates per ton are available from Agronet Colombia. These estimates around the two capital cities of Antioquia (Medellin) and Narino (Pasto) where coupled with distance information form Google Map to calculate the relationship between costs and distance using a regression. The best fit to the relationship obtained a linear function with a fixed cost (F) that does not depend on distance.

Table B.3: Output transport costs

Year	**Fixed costs (F)**	**Variable costs (t)**
Units	**US$/ton**	**US$/ton/km**
2005	15.18	0.038

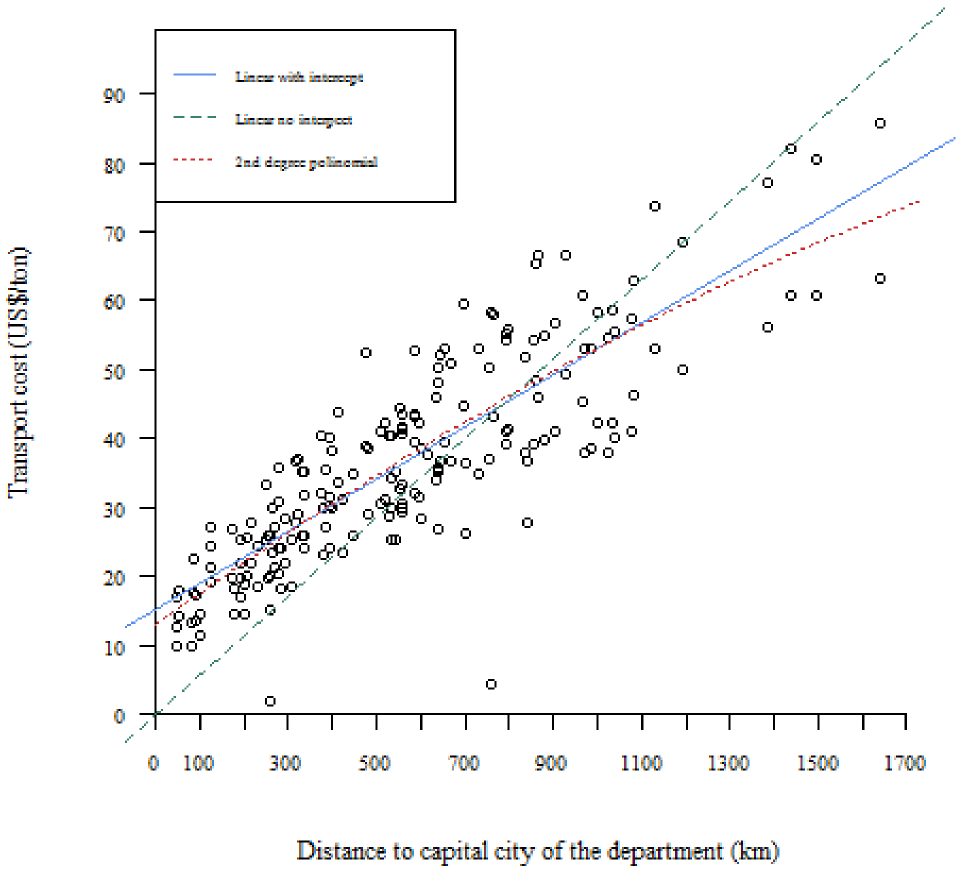


Figure B.1: Transport costs estimated for 2005

B.1.3 Revenue of Potato Farming

The revenue has two components the yield and the price. Yield estimates are available per department from Agronet Colombia for selected years, for the principal products in each department. For Antioquia and Narino the available data for yield between 2000 and 2010 have the following summary statistics.

The prices to the producer is not directly available, however, the market price is

Table B.4: Potato yield per department

Yield (Ton/ha)	Average	Min	Max
Antioquia	17	15	18
Narino	17	15	20

available on a weekly basis starting from 2013 at the National Statistics Department, for each variety sold in each market. A weighted average for the 2013 prices of the principal varieties sold in the markets in Antioquia and Narino was calculated obtaining the following summary statistics, converted to 2005 dollars.

Table B.5: Potato prices

Potato price	Average	Min	Max
US$/Ton - 2005	$ 215	$ 209	$ 220

However, this price, as was explained in the background section is sometimes different than the price received by the producers, which is reduced by the transport costs, and the distribution costs. The farmer's share of the final market retail price is around 50%, when the potatoes are sold in the capital city for example [100–102]. However, the price we included in the calibration estimates corresponds to markets within the same department and a high share of the commercializing margin (and pertaining transport) occurs on transportation to capital cities. Therefore the distribution cost margin used here is 10%.

B.2 Enforcement and Surveillance Costs

The next step was to estimate and calibrate the enforcement cost function. Using the travel time and distance from Google Map between the capital city in each department and all the municipal capital within it, estimates for the enforcement costs per hectare were calculated.

Four different types of costs were taken into account: Wage, Transport, Lodging, Food. They all depend on the distance to the center of the CAR (the administrative center, where the CAR offices are assumed to be located).

Transport - is calculated based on total kilometers driven. It is the distance, times 2, since the monitor has to come back as well. The transport costs per kilometer were estimated in two ways: from bus tickets, and from gasoline prices and average mileage per gallon. Information about bus ride costs is available from ColombiaBusInfo.com. Information on gas prices is available at Sistema de Informacion de petroleo y gas colombiano and was combined with fuel efficiency data available at www.fueleconomy.gov to estimate plausible ranges for fuel costs.

The table below gives the max and min costs per kilometer obtained for each method adjusted to 2005. The higher estimate of gasoline costs were used in this analysis, since most of the enforcement (when done) occurs in private vehicles and these vehicles more than often are all-wheel drive, because of the bad state of the roads.

Wage - is calculated based on the total hours the trip takes. To keep all the estimates depending on the kilometers, a regression coefficient was estimated to turn the km into hours using Google map data. The minimum wage in Colombia, available at Bank of the Republic[4] was used as the minimum estimate and an average "public sector" employee wage estimate presented by [111] was used as the upper

[4] http://banrep.gov.co/es/tags/salario-minimo-0 (Accessed October 2015)

estimate. The wage cost used in the estimation was the average "public" employee estimate, since monitors need to have at least some technical background to be able to do their job.

Food - is calculated based on the number of days monitors spend traveling. A rounding formula is used and a day is assumed to have 8 working hours. When 8 or less hours are needed to travel back and fourth, food for one day is budgeted. If the time is between 8 and 16 hours two days of food are budgeted, and so forth. The following table shows min and max estimates for the costs of food per day, however, given the profiles of the monitors, the higher estimates were chosen.

Hotel - is calculated similar to the food, but based on nights spent (not days). If the enforcement time takes less than 8 hours, no hotel costs are added in. If the time traveling is between 8 and 16 hours, one night is added, and so forth. The lower and upper estimate for the costs per night are shown below, but again the higher one was chosen for the estimation of the enforcement cost curve.

Table B.6: Enforcement and surveillance costs

Costs (US$) - 2005	**Min**	**Max**
Bus (per km)	0.063	0.084
Gasoline (per km)	0.007	0.245
Wage (per hour)	0.68	2.56
Food (per day)	12.93	21.54
Hotel (per night)	21.54	64.63

Regression estimates for different functional forms are added in the graph.

The quadratic form was chosen because of simplicity and better fit. Non-linearity was needed such that the Theoretical model assumptions are met.

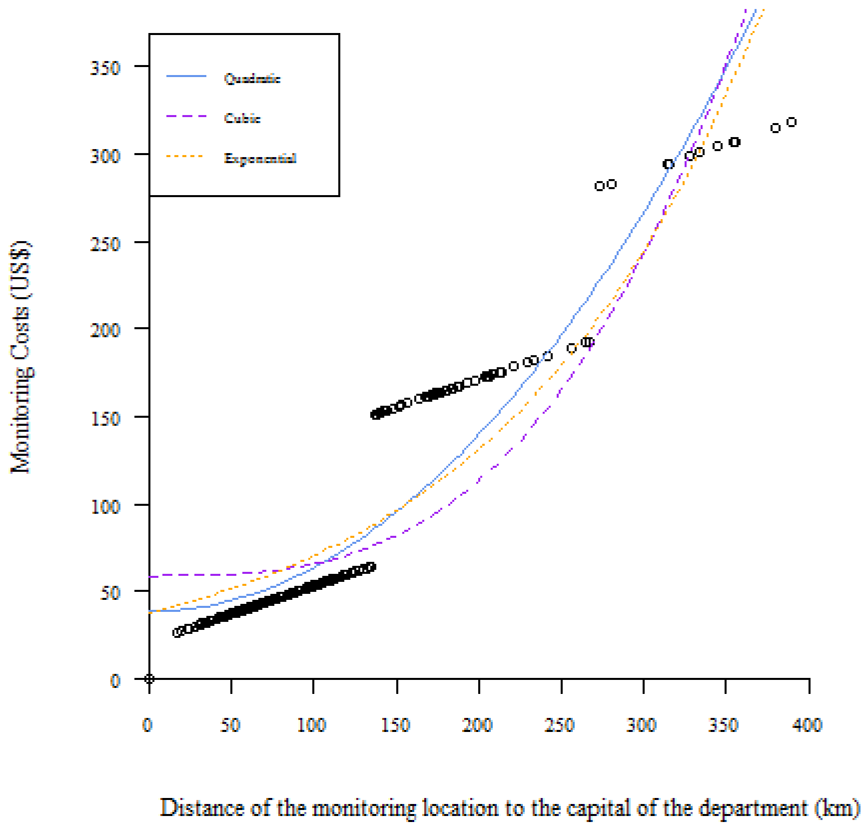


Figure B.2: Enforcement costs estimated for 2005 Antioquia and Narino

Table B.7: Parameters for enforcement costs

Function	k_0	k_1
$k_1 x^2 + k_0$	0.0025	38.5
$k_1 x^3 + k_0$	$6.8e-06$	$5.9e+01$
$k_1 e^{k_0 x}$	38.09	0.0062

B.3 Descartes Rule

In this section we apply Descartes Rule to the quadratic form of enforcement costs to find conditions under which the leapfrog pattern could exist. The conditions are focused on the ecosystem service (ES), transport cost (t), and enforcement cost (k_1) parameters. The analysis is done first numerically and then algebraically.

B.3.1 Numerically

Decision function DF=ES:

$$\frac{ES(174 - st) + k_1 s^2(st - 29) - 20s^2t^2 + 4099st - 102051}{st - 174} = 0 \qquad \text{(D.1)}$$

Reorganizing terms we get:

$$(174ES - 102051) + (4099 - ES)ts - (20t^2 + 29k_1)s^2 + k_1ts^3 = 0 \qquad \text{(D.2)}$$

1. The last term is always positive under the assumptions of the model
2. The third term is always negative under the assumptions of the model
3. The second term is positive if $ES < 4099\ US\$/ha$
4. The first term is negative if $ES < 568\ US\$/ha$

Putting these conditions together, a maximum of 3 positive roots are possible for $ES < 568\ US\$/ha$.

B.3.2 Algebraically

Switch function SF-ES=0:

$$\frac{(k_0 + k_1 s^2 + 1)(c + F + (M-1)p + st)}{F + (M-1)p + st} - ES - y(c + F + (M-1)p + st) = 0 \quad \text{(D.3)}$$

Reorganizing terms we get:

$$\begin{aligned}
&[(1-k_0)(c+F+p(M-1)) - y(c+F+p(M-1))(F+p(M-1)) - ES(F+p(M-1))] \\
&\quad +[(1+k_0) - y(c+F+p(M-1)) - y - ES]ts \\
&\quad +[k_1(c+F+p(M-1)) - ty]s^2 \\
&\quad +[k_1 t]s^3 = 0
\end{aligned}$$

Define: $FF = F + p(M-1)$, then $FF \leq 0$ and $c + FF \leq 0$

$$\begin{aligned}
&[(1-k_0)(c+FF) - y(c+FF)(FF) - ES(FF)] \\
&\quad +[(1+k_0) - y(c+FF) - y - ES]ts \\
&\quad +[k_1(c+FF) - ty]s^2 \\
&\quad +[k_1 t]s^3 = 0
\end{aligned}$$

1. The last term is always positive under the assumptions of the model
2. The third term is always negative under the assumptions of the model
3. The second term is positive if $ES < (1 + k_0) - y(c + F + p(M - 1)) - y$
4. The first term is negative if $ES < \frac{(1-k_0)(c+F+p(M-1))-y(c+F+p(M-1))(F+p(M-1))}{F+p(M-1)}$

B.4 Sensitivity of the derivatives of the decision function

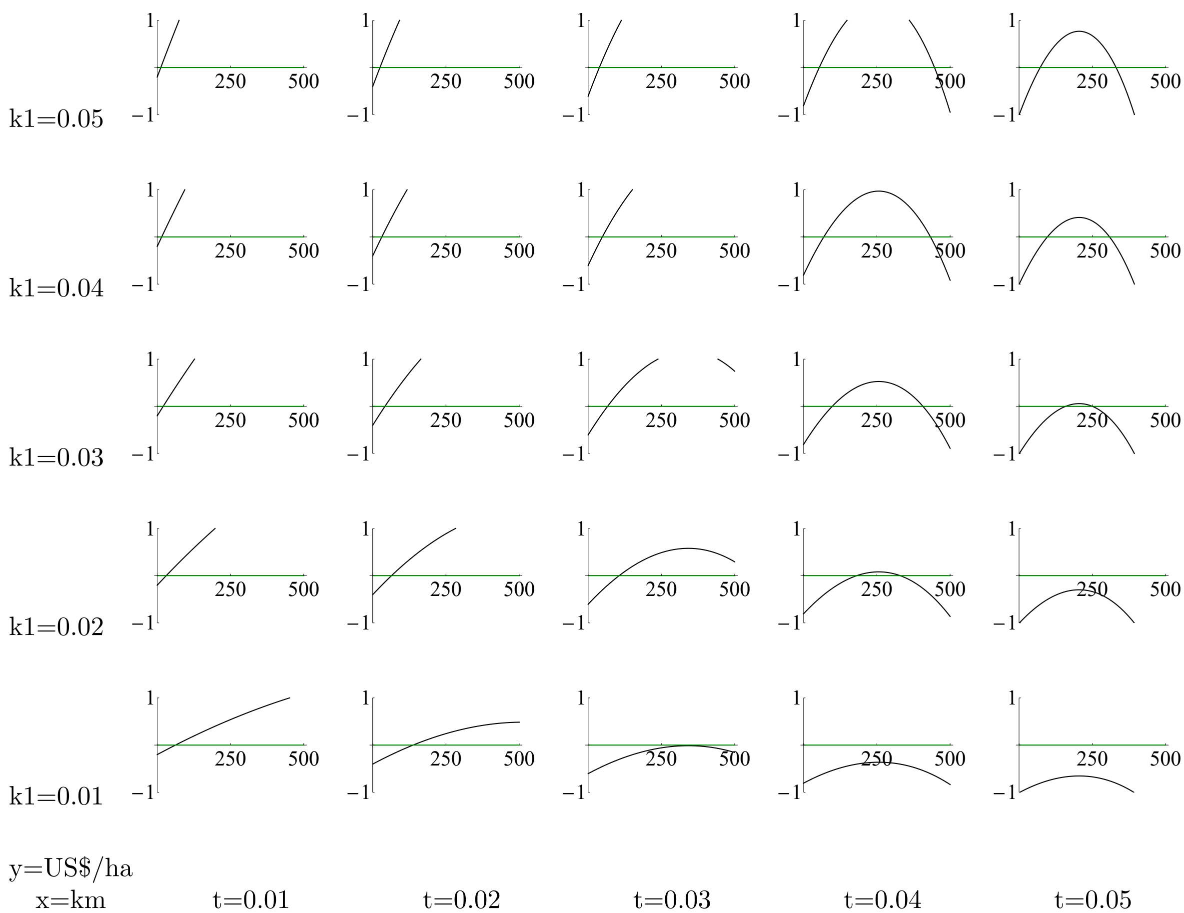


Figure B.3: Derivative of the Decision function

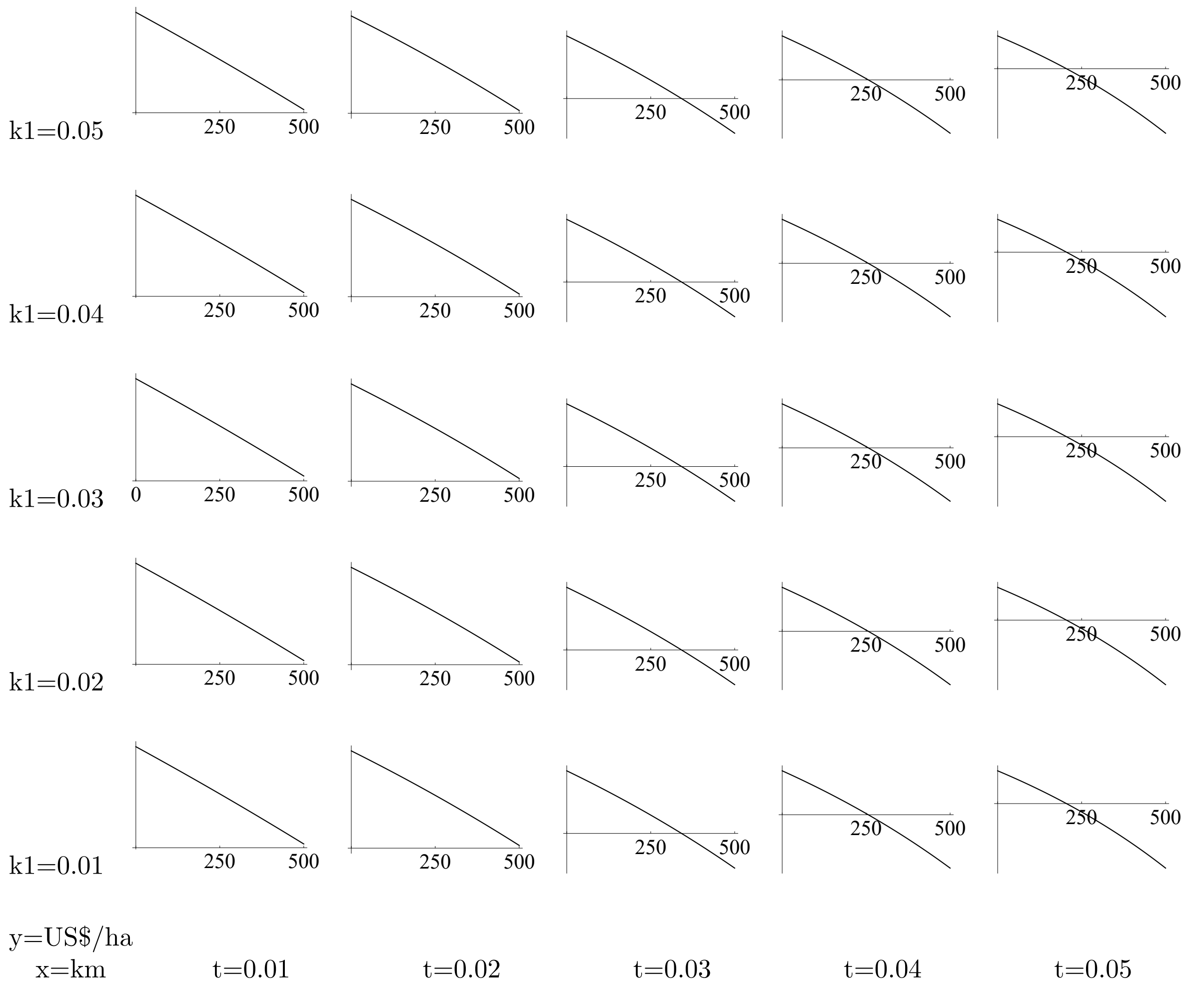


Figure B.4: Second Derivative of the Decision function

Appendix C: Descriptive Statistics Details

C.1 Reserves

Table C.1: Summary statistics for the random sample in reserves year 2000

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Deforestation (0 or 1)	41,992	0.05	0.21	0	0	0	1
Access difficulty to road (0,1)	41,992	0.19	0.16	0.00	0.07	0.28	0.93
Distance to road (km)	41,992	9.12	7.05	0.0004	3.21	14.00	32.92
Fiscal Performance Index (0,100)	36,763	52.82	4.64	41.62	49.91	55.78	68.22
Number of Conflicts (No.)	41,992	2.93	3.40	0	0	4	70
Rural Pop. Dens. (1000pers./km2)	32,798	0.67	0.14	0.35	0.58	0.79	0.97
Land Owner GINI (0,100)	41,992	13.10	12.16	1.36	6.06	15.38	139.26
Dist. Municipio (km)	41,992	23.40	12.17	0.35	13.92	30.91	78.71
Dist. Principal Road (km)	41,992	28.62	21.61	0.01	11.74	41.50	88.83
Slope (degrees)	41,992	17.08	10.11	0.00	9.11	23.92	73.46
Elevation (m)	41,992	1,406.01	991.24	0	561	2,177	3,990

Table C.2: Summary statistics for the grid sample in reserves year 2000

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Deforestation (0 or 1)	36,615	0.04	0.21	0	0	0	1
Access difficulty to road (0,1)	36,615	0.19	0.16	0.00	0.07	0.28	0.92
Distance to road (km)	36,615	9.11	7.02	0.0004	3.21	13.93	33.38
Fiscal Performance Index (0,100)	31,994	52.80	4.64	41.62	49.88	55.78	68.22
Number of Conflicts (No.)	36,615	2.92	3.44	0	0	4	70
Rural Pop. Dens. (1000pers./km2)	28,591	0.67	0.14	0.35	0.58	0.79	0.97
Land Owner GINI (0,100)	36,615	13.16	12.14	1.36	6.06	15.38	139.26
Dist. Municipio (km)	36,615	23.34	12.17	0.28	13.92	30.78	78.21
Dist. Principal Road (km)	36,615	28.61	21.56	0.0004	11.75	41.31	88.92
Slope (degrees)	36,615	17.11	10.10	0.00	9.17	23.98	75.06
Elevation (m)	36,615	1,407.05	992.60	12	557	2,182.5	3,882

Table C.3: Summary statistics for the random sample in reserves year 2005

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Deforestation (0 or 1)	37,823	0.04	0.20	0	0	0	1
Access difficulty to road (0,1)	37,823	0.19	0.15	0.00	0.07	0.28	0.93
Distance to road (km)	37,823	9.19	7.11	0.0004	3.19	14.16	32.92
Fiscal Performance Index (0,100)	37,766	57.96	6.19	37.59	55.03	62.75	74.31
Number of Conflicts (No.)	37,823	6.54	6.18	0	2	8	38
Rural Pop. Dens. (1000pers./km2)	33,772	0.67	0.14	0.00	0.55	0.79	0.98
Land Owner GINI (0,100)	37,823	12.97	12.30	1.56	5.78	14.49	102.57
Dist. Municipio (km)	37,823	23.42	12.22	0.35	13.86	31.06	78.71
Dist. Principal Road (km)	37,823	29.16	21.79	0.002	12.05	42.65	88.83
Slope (degrees)	37,823	16.97	10.02	0.00	9.05	23.76	73.46
Elevation (m)	37,823	1,377.21	980.71	0	553	2,117	3,990

Table C.4: Summary statistics for the grid sample in reserves year 2005

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Deforestation (0 or 1)	32,933	0.04	0.20	0	0	0	1
Access difficulty to road (0,1)	32,933	0.19	0.15	0.00	0.07	0.27	0.92
Distance to road (km)	32,933	9.17	7.09	0.0004	3.20	14.10	33.38
Fiscal Performance Index (0,100)	32,875	57.99	6.20	37.59	55.03	63.03	74.31
Number of Conflicts (No.)	32,933	6.60	6.27	0	2	8	38
Rural Pop. Dens. (1000pers./km2)	29,370	0.67	0.14	0.00	0.55	0.79	0.98
Land Owner GINI (0,100)	32,933	12.92	12.12	1.56	5.78	14.49	131.53
Dist. Municipio (km)	32,933	23.41	12.21	0.28	13.93	30.98	78.49
Dist. Principal Road (km)	32,933	29.20	21.75	0.002	12.08	42.56	88.92
Slope (degrees)	32,933	17.00	9.98	0.00	9.16	23.81	63.86
Elevation (m)	32,933	1,375.70	982.33	20	550	2,120	3,882

C.2 Not Protected

Table C.5: Summary statistics for the random sample in not protected year 2000

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Deforestation (0 or 1)	62,245	0.07	0.25	0	0	0	1
Access difficulty to road (0,1)	62,245	0.11	0.12	0.00	0.03	0.15	1.00
Distance to road (km)	62,245	4.38	4.54	0.0000	1.24	5.91	34.15
Fiscal Performance Index (0,100)	57,726	53.61	5.09	39.14	50.07	56.01	77.24
Number of Conflicts (No.)	62,245	3.55	6.85	0	0	4	70
Rural Pop. Dens. (1000pers./km2)	45,230	0.68	0.11	0.32	0.60	0.77	0.97
Land Owner GINI (0,100)	61,458	18.70	20.62	1.36	8.39	20.74	1,239.82
Dist. Municipio (km)	62,245	14.57	9.10	0.02	7.50	19.85	55.32
Dist. Principal Road (km)	62,245	17.93	14.95	0.0000	6.50	25.63	84.70
Slope (degrees)	62,245	17.69	10.80	0.00	8.99	25.40	77.94
Elevation (m)	62,245	1,514.19	964.50	0	616	2,340	3,878

Table C.6: Summary statistics for the grid sample in not protected year 2000

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Deforestation (0 or 1)	54,001	0.07	0.26	0	0	0	1
Access difficulty to road (0,1)	54,001	0.11	0.12	0.00	0.03	0.15	1.00
Distance to road (km)	54,001	4.37	4.52	0.0001	1.23	5.90	34.37
Fiscal Performance Index (0,100)	50,098	53.60	5.10	39.20	50.07	56.01	77.24
Number of Conflicts (No.)	54,001	3.51	6.69	0	0	4	70
Rural Pop. Dens. (1000pers./km2)	39,273	0.68	0.11	0.32	0.60	0.77	0.97
Land Owner GINI (0,100)	53,293	18.63	20.23	1.36	8.39	20.74	560.93
Dist. Municipio (km)	54,001	14.58	9.12	0.05	7.52	19.85	55.35
Dist. Principal Road (km)	54,001	17.85	14.89	0.001	6.50	25.41	84.46
Slope (degrees)	54,001	17.65	10.79	0.00	8.93	25.48	72.41
Elevation (m)	54,001	1,514.83	964.77	17	620	2,343	3,826

Table C.7: Summary statistics for the random sample in not protected year 2005

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Deforestation (0 or 1)	54,448	0.08	0.27	0	0	0	1
Access difficulty to road (0,1)	54,448	0.11	0.12	0.00	0.02	0.15	0.99
Distance to road (km)	54,448	4.31	4.45	0.0000	1.22	5.82	34.15
Fiscal Performance Index (0,100)	54,435	58.58	6.29	29.57	54.74	62.17	83.58
Number of Conflicts (No.)	54,448	5.55	8.21	0	0	8	38
Rural Pop. Dens. (1000pers./km2)	52,031	0.68	0.11	0.02	0.60	0.76	0.98
Land Owner GINI (0,100)	53,771	18.62	21.67	1.56	8.13	20.36	1,281.53
Dist. Municipio (km)	54,448	14.59	9.05	0.02	7.58	19.88	55.32
Dist. Principal Road (km)	54,448	18.00	15.06	0.0000	6.54	25.45	84.70
Slope (degrees)	54,448	17.62	10.82	0.00	8.82	25.40	77.94
Elevation (m)	54,448	1,485.47	967.47	0	579	2,316	3,878

Table C.8: Summary statistics for the grid sample in not protected year 2005

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Deforestation (0 or 1)	47,029	0.08	0.27	0	0	0	1
Access difficulty to road (0,1)	47,029	0.11	0.12	0.00	0.02	0.15	0.92
Distance to road (km)	47,029	4.32	4.45	0.0001	1.22	5.86	34.37
Fiscal Performance Index (0,100)	47,014	58.54	6.24	29.57	54.82	61.97	82.59
Number of Conflicts (No.)	47,029	5.52	8.23	0	0	8	38
Rural Pop. Dens. (1000pers./km2)	45,003	0.68	0.11	0.02	0.60	0.76	0.98
Land Owner GINI (0,100)	46,427	18.46	20.91	1.56	8.13	20.36	675.66
Dist. Municipio (km)	47,029	14.62	9.07	0.09	7.61	19.89	55.35
Dist. Principal Road (km)	47,029	17.98	15.03	0.001	6.58	25.34	84.46
Slope (degrees)	47,029	17.61	10.82	0.00	8.77	25.55	72.41
Elevation (m)	47,029	1,490.06	966.72	17	588	2,321	3,886

Appendix D: Supporting Results

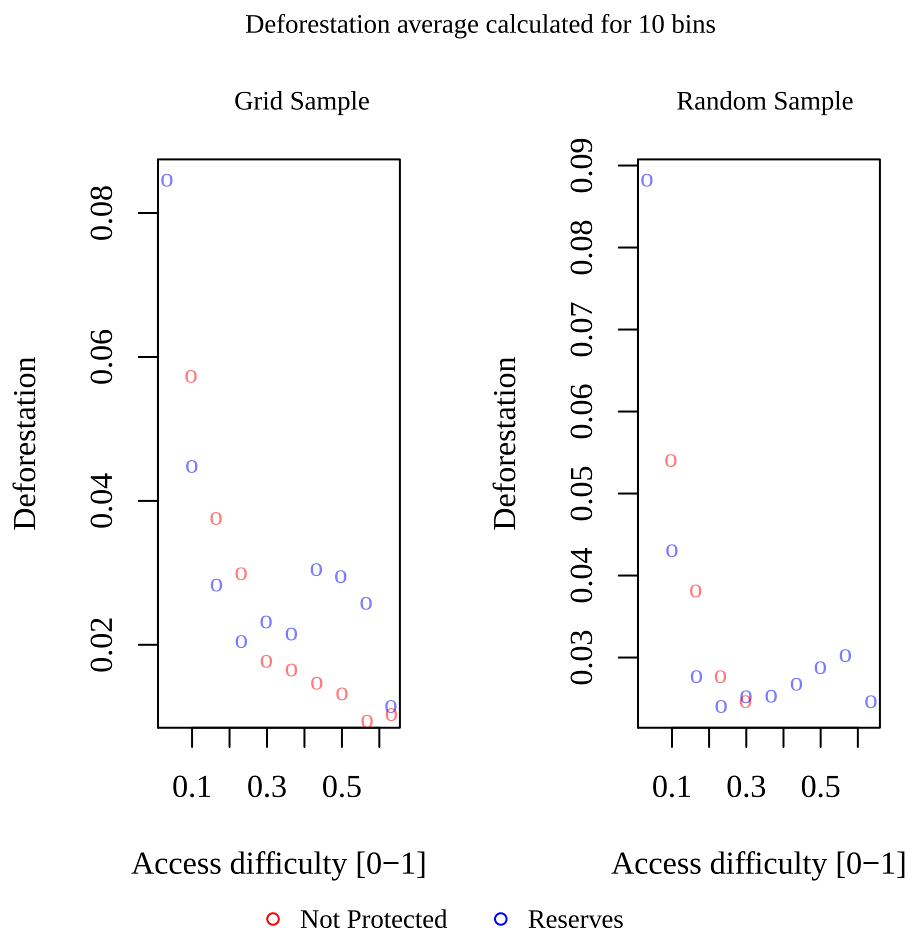


Figure D.1: Deforestation average for access difficulty 10 bins

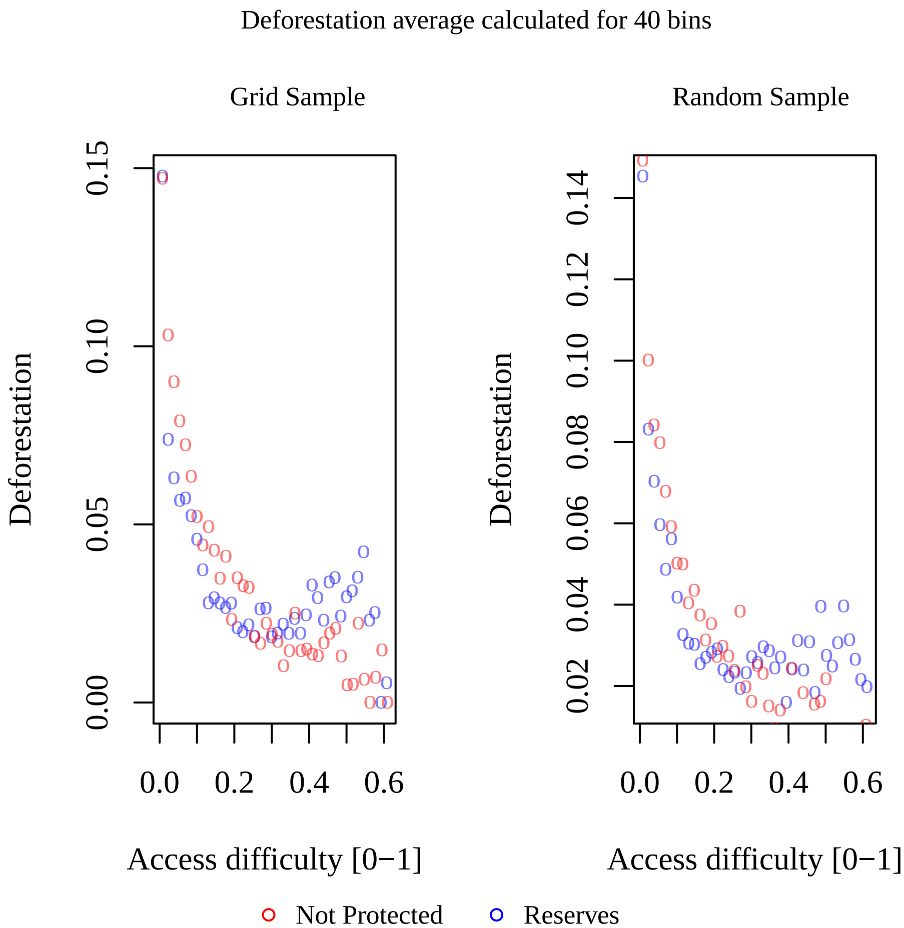


Figure D.2: Deforestation average for access difficulty 40 bins

Table D.1: Non-parametric Accessibility Regression Results 10 bins

	Dependent Variable: Deforestation			
	Reserves Random	Not Protect Random	Reserves Grid	No Protect Grid
	(1)	(2)	(3)	(4)
Acc. Diff. bin 2	-0.014^{***}	-0.027^{***}	-0.013^{***}	-0.023^{***}
Acc. Diff. bin 3	-0.022^{***}	-0.029^{***}	-0.023^{***}	-0.028^{***}
Acc. Diff. bin 4	-0.025^{***}	-0.030^{***}	-0.029^{***}	-0.026^{***}
Acc. Diff. bin 5	-0.023^{***}	-0.020^{***}	-0.027^{***}	-0.026^{***}
Acc. Diff. bin 6	-0.027^{***}	-0.020^{***}	-0.034^{***}	-0.019^{***}
Acc. Diff. bin 7	-0.031^{***}	-0.010^{*}	-0.034^{***}	-0.009^{*}
Acc. Diff. bin 8	-0.035^{***}	0.001	-0.042^{***}	-0.004
Acc. Diff. bin 9	-0.022^{***}	-0.011^{**}	-0.036^{***}	-0.003
Acc. Diff. bin 10	-0.019^{***}	0.006	-0.040^{***}	-0.002
Dist.Mun.	-0.001^{***}	-0.001^{***}	-0.001^{***}	-0.001^{***}
Observations	65,567	94,500	57,047	81,912
F Statistic	15.136^{***}	13.565^{***}	13.560^{***}	12.195^{***}

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Table D.2: Non-parametric Accessibility Regression Results 40 bins

	Dependent Variable: Deforestation			
	Reserves Random	Not Protect Random	Reserves Grid	No Protect Grid
	(1)	(2)	(3)	(4)
Acc. Diff. bin 2	-0.040^{***}	-0.026^{***}	-0.054^{***}	-0.023^{***}
Acc. Diff. bin 3	-0.046^{***}	-0.039^{***}	-0.059^{***}	-0.028^{***}
Acc. Diff. bin 4	-0.053^{***}	-0.040^{***}	-0.061^{***}	-0.039^{***}
Acc. Diff. bin 5	-0.056^{***}	-0.047^{***}	-0.057^{***}	-0.036^{***}
Acc. Diff. bin 6	-0.042^{***}	-0.052^{***}	-0.058^{***}	-0.044^{***}
Acc. Diff. bin 7	-0.056^{***}	-0.058^{***}	-0.062^{***}	-0.052^{***}
Acc. Diff. bin 8	-0.066^{***}	-0.057^{***}	-0.071^{***}	-0.057^{***}
Acc. Diff. bin 9	-0.065^{***}	-0.066^{***}	-0.076^{***}	-0.046^{***}
Acc. Diff. bin 10	-0.062^{***}	-0.055^{***}	-0.076^{***}	-0.052^{***}
Acc. Diff. bin 11	-0.068^{***}	-0.058^{***}	-0.073^{***}	-0.057^{***}
Acc. Diff. bin 12	-0.063^{***}	-0.064^{***}	-0.076^{***}	-0.049^{***}
Acc. Diff. bin 13	-0.065^{***}	-0.060^{***}	-0.076^{***}	-0.067^{***}
Acc. Diff. bin 14	-0.062^{***}	-0.063^{***}	-0.080^{***}	-0.053^{***}
Acc. Diff. bin 15	-0.070^{***}	-0.060^{***}	-0.085^{***}	-0.052^{***}
Acc. Diff. bin 16	-0.070^{***}	-0.064^{***}	-0.077^{***}	-0.048^{***}
Acc. Diff. bin 17	-0.068^{***}	-0.058^{***}	-0.082^{***}	-0.057^{***}
Acc. Diff. bin 18	-0.074^{***}	-0.042^{***}	-0.075^{***}	-0.062^{***}
Acc. Diff. bin 19	-0.068^{***}	-0.060^{***}	-0.075^{***}	-0.052^{***}
Acc. Diff. bin 20	-0.061^{***}	-0.060^{***}	-0.083^{***}	-0.052^{***}
Acc. Diff. bin 21	-0.065^{***}	-0.044^{***}	-0.084^{***}	-0.051^{***}
Acc. Diff. bin 22	-0.064^{***}	-0.044^{***}	-0.083^{***}	-0.053^{***}
Acc. Diff. bin 23	-0.067^{***}	-0.051^{***}	-0.089^{***}	-0.049^{***}
Acc. Diff. bin 24	-0.070^{***}	-0.059^{***}	-0.083^{***}	-0.042^{***}
Acc. Diff. bin 25	-0.069^{***}	-0.051^{***}	-0.091^{***}	-0.047^{***}
Acc. Diff. bin 26	-0.085^{***}	-0.051^{***}	-0.086^{***}	-0.045^{***}
Acc. Diff. bin 27	-0.076^{***}	-0.033^{***}	-0.079^{***}	-0.040^{***}
Acc. Diff. bin 28	-0.068^{***}	-0.050^{***}	-0.087^{***}	-0.041^{***}
Acc. Diff. bin 29	-0.077^{***}	-0.040^{***}	-0.097^{***}	-0.034^{***}
Acc. Diff. bin 30	-0.077^{***}	-0.043^{***}	-0.089^{***}	-0.032^{***}
Acc. Diff. bin 31	-0.089^{***}	-0.037^{***}	-0.088^{***}	-0.030^{**}
Acc. Diff. bin 32	-0.069^{***}	-0.032^{***}	-0.100^{***}	-0.036^{***}
Acc. Diff. bin 33	-0.085^{***}	-0.021	-0.099^{***}	-0.044^{***}
Acc. Diff. bin 34	-0.083^{***}	-0.042^{***}	-0.095^{***}	-0.038^{***}
Acc. Diff. bin 35	-0.077^{***}	-0.037^{***}	-0.089^{***}	-0.012
Acc. Diff. bin 36	-0.067^{***}	-0.046^{***}	-0.079^{***}	-0.040^{***}
Acc. Diff. bin 37	-0.066^{***}	-0.044^{***}	-0.099^{***}	-0.043^{***}
Acc. Diff. bin 38	-0.065^{***}	-0.045^{***}	-0.087^{***}	-0.036^{***}
Acc. Diff. bin 39	-0.064^{***}	-0.045^{***}	-0.111^{***}	-0.024^{*}
Acc. Diff. bin 40	-0.069^{***}	-0.037^{***}	-0.100^{***}	-0.048^{***}
Dist.Mun.	-0.001^{***}	-0.001^{***}	-0.0005^{***}	-0.001^{***}
Observations	64,946	94,295	56,555	81,727
F Statistic	14.132^{***}	13.254^{***}	12.799^{***}	11.863^{***}

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

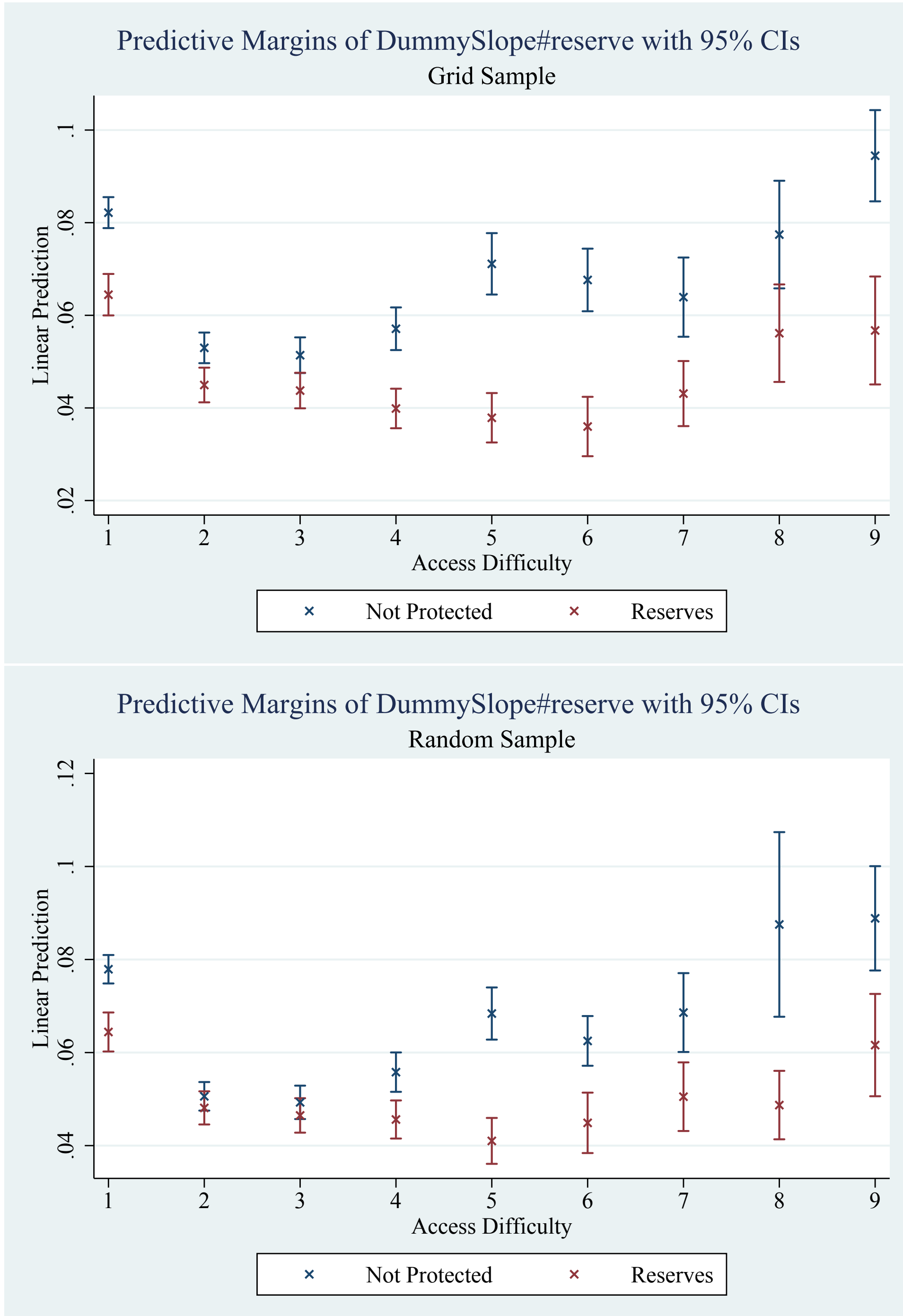


Figure D.3: Effect of access difficulty on deforestation w/o enforcement interactions (10 bins)

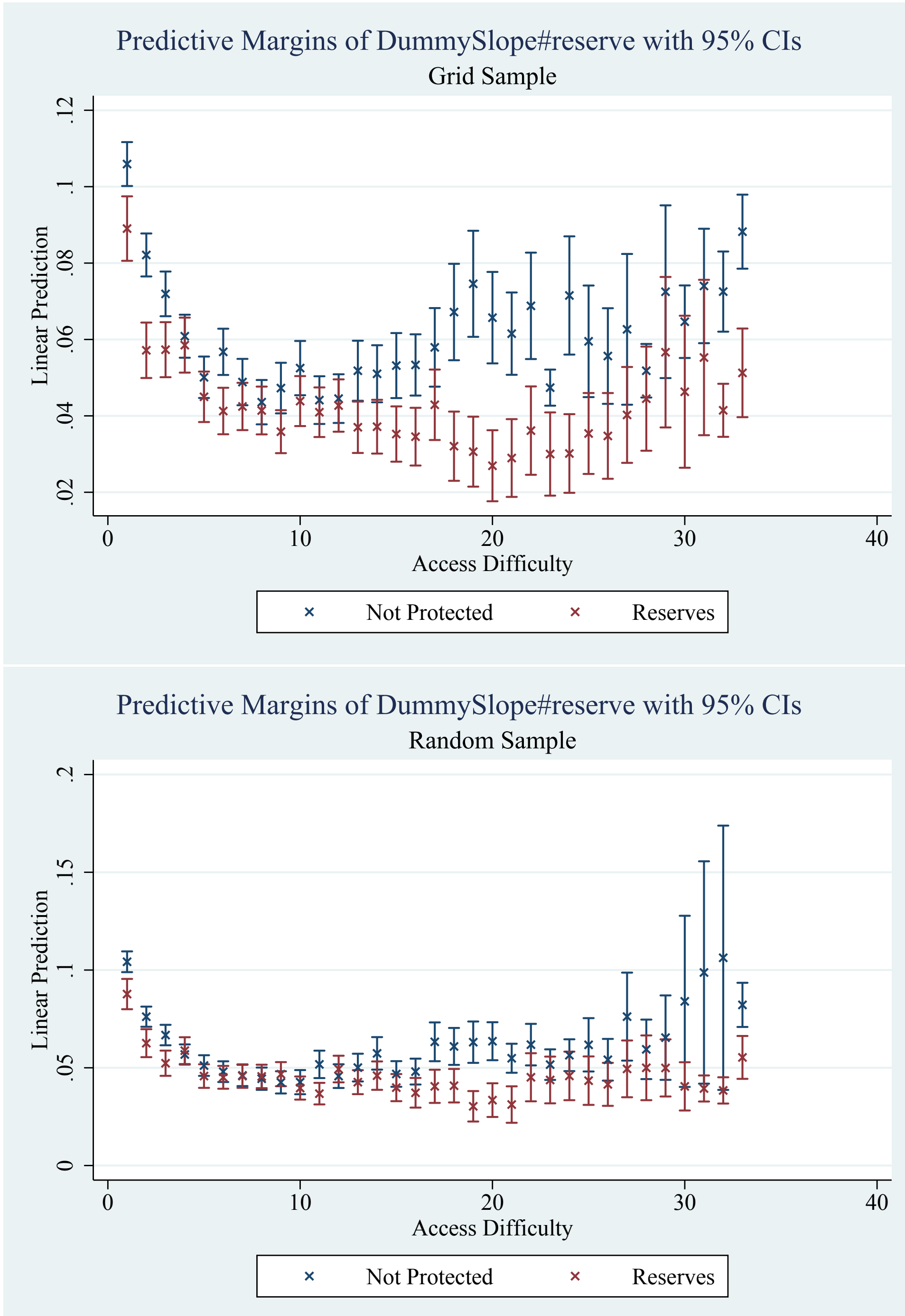


Figure D.4: Effect of access difficulty on deforestation w/o enforcement interactions (40 bins)

Effect of Enforcement and Access Difficulty on Deforestation

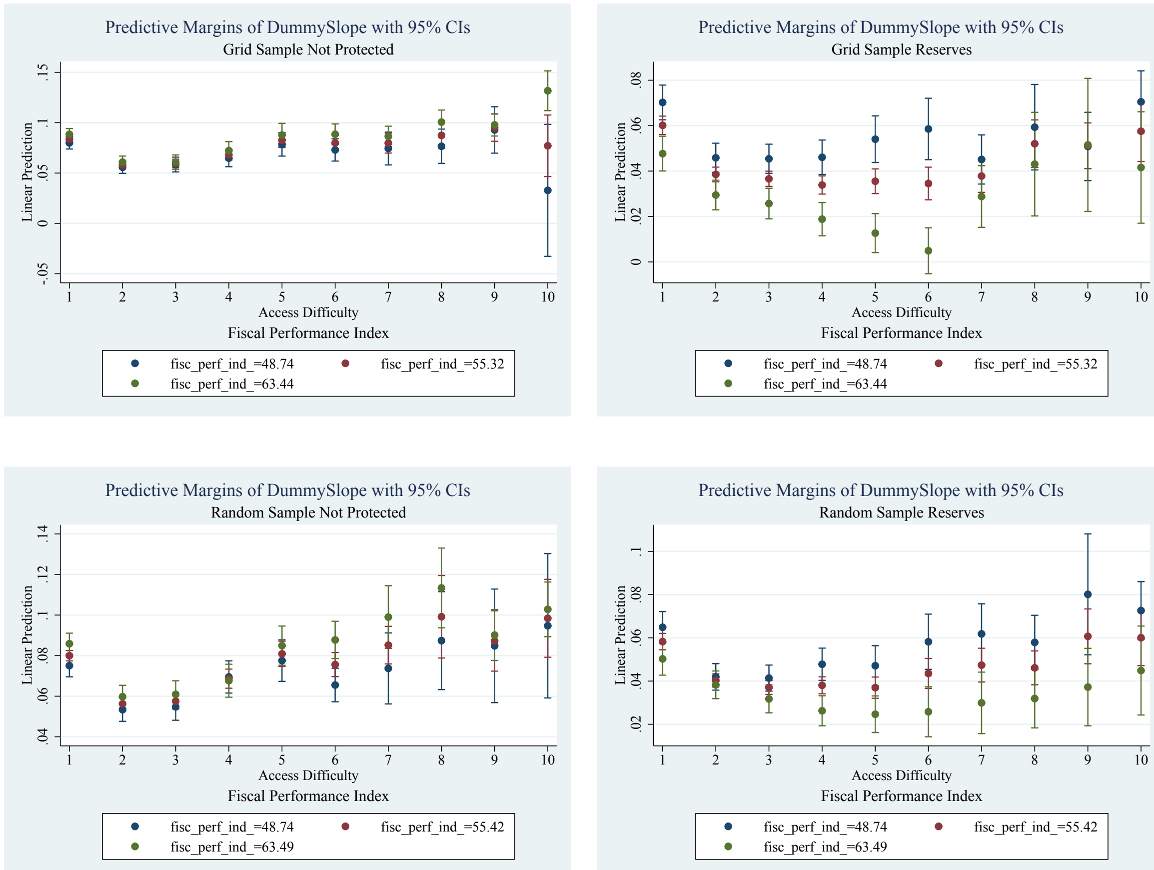


Figure D.5: Non parametric analysis results, coefficients for 10 bins

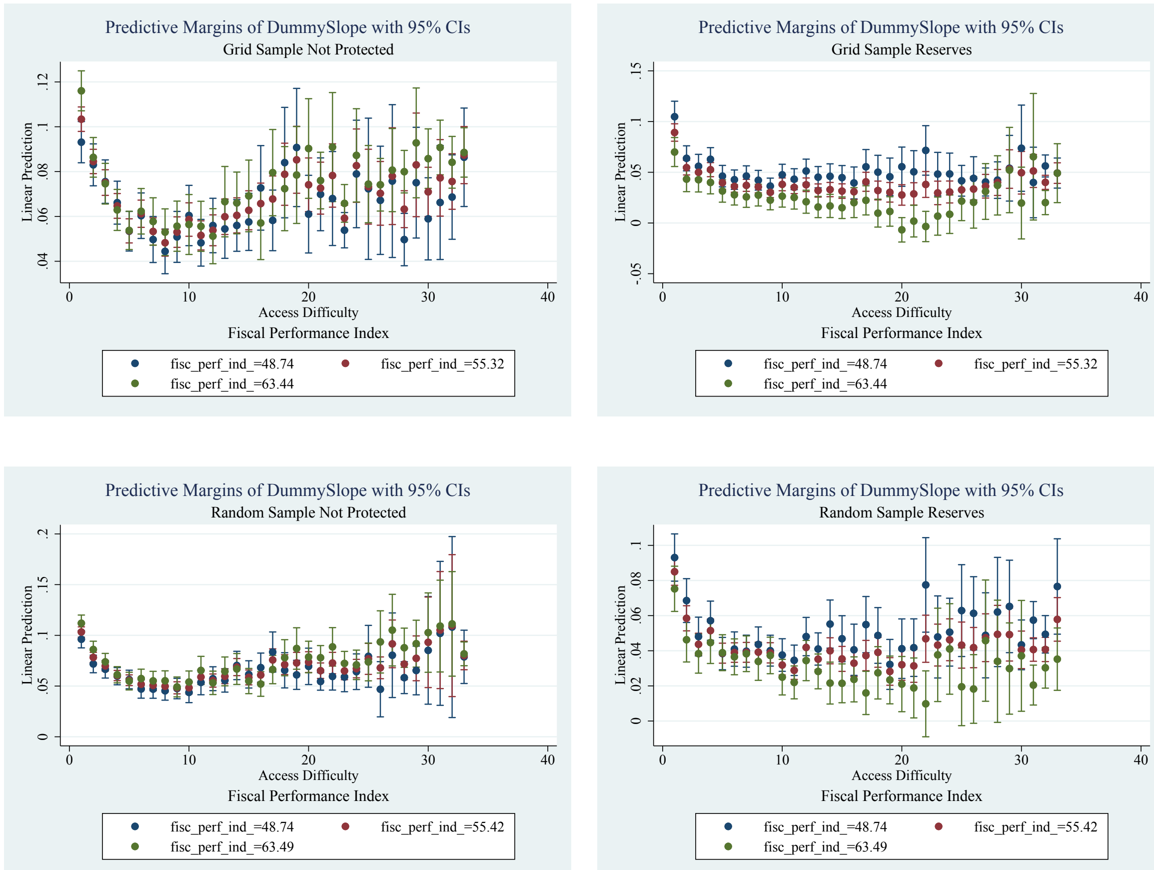


Figure D.6: Non parametric analysis results, coefficients for 40 bins

Table D.3: Non-parametric effect of enforcement and access difficulty on deforestation (10 bins)

	Dependent Variable: Deforestation			
	Res Random	Not Prot. Random	Res Grid	Not Prot. Grid
	(1)	(2)	(3)	(4)
dumdist.Road.Slope2	-0.023	0.055^{***}	-0.017	0.045^{**}
dumdist.Road.Slope3	-0.054^{**}	0.033	-0.048^{*}	0.038^{*}
dumdist.Road.Slope4	-0.033	0.046^{*}	-0.027	0.049^{*}
dumdist.Road.Slope5	0.003	0.099^{***}	-0.025	0.056^{**}
dumdist.Road.Slope6	0.039	0.071^{**}	0.003	0.036
dumdist.Road.Slope7	0.031	0.046	0.046	0.024
dumdist.Road.Slope8	0.062	0.043	0.117^{**}	0.062
dumdist.Road.Slope9	0.025	0.051^{*}	0.147^{**}	0.084^{*}
dumdist.Road.Slope10	0.047	0.085	-0.035	0.045
Fisc.Perf.Ind.	-0.001^{**}	0.002^{***}	-0.001^{***}	0.001^{***}
dumdist.Road.Slope2:Fisc.Perf.Ind.	-0.0000	-0.001^{***}	-0.0000	-0.001^{***}
dumdist.Road.Slope3:Fisc.Perf.Ind.	0.0004	-0.001^{***}	0.0003	-0.001^{***}
dumdist.Road.Slope4:Fisc.Perf.Ind.	-0.0002	-0.001^{***}	-0.0002	-0.001^{***}
dumdist.Road.Slope5:Fisc.Perf.Ind.	-0.001^{*}	-0.002^{***}	-0.0003	-0.002^{***}
dumdist.Road.Slope6:Fisc.Perf.Ind.	-0.002^{***}	-0.002^{***}	-0.001	-0.001^{*}
dumdist.Road.Slope7:Fisc.Perf.Ind.	-0.001^{**}	-0.001^{**}	-0.002^{**}	-0.001
dumdist.Road.Slope8:Fisc.Perf.Ind.	-0.002^{***}	-0.001^{*}	-0.003^{***}	-0.001^{**}
dumdist.Road.Slope9:Fisc.Perf.Ind.	-0.001	-0.001^{***}	-0.004^{***}	-0.002^{**}
dumdist.Road.Slope10:Fisc.Perf.Ind.	-0.002	-0.002	-0.0004	-0.001

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Table D.4: Non-parametric effect of enforcement and access difficulty on deforestation (30bins)

	Dependent Variable: Deforestation			
	Res Random	Not Prot. Random	Res Grid	Not Prot. Grid
	(1)	(2)	(3)	(4)
Acc. Diff. bin 2	−0.008	0.047	−0.084	0.071**
Acc. Diff. bin 3	−0.059	0.033	−0.128**	0.094***
Acc. Diff. bin 4	−0.024	0.047	−0.143**	0.074**
Acc. Diff. bin 5	−0.055	0.083***	−0.076	0.095***
Acc. Diff. bin 6	−0.105**	0.081**	−0.121**	0.087***
Acc. Diff. bin 7	−0.099**	0.044	−0.143***	0.067*
Acc. Diff. bin 8	−0.100**	0.053	−0.150***	0.071*
Acc. Diff. bin 9	−0.079	0.072**	−0.121**	0.113***
Acc. Diff. bin 10	−0.090*	0.047	−0.138**	0.084**
Acc. Diff. bin 11	−0.084	0.072*	−0.126**	0.085*
Acc. Diff. bin 12	−0.042	0.067*	−0.110*	0.091*
Acc. Diff. bin 13	−0.069	0.055	−0.116**	0.065
Acc. Diff. bin 14	−0.029	0.146***	−0.118**	0.108**
Acc. Diff. bin 15	−0.080	0.107**	−0.115**	0.093**
Acc. Diff. bin 16	−0.003	0.056	−0.102*	0.100*
Acc. Diff. bin 17	0.024	0.105*	−0.083	0.084
Acc. Diff. bin 18	0.005	0.055	−0.076	0.068
Acc. Diff. bin 19	0.003	0.084**	−0.143**	0.093
Acc. Diff. bin 20	−0.001	0.129**	−0.095	0.004
Acc. Diff. bin 21	0.010	0.035	−0.047	0.049
Acc. Diff. bin 22	−0.011	−0.0004	0.009	0.106*
Acc. Diff. bin 23	−0.112*	0.070	−0.033	0.155*
Acc. Diff. bin 24	−0.026	0.077	0.062	0.039
Acc. Diff. bin 25	0.018	0.042	−0.046	0.123***
Acc. Diff. bin 26	0.165*	0.076**	0.128	0.113
Acc. Diff. bin 27	0.004	0.093*	0.039	0.152*
Acc. Diff. bin 28	−0.024	0.052	0.035	0.155*
Acc. Diff. bin 29	−0.142	0.079**	−0.032	0.107
Acc. Diff. bin 30	0.040	0.180**	−0.156*	0.045
Fisc.Perf.Ind.	−0.001	0.002***	−0.002***	0.002***
Acc. Diff. bin 2:Fisc.Perf.Ind.	−0.001	−0.001**	0.001	−0.002***
Acc. Diff. bin 3:Fisc.Perf.Ind.	0.0002	−0.001**	0.001	−0.002***
Acc. Diff. bin 4:Fisc.Perf.Ind.	−0.001	−0.002***	0.002*	−0.002***
Acc. Diff. bin 5:Fisc.Perf.Ind.	0.0000	−0.002***	0.001	−0.002***
Acc. Diff. bin 6:Fisc.Perf.Ind.	0.001	−0.002***	0.001	−0.002***
Acc. Diff. bin 7:Fisc.Perf.Ind.	0.001	−0.002***	0.001	−0.002***
Acc. Diff. bin 8:Fisc.Perf.Ind.	0.001	−0.002***	0.001	−0.002***
Acc. Diff. bin 9:Fisc.Perf.Ind.	0.0002	−0.002***	0.001	−0.003***
Acc. Diff. bin 10:Fisc.Perf.Ind.	0.0004	−0.002***	0.001	−0.002***
Acc. Diff. bin 11:Fisc.Perf.Ind.	0.0003	−0.002***	0.001	−0.002***
Acc. Diff. bin 12:Fisc.Perf.Ind.	−0.001	−0.002***	0.001	−0.002***
Acc. Diff. bin 13:Fisc.Perf.Ind.	−0.0002	−0.002**	0.001	−0.002***
Acc. Diff. bin 14:Fisc.Perf.Ind.	−0.001	−0.004***	0.001	−0.003***
Acc. Diff. bin 15:Fisc.Perf.Ind.	0.0001	−0.003***	0.001	−0.003***
Acc. Diff. bin 16:Fisc.Perf.Ind.	−0.001	−0.002*	0.0005	−0.003***
Acc. Diff. bin 17:Fisc.Perf.Ind.	−0.002*	−0.003***	−0.0000	−0.002**
Acc. Diff. bin 18:Fisc.Perf.Ind.	−0.001	−0.002**	−0.0001	−0.002**
Acc. Diff. bin 19:Fisc.Perf.Ind.	−0.002	−0.002***	0.001	−0.003**
Acc. Diff. bin 20:Fisc.Perf.Ind.	−0.002	−0.003***	0.0003	−0.001
Acc. Diff. bin 21:Fisc.Perf.Ind.	−0.002	−0.002	−0.001	−0.002**
Acc. Diff. bin 22:Fisc.Perf.Ind.	−0.001	−0.001	−0.002	−0.003**
Acc. Diff. bin 23:Fisc.Perf.Ind.	0.0002	−0.002**	−0.001	−0.003**
Acc. Diff. bin 24:Fisc.Perf.Ind.	−0.001	−0.002**	−0.003**	−0.001
Acc. Diff. bin 25:Fisc.Perf.Ind.	−0.002	−0.001*	−0.001	−0.003***
Acc. Diff. bin 26:Fisc.Perf.Ind.	−0.005***	−0.002***	−0.004**	−0.002*
Acc. Diff. bin 27:Fisc.Perf.Ind.	−0.002	−0.003***	−0.002	−0.003**
Acc. Diff. bin 28:Fisc.Perf.Ind.	−0.001	−0.002***	−0.002	−0.004***
Acc. Diff. bin 29:Fisc.Perf.Ind.	0.001	−0.002***	−0.001	−0.003**
Acc. Diff. bin 30:Fisc.Perf.Ind.	−0.002	−0.004***	0.001	−0.002

Notes: *p<0.1; **p<0.05; ***p<0.01
All the regressions control for: Soils, Precipitation, Temperature, Slope, Elevation, Municipio and Year Effects

Table D.5: Effect of enforcement and access difficulty on deforestation - logit average marginal effects

	Random Sample		Grid Sample	
	Reserves	Not Protected	Reserves	Not Protected
Access difficulty linear	-0.574	0.547	-1.029**	1.513**
	(0.358)	(0.432)	(0.397)	(0.461)
Access difficulty squared	1.766	-3.149	4.529**	-8.717***
	(1.357)	(2.464)	(1.602)	(2.578)
Access difficulty cubic e	-1.157	3.913	-4.851**	11.25***
	(1.407)	(3.300)	(1.779)	(3.391)
Fiscal Performance Index	-0.00131*	0.00150***	-0.00205***	0.00196***
	(0.000518)	(0.000381)	(0.000539)	(0.000418)
Acc. dif.linear Interaction	0.00579	-0.0191*	0.0126	-0.0356***
	(0.00637)	(0.00765)	(0.00699)	(0.00822)
Acc. dif. squared Interaction	-0.0257	0.0805	-0.0702*	0.175***
	(0.0241)	(0.0438)	(0.0279)	(0.0464)
Acc. dif. cubic Interaction	0.0188	-0.0895	0.0790**	-0.214***
	(0.0250)	(0.0588)	(0.0306)	(0.0619)
Number of Conflicts	-0.00161***	-0.000496**	-0.00161***	-0.000536**
	(0.000281)	(0.000178)	(0.000309)	(0.000196)
Land Owner GINI	0.0832	-0.163*	0.140*	-0.208**
	(0.0533)	(0.0677)	(0.0590)	(0.0705)
Rural Population Density	0.00375***	0.00434***	0.00282**	0.00230***
	(0.000937)	(0.000731)	(0.000941)	(0.000694)
Dist. Municipio	-0.00114***	-0.00116***	-0.000795***	-0.000848***
	(0.000145)	(0.000169)	(0.000149)	(0.000183)
Dist. Principal Road	-0.000622***	-0.000594***	-0.000464**	-0.000571***
	(0.000151)	(0.000137)	(0.000156)	(0.000144)
N	59508	89093	51480	77417

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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