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Optimal protected area implementation under spillover effects

S. Schwartz*, J. Choumert†, J-L Combes‡, P. Combes-Motel§, E. Kere¶

Abstract

This paper determines the best implementation level of protected areas in the presence of two spillover effects, the infrastructure and scarcity effects. We show that decentralized regulation always leads to an overall decrease in deforestation under the infrastructure effect but not under the scarcity effect. Centralized regulation always leads to a larger protected area than decentralized regulation under the scarcity effect, which is not always true under the infrastructure effect. Finally, we conduct a case study of the Brazilian Legal Amazônia and find that spillover effects matter in the size of protected area design.

Keywords: Protected areas; deforestation; environmental federalism, Brazilian Legal Amazônia.

JEL classification: Q58, H77

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1 Introduction

Deforestation is the permanent destruction of forests for agricultural expansion, timber exploitation and urbanization. Tropical rainforests, which represent the largest proportion of the world's forests, are particularly under threat today. Between 2010 and 2020, they underwent the largest annual rates of net forest loss worldwide (FAO, 2020). Tropical forests provide ecosystem services. They host local benefits such as water recycling, soil erosion control, and provisioning services of forest products including timber and fruits and global environmental benefits such as carbon storage and biodiversity shelter (Sandler, 1993). Some global benefits from the forest are non-excludable and can, therefore, be seen as pure public goods, while some local benefits have the characteristics of local public goods (Chomitz & Kumari, 1998) or private goods when they generate excludable benefits. As tropical deforestation yields several market failures, there is a need for public intervention.

Different types of policies have aimed at curbing deforestation (see e.g., Angelsen 2010). Some policies target land rents by either downsizing agricultural rents or increasing protective forest rents. Neglecting infrastructures or generating alternative incomes outside the agricultural sector reduce agricultural rents. Protective forest rents are increased through the creation of institutions that implement, for example, community forest management or markets as payment for environmental services that enable land users to capture a larger share of the protective forest rent. Alternatively, some policies aim to limit forest conversion directly by establishing protected areas via a command-and-control policy. Deforestation is then forbidden, reducing to zero the agricultural rent on the forest plots.

This paper focuses on the strategy of protected areas. Forest protected areas recorded in IUCN categories 1 to 6 make up 13.5% of the world's forests (Schmitt et al. 2009), the share in rainforests being significantly higher (20.8%). More specifically, forest protected areas cover an estimated 726 million hectares worldwide. Forest in protected areas is mostly found in developing countries; South America has the largest proportion (31%), followed by Africa (27%) and Asia (25%), according to the latest FAO FRA (FAO, 2020).

Existing economic studies dedicated to terrestrial protected areas investigate whether protected areas effectively reduce deforestation. Abman (2018) shows that protected areas are most effective in countries with higher levels of corruption control and greater protection of property rights.¹ According to Bruner et al. (2001) and DeFries et al. (2005), protected areas are often located in remote areas where there is less pressure on forests. It is now widely acknowledged in the literature that not controlling for location bias could drastically overestimate the benefits of protected areas (Andam et al. 2008). According to

¹On this last point, Albers (2010) determines the optimal protected area enforcement under budget constraints.

Gaveau et al. (2009), protected areas reduced deforestation by 24% from 1990 to 2000 in Sumatra while a naïve (i.e., simple mean differences) comparison of protected areas and adjacent areas would have suggested that protected areas had reduced deforestation by 59%. For instance, Pfaff and al. (2016) analyze the impacts of Mexican protected areas on loss of natural land cover from 2000–2005 using matching to reduce location bias. They find that protected areas have reduced the loss of natural land cover by an average of 3%. Once established, deforestation activities might also shift from inside to outside protected areas and, therefore, generate spatial spillovers, namely deforestation leakages. Taking into account both location bias and spatial spillover effects, Amin et al. (2019) show that integral protected areas and indigenous lands allow for reducing deforestation in the Brazilian Legal Amazônia. For Para, Herrera and al. (2019) highlight spillover effects leading to increased deforestation of indigenous lands and decreased deforestation of federal protected areas. Therefore, the political level of protected area implementation seems to matter.

The aim of this article is to determine the best political level of protected area implementation when there are spillover effects present. We conduct our study from a theoretical point of view; thus, the results are not linked to a particular geographical context or period. Firstly, we deepen the spatial spillover effects between municipalities. Secondly, we analyze the optimal protected area implementation assuming different political levels: centralized or decentralized level. The objective is to give policy implications in terms of public economics on the optimal size of protected areas.

We consider two types of spatial spillover relating to the accessibility of the forest. By synthesizing the results of more than 140 economic models analyzing the causes of tropical deforestation, Angelsen and Kaimovitz (1999) note that greater access to forest accelerates deforestation.² Most studies show that forest clearing declines rapidly beyond distances of two or three kilometers from a road. The so-called "infrastructure effect" can be seen as a spillover effect, since the transport infrastructure put in place by the agent who deforests in one area can be used by others free of cost. Furthermore, deforestation occurs first in the most geographically accessible areas, i.e., where the slopes are the smallest. Therefore, agents begin by deforesting in the most accessible areas, thus reducing geographical accessibility to forest resources for others. The remaining forest is located on the areas that are least accessible. Thus, the so-called "scarcity effect" can also be considered as a spillover effect (Angelsen 2001). Both spillover effects modify deforestation costs differently: the scarcity effect raises costs (as it describes a lesser accessibility to the forest), whereas the infrastructure effect reduces costs (describing greater accessibility to the forest).

Considering that integral protected areas are enacted by different levels of government, we will consider two political levels of protected area implemen-

²See, among others, Ludeke et al. (1990) for Honduras, Nelson and Hellerstein (1997) for Mexico, Liu et al. (1993) for the Philippines, Mertens and Lambin (1997) for Cameroon, Chomitz and Gray (1996) for Belize, Sader and Joyce (1988) and Rosero-Bixby and Palloni (1998) for Costa Rica, Cropper et al. (2001) for North Thailand, and Pfaff et al. (2007) for Brazil.

tation. First, protected areas can be implemented by local authorities, such as municipalities (i.e., a decentralized level of regulation). As such, protected areas can be established in every municipality or only in some municipalities. Second, a state decision maker can implement protected areas in municipalities (i.e., a centralized level of regulation). The centralized or decentralized implementation of protected areas can be seen as a key aspect of their effectiveness. Using Oates' decentralization theorem, we can infer that a decentralized system will ultimately be more effective. However, Besley and Coate (2003) note that this may be not the case in the presence of spillover effects in the consumption of local public goods. In this article, we want to determine which policy level allows the forest to be better protected in the presence of spillover effects in the deforestation process. To our knowledge, this study is the first to address this topic.

Other assumptions of our model are the following. Deforestation occurs in the primary forest that spans different local jurisdictions, i.e., municipalities. Forest has several uses. It generates benefits for local populations that can be considered as local public goods and provides timber, which is a private good. We assume that timber is used in order to produce a final goods, leading to deforestation and, therefore, to environmental degradation. This leads the regulator to attempt to protect the forest by implementing a protected area.

We show that the optimal integral protected area size depends on the type of spillover effects present.³⁴ The implementation of a protected area in a single municipality reduce global deforestation under the infrastructure effect, but this result does not hold under the scarcity effect. Therefore, if a unilateral initiative to create a protected area always leads to less deforestation in one municipality, it may lead to more overall deforestation. Our study also highlights the fact that centralized regulation always leads to a larger protected area than decentralized regulation under the scarcity effect, while this is not always true under the infrastructure effect. Our results are important because they identify the political level of implementation that best protects the forest, and this depends, in turn, on the type of spillover effects present. We complete our analysis with a study of Brazil's protected areas, which shows that the size of protected areas does indeed depend on the type of spillover effects present.

The article is organized as follows. In Section 2, we present the assumptions of our model and the benchmark, i.e., the equilibrium of the economy in the absence of protected areas. Decentralized and centralized regulation are presented in Section 3. Section 4 details our results. In Section 5, we study protected areas in Brazil. A conclusion is given in Section 6.

³Using a spatial game-theoretic model Robinson and al. (2011) also establishes the optimal size of protected areas, which depends on ecological characteristics as well as rural welfare and the surrounding landscape. We contribute to this branch of the literature by taking into account spillover effects.

⁴We will focus on the size of the protected area for two reasons. Firstly, we assume no illegal deforestation, which enables us to associate the size of the protected area with its effectiveness in protecting the forest. Secondly, the theoretical setup does not consider other characteristics of the protected area that might affect firm compliance.

2 Assumptions and the benchmark

Companies cut down the forest to produce a private good. Since the forest provides a large range of local and global benefits, the amount of forest resources harvested by a company is potentially detrimental to the provision of other forest goods and services. Our theoretical setup is organized as follows. We first present the assumptions and then the benchmark, which is described as "laissez faire", i.e., a deforestation situation without any public intervention.

2.1 Assumptions

We consider two local jurisdictions (e.g., municipalities) i , $i = 1, 2$. In each municipality, we denote by T_i the forest cover before any regulation (with $T_i = T_{-i} = T$). The subscript $-i$ refers to the other municipality. We assume a representative consumer in each municipality. Her preferences are represented by the following quasi-linear utility function: $U(x_i, g_i, g_{-i}, M) = B(x_i) + \lambda[kJ(g_i) + (1 - k)(J(g_{-i}))] + M$, where x_i is the private good produced in municipality i sold at price p_i , g_i is a local public good whose quantity is measured by the forest cover and M is the residual revenue. Preferences for private goods and local public goods are respectively given by the increasing and concave functions $B(x_i)$ and $J(g_i)$. The parameter $k \in [1/2, 1]$ indexes the degree of free-riding in the consumption of local public goods: $k = 1$ means that citizens care only about forest in their own municipality while $k = 1/2$ means that they care equally about forest in both municipalities (Besley and Coate 2003). The higher k is, the more consumers confine themselves to enjoying the forest in the municipality they are living in. Put differently, a high value of the parameter k deters consumers from free-riding the forest in municipality $-i$. The parameter λ is a weight representing preferences for forest in general ($\lambda > 1$) and, so, for maintaining forest cover.

The quantity x_i of the final good is produced by a representative and competitive firm in municipality i . The production of one unit of goods requires a certain amount of wood. Assuming that the trees are evenly distributed in the forest, we can deduce the corresponding forest area. Thus we set the simplifying assumption that producing x_i units requires x_i units of forest cover and incurs costs $C_i(x_i, x_{-i})$ borne by the producing firm. This function is convex and the marginal cost of production in municipality i is given by C_{ix_i} , the derivative of the cost with respect to x_i , with $C_{ix_i} > 0$. We assume that the production cost of firm i depends on its production level (x_i) but also on the production level of the representative firm in municipality $-i$ (x_{-i}). We alternatively take into account the following assumptions $C_{ix_{-i}} < 0$ and $C_{ix_i x_{-i}} < 0$ or $C_{ix_{-i}} > 0$ and $C_{ix_i x_{-i}} > 0$ in order to represent the spillover effects in the production field between municipalities. We assume that the cost of production and the marginal cost of production of a firm in a municipality depends positively or negatively on the production level in another municipality. If the production level increases in municipality $-i$, forest becomes more accessible and the production costs in i diminish, representing hereafter the "infrastructure" effect. Conversely, if

forest becomes less accessible due to deforestation in another municipality, the cost of production will increase in municipality i , giving the "scarcity effect".⁵

2.2 The benchmark

The benchmark comes from the market equilibrium in each municipality in the absence of regulation, i.e., without a policy to fight against deforestation. We first derive the demand for the private good. The representative consumer chooses the private good quantity by maximizing her utility. If R is the revenue before any spending, we have $M = R - p_i x_i$. Thus, we obtain:

$$\text{Max}_{x_i} U(x_i, g_i, g_{-i}) = B(x_i) + \lambda[kJ(g_i) + (1 - k)(J(g_{-i}))] + R - p_i x_i$$

The first-order condition is:

$$B'(x_i) = p_i \tag{1}$$

From Equation (1), the private good quantity is such that the marginal benefit from consumption is equal to price of the good. This equation gives us the inverse demand function. The representative firm maximizes its profit, *i.e.*:

$$\text{Max}_{x_i} \pi_i(x_i, x_{-i}) = p_i x_i - C_i(x_i, x_{-i})$$

The first-order condition gives:

$$p_i - C_{ix_i}(x_i, x_{-i}) = 0 \tag{2}$$

From (1) and (2), the market equilibrium condition is given by:

$$B'(x_i) - C_{ix_i}(x_i, x_{-i}) = 0 \quad \forall i = 1, 2 \tag{3}$$

From (3), we observe that the quantity produced in one municipality depends on the quantity produced in the other municipality: $x_i(x_{-i})$. The infrastructure effect or the scarcity effect imply that this economy is characterized by spillover effects in the production field given by cost externalities. Thus, this equilibrium with cost externalities is obtained by the resolution of the system given by both best-reply functions. Hence the size of the forest without public intervention is $g_i^\circ = T - x_i^\circ \quad \forall i = 1, 2$.

Applying the Implicit Function Theorem on Equation (3) shows that the nature of the strategic interaction between the production and deforestation levels depends on the cost function. We have $\frac{dx_i}{dx_{-i}} > 0$ if $C_{ix_i x_{-i}}(x_i, x_{-i}) < 0$. Under the infrastructure effect deforestation in i increases if the level of production increases in $-i$. However, we obtain $\frac{dx_i}{dx_{-i}} < 0$ if $C_{ix_i x_{-i}}(x_i, x_{-i}) > 0$: the

⁵Our modelling choice differs from that of Angelsen (2001), who analyzes the deforestation process with a "game" between the state and a local community seeking to appropriate tropical forestland. He sets a marginal cost to expand available land, which depends on the total forest and the land appropriated by the state. As the state provides infrastructure, this marginal cost diminishes with state land appropriation (corresponding to the infrastructure effect) and with forest cover as new land is more easily available (the scarcity effect).

scarcity effect decreases deforestation in i if the level of production increases in $-i$. Hence the levels of deforestation and production are strategic complements under the infrastructure effect and strategic substitutes under the scarcity effect.

Several market imperfections prevent this economy from reaching the optimum level. When the consumer defines her demand function for the private good, she does not account for the deforestation induced by her consumption. Second, as defined above, the infrastructure and scarcity effects generate cost interdependencies and, third, the forests have characteristics that provide local public goods for consumers.

3 Regulation: decentralized and centralized

In this section, we introduce a third actor namely, the regulator, whose objective is to protect the forest to secure the other benefits derived from it. She enacts forest protections while determining the optimal area of forest and implementing it through a protected area. One crucial aspect of the local regulator's action, as opposed to that of a regulator at the state level, is that she can only operate within the geographical and or legal framework of her jurisdiction. For the sake of simplicity, the jurisdiction will hereafter be referred to as the "municipality". In the following, we also assume perfect information and that property rights are well defined and secured, such that there is no illegal deforestation. We will first determine the protected area size under decentralized regulation, then under centralized regulation. The optimal size of protected areas will crucially depend on two features: first, the political implementation level (decentralized or centralized level) and second, the type of spillover effects present in the production field (the scarcity or the infrastructure effect).

3.1 Decentralized regulation

A regulator in one municipality decides to protect the forest and, therefore, to tackle deforestation induced environmental degradation: she chooses to implement an "integral" protected area whereby any economic activity such as clearing the forest for production purposes is strictly forbidden.⁶ The regulator maximizes the welfare in her municipality while choosing the optimal amount of the private good x_i . Taking into account $g_i = T_i - x_i$, the problem solved by the regulator is written as:

$$\text{Max}_{x_i} W^d(x_i, x_{-i}) = [B(x_i) - C_i(x_i, x_{-i})] + \lambda[kJ(T - x_i) + (1 - k)J(T - x_{-i})]$$

The first-order condition is:

$$B'(x_i) - C_{ix_i}(x_i, x_{-i}) - k\lambda J'(T - x_i) = 0 \quad (4)$$

⁶In order to focus our analysis on spillover effects, we do not take into account sustainable protected areas, in which some deforestation activity is possible. However, Pfaff and al. (2014) empirically show that, in the State of Acre, in the Brazilian Amazon, sustainable protected areas prevent more deforestation than integral protection does, because these sustainable areas are closer to clearing threats.

By consuming the good in quantity x_i , the consumer indirectly contributes to deforestation. His utility is then reduced by $k\lambda J'(T - x_i)$. The consumption of good i generates a negative externality. Compared to Equation (3) the regulator internalizes the negative externality from consumption taking into account the third term in (4), thereby reducing the level of production x_i .

As the optimal level of private goods in municipality i depends on the quantity produced in municipality $-i$, we also find best-reply functions. Applying the Implicit Function Theorem on (4) shows that the quantity x_i also increases with x_{-i} if $C_{ix_ix_{-i}}(x_i, x_{-i}) < 0$ or decreases with x_{-i} if $C_{ix_ix_{-i}}(x_i, x_{-i}) > 0$, and decreases with preferences with nature (λ) and the parameter of free riding in the utility field (k).

The equilibrium depends on the behavior of the regulator in the other municipality. The regulator in municipality $-i$ can either regulate logging activities or opt for a “laissez-faire” situation. We assume that both regulators take their decision simultaneously.

The symmetric equilibrium If each municipality implements a protected area, the resolution of Equation (4) for $i = 1, 2$ gives a symmetric equilibrium. The quantities of private goods in each municipality are given by x^s (the superscript meaning “symmetric”) and the optimal size of the protected area (AP) is $AP^s = g^s = T - x^s$.

The asymmetric equilibrium If municipality 1 chooses to fight against deforestation while municipality 2 does not, we find an asymmetric equilibrium (x_1^a, x_2^a) from best-reply functions given by Equations (4) and (3), the superscripts meaning “asymmetric”. The optimal size of the protected area is $AP_1^a = g_1^a = T - x_1^a$ and the forest cover in municipality 2 is $g_2^a = T - x_2^a$.

3.2 Centralized regulation

Decentralized regulation that is implemented in each municipality internalizes the negative consumption externality. It cannot, however, internalize the free riding in the consumption of local public goods and the spillover effect in the production field. The free riding effect arises from consumers’ preferences for forest that is a local public good and is represented by the parameter k . The spillover effect comes from the production cost interdependencies that give rise to either an infrastructure or a scarcity effect. Hence, the equilibrium described in the preceding section cannot be optimal.

A higher level of government, such as the national government has the capacity to address these three types of externality (the negative consumption externality, the free riding and the spillover effect) and acts as a “central regulator”. This higher government level will be denoted the “central regulator” hereafter. The central regulator establishes the size of protected areas in each municipality, in an attempt to maximize the overall welfare, which is composed

of the sum of the welfare of both municipalities:

$$\text{Max } W^c(x_i, x_{-i}) = \sum_{i=1}^2 [B(x_i) - C_i(x_i, x_{-i})] + \lambda[J(T - x_i) + J(T - x_{-i})]$$

The first-order conditions are the following:

$$B'(x_i) - \underbrace{[C_{ix_i}(x_i, x_{-i}) + C_{-ix_i}(x_i, x_{-i})]}_{\text{Global cost effect}} - \lambda J'(T - x_i) = 0, \quad i = 1, 2 \quad (5)$$

Solving both equations given by (5) gives the cooperative equilibrium denoted by (x_c, x_c) , the superscript c meaning "cooperative". All externalities are internalized. The negative consumption externality is taken into account as under the decentralized regulation. Moreover, the centralized equilibrium internalizes the free riding effect since the levels of production no longer depend on k . It is worth noting that a "global cost effect" given by the second and third term of Equation (5) substitutes for the marginal production cost C_{ix_i} . Hence, only a central regulator can internalize the three types of imperfections in this type of economy. However, this does mean that a centralized equilibrium will always lead to a larger protected area than a decentralized one.

4 Cost functions

We investigate the effect of the production cost function on the protected area size and the overall level of deforestation. We begin by examining how the scarcity and infrastructure effects affect the production of the private good. We establish that under the scarcity effect, produced quantities of the private good in municipalities i and $-i$ are strategic substitutes, while under the infrastructure effect, they are complements. We then compare the provision of the protected area under centralized, decentralized and laissez-faire situations.

4.1 The scarcity effect

The scarcity effect prevails when the cost of production in i increases with deforestation in $-i$, i.e. $C_{ix_{-i}} > 0$ and $C_{ix_ix_{-i}}(x_i, x_{-i}) > 0$. The scarcity effect arises when further encroaching on the forest is difficult, making clearing more difficult and costly. Further cutting the drilling reduces the availability of drilling for other firms, which increases their cost of deforestation. The scarcity effect therefore represents a negative externality in the production field. From (3) and (4), we found $\frac{dx_i}{dx_{-i}} < 0$ in each case. The best-reply functions decrease. Thus, produced quantities in Municipalities i and $-i$ are strategic substitutes. If the production level increases in i , the production cost increases in $-i$ and its production level diminishes.

We want to understand how the scarcity effect plays out when a protected area is implemented. This implies studying a protected area's impact on the municipal or national levels of deforestation. We place on Graph 1 best-reply

functions which are obtained in each situation from Equations (3), (4) and (5). They all decrease and can be ranked: the best-reply function of municipality 1 without regulation ($R1$) is higher than its best reply function with decentralized regulation ($R1AP$), which is itself higher than under centralized regulation ($R1c$). The same holds applies for best-reply functions in municipality 2. If both municipalities do not set a protected area, the equilibrium (x°, x°) is obtained by the intersection of $R1$ and $R2$. The equilibrium (xs, xs) sums up the case where both municipalities implement a protected area, obtained by the intersection of $R1AP$ and $R2AP$, and (xc, xc) gives the results of the centralized equilibrium. As municipalities are identical and take the same decision, these three equilibria are symmetrical and located on the first bisecting line.

Graph 1: Equilibria under the scarcity effect

The following result is straightforward:

$$xc < xs < x^\circ.$$

Establishing a protected area always reduces deforestation, but the forest is better protected by centralized than by decentralized regulation.

If each municipal regulator establishes a protected area, they take into account solely the negative consumption externality. Hence, the production levels are lower than in a "laissez faire" situation. If the central regulator sets a protected area in each municipality, she also takes into account both the free riding and the global cost effects (Equation 5). On the one hand, we know that establishing a protected area in municipality i leads to a decrease in the production costs in municipality $-i$. Reducing the "global cost effect" is possible when both production levels also decrease. On the other hand, since the centralized regulator considers the forest as a whole, the free riding effect disappears, enabling further reduction in deforestation. In short, centralized regulation always better protects the forest compared to the decentralized symmetric equilibrium because the three externalities (consumption externality, free-riding and cost interdependency) always work in the same direction, i.e., they reduce the production level.

Let us now consider the case where a protected area is implemented only in municipality 1. Establishing a protected area only in municipality 1 leads to a decrease in the production costs in municipality 2. Hence the firm located in this municipality can increase its production level with respect to the unconstrained production level (the quantity produced without regulation). This situation is depicted on Graph 1. Departing from the "laissez faire" situation (x°, x°) , if municipality 1 implements a protected area and municipality 2 does not, the best-reply function $R1$ shifts downwards and becomes $R1AP$. The new equilibrium moves along the orange curve in $R2$, as indicated by the arrow in Graph 1. Thus, x_1 diminishes, whereas x_2 increases with respect to the equilibrium of production without protected areas. We have:

$$\begin{aligned} x_1^a &< x_2^a, \\ \text{with } x_1^a &< x^\circ \text{ and } x_2^a > x^\circ. \end{aligned}$$

Now let's depart from the symmetric equilibrium with decentralized protected areas (xs, xs). If municipality 2 does not implement a protected area, its best-reply function shifts upright and moves from $R2AP$ to $R2$. The new equilibrium moves along the green curve in $R1AP$, as indicated by the arrow in Graph 1. As the cost in municipality 1 increases, its production level decreases whereas the cost in municipality 2 decreases and so its production level increases. Thus, we have:

$$x_1^a < xs \text{ and } x_2^a > xs.$$

We finally obtain the following results as far as production levels are concerned:

$$\begin{aligned} x_1^a &< xs < x^\circ, \\ xs &< x^\circ < x_2^a. \end{aligned}$$

From these results, we can infer consequences related to global deforestation:

$$\sum_{i=1}^2 g_i^c > \sum_{i=1}^2 g_i^s > \sum_{i=1}^2 g_i^\circ.$$

The implementation of centralized protected areas allows for the best possible protection of the forest. However, this issue is crucial with regard to the asymmetric equilibrium. Establishing a protected area only in municipality 1 leads to an increase of deforestation in municipality 2. The net effect depends on the cost interdependency magnitude. Hence, the decentralized asymmetric implementation of a protected area has an ambiguous effect on national deforestation:

$$\sum_{i=1}^2 g_i^a \leq \sum_{i=1}^2 g_i^\circ.$$

Thus, careful attention needs to be paid to the cost function, i.e. the scarcity effect.

4.2 The infrastructure effect

When a firm chooses to deforest a plot of land, it may have to put roads or communication routes in place. Such communication infrastructure generates cost-saving effects that benefit other productive firms. The infrastructure effect therefore represents a positive externality in the production field. We model this effect as the infrastructure effect that is channeled by the cost production function while assuming that the production cost and the marginal cost of production decrease with production in other municipalities, i.e. $C_{ix-i} < 0$ and $C_{ix_ix-i}(x_i, x_{-i}) < 0$. From (3), (4), we find $\frac{dx_i}{dx_{-i}} > 0$ in each case. The best-reply functions increase. Thus, produced quantities in municipality i and $-i$ are strategic complements. If the production level increases in i , the production cost decreases in $-i$ leading to an increase in $-i$'s level of production.

As with the scarcity effect, we want to understand the impact on deforestation from protected area implementation when the infrastructure effect dominates. We proceed in the same way as in the previous section and use the same notation. As Equations (3) and (4) can be ranked, we plot the best-reply functions on Graph 2. The intersection of $R1$ and $R2$ gives the equilibria without a protected area (x°, x°) , and the intersection of $R1AP$ and $R2AP$ gives the equilibrium with decentralized protected areas (xs, xs) . As they are symmetric, they are located on the first bisecting line.

Graph 2: Equilibria under the infrastructure effect

If regulators in both municipalities implement protected areas, they internalize the negative externality coming from consumption. Thus, the best-reply function in municipality 1 moves to the left from $R1$ to $R1AP$ and the best-reply function in municipality 2 moves downwards from $R2$ to $R2AP$. We deduce the following:

$$xs < x^\circ.$$

If protected areas are implemented in each municipality, production levels decrease.

Let us analyze now a scenario where only one municipality (e.g., municipality 1) regulates logging. In this case, municipality 1's best-reply function moves to the left (from $R1$ to $R1AP$) but the best-reply function ($R2$) in municipality 2 does not change. Departing from the symmetric equilibrium in the absence of protected areas (x°, x°) , the new equilibrium moves along the $R2$ curve as indicated by the arrow and we obtain:

$$x^\circ > x_i^a \quad \forall i = 1, 2.$$

Under the infrastructure effect, establishing a protected area only in municipality 1 leads to an increase of the production costs in municipality 2. Hence the firm located in municipality 2 bears the cost effect and has to decrease its production level.

Now let's depart from the symmetric equilibrium with decentralized protected areas (xs, xs) . If municipality 2 does not implement a protected area, its best-reply function shift uprights (from $R2AP$ to $R2$), whereas the best-reply function in municipality 1 does not change. Thus, the asymmetric equilibrium moves along $R1AP$, as the arrow in Graph 2 shows. We find:

$$xs < x_i^a \quad \forall i = 1, 2.$$

If municipality 2 does not regulate logging, its production level increases, which reduces production costs in municipality 1. Hence, production levels in each municipality increase. Finally, we find:

$$xs < x_i^a < x^\circ \quad \forall i = 1, 2.$$

Quantities of the produced goods under the asymmetric equilibrium are higher than quantities at the symmetric equilibrium in both municipalities but lower than the "laissez faire" quantities. As far as forest protection is concerned, we have:

$$\sum_{i=1}^2 g_i^s > \sum_{i=1}^2 g_i^a > \sum_{i=1}^2 g_i^o.$$

If forest is best preserved when all municipalities implement a protected area, it appears that establishing a protected area only in one municipality leads to preserving forest in another municipality although this municipality does not regulate. Hence, asymmetric decentralized regulation is better than no regulation at all for forest preservation whatever the magnitude of the infrastructure cost effect.

However, these non-cooperative equilibria are not optimal because they neither take into account the free riding or cost interdependency whereas, the cooperative equilibrium takes into account all these effects. The negative consumption externality and the free ridding effect lead to a decrease in the level of production (as under the scarcity effect) contrary to the cost interdependency effect. Under the infrastructure effect, the production in one municipality reduces the cost of production in the other municipality. A way to reduce the global cost is to increase levels of production, and thus to reduce the size of protected areas. Hence, if the negative consumption externality and the free-riding effects are greater than the cost-interdependency effect, the centralized equilibrium will protect more forest than the decentralized symmetric equilibrium. In contrast, if the cost-interdependency effect is large enough, the amount of protected area at the centralized equilibrium will be smaller than at the decentralized symmetric equilibrium. Contrary to conventional wisdom, centralized regulation may not deliver the best results in terms of forest conservation.

Under the infrastructure effect, the centralized equilibrium may coincidentally correspond to the decentralized equilibrium. In this case, the optimal allocation can be achieved without cooperation. This point is interesting because it is difficult to obtain cooperation in the real world.

4.3 Results

In this section, we compare the results obtained under the scarcity and infrastructure effects. Producing in a given municipality when the infrastructure effect dominates leads to increased production in neighboring municipalities. If the scarcity effect dominates, production in neighboring municipalities decreases. Therefore, output under the infrastructure effect is expected to be higher than under the scarcity effect when other characteristics of the economy are equal. Our results are summed up in the following propositions :

Proposition 1 *As far as total deforestation is concerned, asymmetric regulation is better than no regulation under the infrastructure effect but not necessarily in the presence of the scarcity effect.*

Proposition 2 *A centralized policy does not always work more in favor of a larger protected area than a decentralized policy does under the infrastructure effect, contrary to under the scarcity effect.*

Proposition 3 *The infrastructure effect always leads to a smaller protected area than the scarcity effect.*

Corollary 4 *The infrastructure effect always leads to more deforestation than the scarcity effect.*

Proposition 5 *Under the infrastructure effect, the decentralized equilibrium can reach the first best equilibrium.*

A local regulator can help reduce deforestation even if he acts alone, provided that the spillover effect is the infrastructure effect. Under the scarcity effect, a well-intentioned local regulator could ultimately cause an increase in overall deforestation. On the other hand, if socially optimal level of drilling is achieved under centralized regulation, it does not necessarily correspond to better protection of the forest.

5 A case study: The Brazilian Legal Amazônia

We showed that both the scarcity and infrastructure effects matter in the protected area size to fight against deforestation. However, these effects pass through the cost function, and the cost function is private information for firms. We conduct a case study of the Brazilian Legal Amazônia in order to see whether or not the size of protected areas depends on spillover effects.

Deforestation in the Brazilian Legal Amazônia has been greatly studied in the literature because of the extent of the phenomenon and its adverse effects on biodiversity and the ecological system of the region and climate. Deforestation in the Brazilian Legal Amazônia rainforest declined from 54,534 square kilometers in 2001 to 27,136 square kilometers in 2004 and to about 5,800 square kilometers in 2014 according to INPE (National Institute for Space Research). This decline of deforestation in Brazil is explained not only by the 2008-2009 financial crisis (Nepstad et al. 2009) but especially by the hardening of conservation policies (Assunção et al. 2012; Hargrave and Kis-Katos 2012; Nolte et al. 2013; Palmer and Di Falco 2012 among others).

These policies have consisted mainly in the establishment of protected areas, monitoring of deforestation and hardening legislation via the Action Plan for the Prevention and Control of Deforestation in the Legal Amazônia (Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal , PPC-DAm). Protected areas represented 42% of the area of the Brazilian Amazônia in 2009, about 2 million square kilometers.⁷

⁷In spite of this law, we can observe a recent rise of deforestation. Some protected areas have been made smaller or have been degazetted entirely, notably in the Amazon. In such cases, we can surmise that economic benefits take precedence over the effects of safeguarding

Graph 3: Evolution of protected areas and deforestation in the Brazilian Legal Amazon in square kilometers.

Source : INPE, authors' calculations.

Note that protected areas are from federal and state entities but indigenous lands are not included.

With the passing of Law No. 9.985 of 18 July 2000, Brazil created a formal, unified system for federal, state and municipal parks, that classified protected areas into three categories: integral protection areas, sustainable use areas, and indigenous lands. Integral areas are defined as fully protected areas. They are intended to maintain the natural ecosystem without human interference and can be classified in the most restrictive categories of the International Union for Conservation of Nature (IUCN) classification (Categories I, II and III). In 2009, they accounted for 19% of the country's protected land areas. Sustainable use areas, which represented 32% of the protected land area in 2009, aim for the sustainable use of renewable environmental resources and maintain biodiversity and other ecological attributes. These sustainable use areas are equivalent to categories IV, V, and VI of the IUCN classification. Indigenous lands are lands traditionally occupied by indigenous peoples. The Brazilian constitution recognizes their inalienable rights to live on and take permanent possession of these lands after a formal process of demarcation. Indigenous lands are devoted to the protection of the living space of indigenous peoples.⁸

To conduct our study, we use data from the PRODES System of the Instituto Nacional de Pesquisa Espacial-INPE on forest cover and protected areas in the Brazilian Legal Amazônia for the period 2001-2009. We aggregate the municipal data into the 248 Minimum Comparable Areas (MCAs) located in the Brazilian Legal Amazônia.⁹ Where the forest is very large, we can assume that it can be accessed through the provision of infrastructure, so the most accessible forest is cut first. We can also assume, then, that when deforestation increases, the least accessible areas will remain. Thus, we assume that the scarcity effect is likely to prevail in MCAs of which remaining forested lands represent the smallest share of their total land area. Following Angelsen (2001), we consider that the infrastructure effect decreases relative to the scarcity effect as deforestation increases.

We rank MCAs into four quartiles of forested areas. The first quartile is composed of MCAs where the forested areas represent less than 5.2% of the MCA land area; the second quartile corresponds to MCAs where the forested

the forest. As Naughton-Treves and Buck Holland (2019) note, this illustrates the gap between official rules and actual management. An interesting future analysis would be to compare the optimal level of protection of a protected area with its actual area, in order to examine to what extent political decisions deviate from optimal decisions. These fundamental political economy considerations are outside the scope of this article.

⁸In this case study, we do not take into account indigenous lands because they were mostly created before the period 2001-2009. Moreover, the aim of indigenous lands is different than that of integral or sustainable protected areas.

⁹Using MCA data allows for comparison (the number and size of municipalities may change over time). The list of MCAs is available from the Brazilian Institute of Applied Economic Research (IPEA - Instituto de Pesquisa Econômica Aplicada).

areas represent between 5.2% and 25.4% of the MCA land area, while the third quartile's forested areas make up between 25.4% and 61.8% of the MCA land area. The fourth quartile is composed of the forest-richest MCAs, where forested areas represent more than 61.8% of the total land area. We therefore assume that the scarcity effect is more likely in the MCAs ranked in the first quartile and that the infrastructure effect prevails in the MCAs in the fourth quartile.

Graph 4: Percent of protected area in terms of forest area by forest area quartile. *Source: INPE, authors' calculations.*

Graph 4 plots on the vertical axis the proportion of protected areas in the remaining stock of forest according to quartiles of MCA forested areas. It also makes a distinction between integral and sustainable protected areas. For instance, sustainable and integral protected areas amount to 47.1 % and 47.3% of the forested areas, respectively. We can observe that protected areas are not uniformly represented in the different quartiles, whatever their types. The number of sustainable protected areas are still higher in the first quartile than in the three others, while integral protected areas are relatively higher in the first two quartiles. In line with our assumptions, Graph 4 shows that protected areas represent a larger share of the forested lands under the scarcity effect than under the infrastructure effect. Therefore, it would appear that spillover effects matter in the establishment of protected areas in Brazil. This feature seems to corroborate our Proposition 3, according to which the infrastructure effect leads to smaller protected areas than the scarcity effect. It is true regardless of the type of protected area (integral or sustainable protected area). Furthermore, Graph 5 shows that the amount of deforestation decreases when the scarcity effect prevails, which is consistent with Corollary 4.

Graph 5: Average surface cleared (deforestation) by forest area quartile. *Source: INPE, authors' calculations.*

To properly test our theoretical model, all protected areas should have the same type of governance. For instance, integral protected areas should all be governed at the municipal level while sustainable use protected areas at the state or federal level. The issue is that the Ministry of Environment reports that management decisions of sustainable use or integral protected areas originate from different levels of governance.¹⁰

6 Concluding remarks

In this article, we highlighted the mechanism leading to the implementation of optimal terrestrial protected areas. We set up an economy composed of two municipalities affected by three kinds of externalities: a negative consumption externality, local public goods and production cost interdependency between

¹⁰We are very grateful to one of the reviewers for this very useful clarification.

firms. The cost interdependence stems from two well-identified effects in the deforestation literature: namely, the scarcity and infrastructure effects. Our theoretical framework also allows us to compare a decentralized and centralized process of implementing protected areas and to identify the best political implementation level of protected areas under spillover effects.

We theoretically establish that the provision of forest protection through protected areas depends on consumer preferences, on free riding stemming from the consumption of local public goods and on the nature of production costs. In an economy where the infrastructure effect dominates, implementing a protected area unilaterally in one municipality leads to a decrease in total deforestation. Hence, for forest preservation, asymmetric regulation is better than no regulation. This result does not necessarily hold for the scarcity effect, in the presence of which an increase in total deforestation following the establishment of a single-sided protected area may occur.

Our results also show that though centralized regulation achieves the first-best situation, it does not always coincide with forest preservation. Again, production costs come into play. Under the scarcity effect, centralized regulation always leads to a larger protected area than decentralized regulation, which is not always true under the infrastructure effect. Finally, it appears that whatever the considered case (centralized or decentralized regulation), the infrastructure effect leads to smaller protected areas than does the scarcity effect. Taking the particular case of the Brazilian Legal Amazônia shows that spillover effects seem to matter and should, therefore, be accounted for in the assessment of protected areas.

This article provides answers to questions that the regulator may have when designing anti-deforestation initiatives. First, does the establishment of a protected area always lead to a reduction in overall deforestation? Second, taking into account the different levels of government raises the question of the suitable level of regulation for curbing deforestation. We show that the answer to these questions is not straightforward, while putting emphasis on the role of spillover effects. Before implementing a protected area, the regulator must therefore ascertain what effect is greater, the scarcity or infrastructure effect. If the aim of the regulator is to protect the forest, under the scarcity effect, implementing a protected area on its own may lead to further deforestation than not implementing any protected areas. Under the infrastructure effect, centralized implementation of protected areas may lead to more deforestation than decentralized implementation. It is also important to note that centralized regulation is not always possible since it requires cooperation between regulators beforehand.

Of course, the results established in this paper hold under specific assumptions. We assumed access to perfect information. We know that in the real world regulators do not have complete information about production costs. Also, to designate the right level of implementation of a protected area, the regulator will need to conduct empirical analyses to assess what spillover effects prevail in their jurisdiction. Perfect information is also crucial when it comes to evaluating the benefits of forests. We also considered well-defined and secure property

rights and no enforcement costs. These assumptions are questionable in the real world, particularly in a country with weak institutions. We also assumed two symmetrical municipalities for ease of analysis. Finally, we did not take into account political economy arguments in the decision to set up a protected area. These different points could constitute avenues for future research.

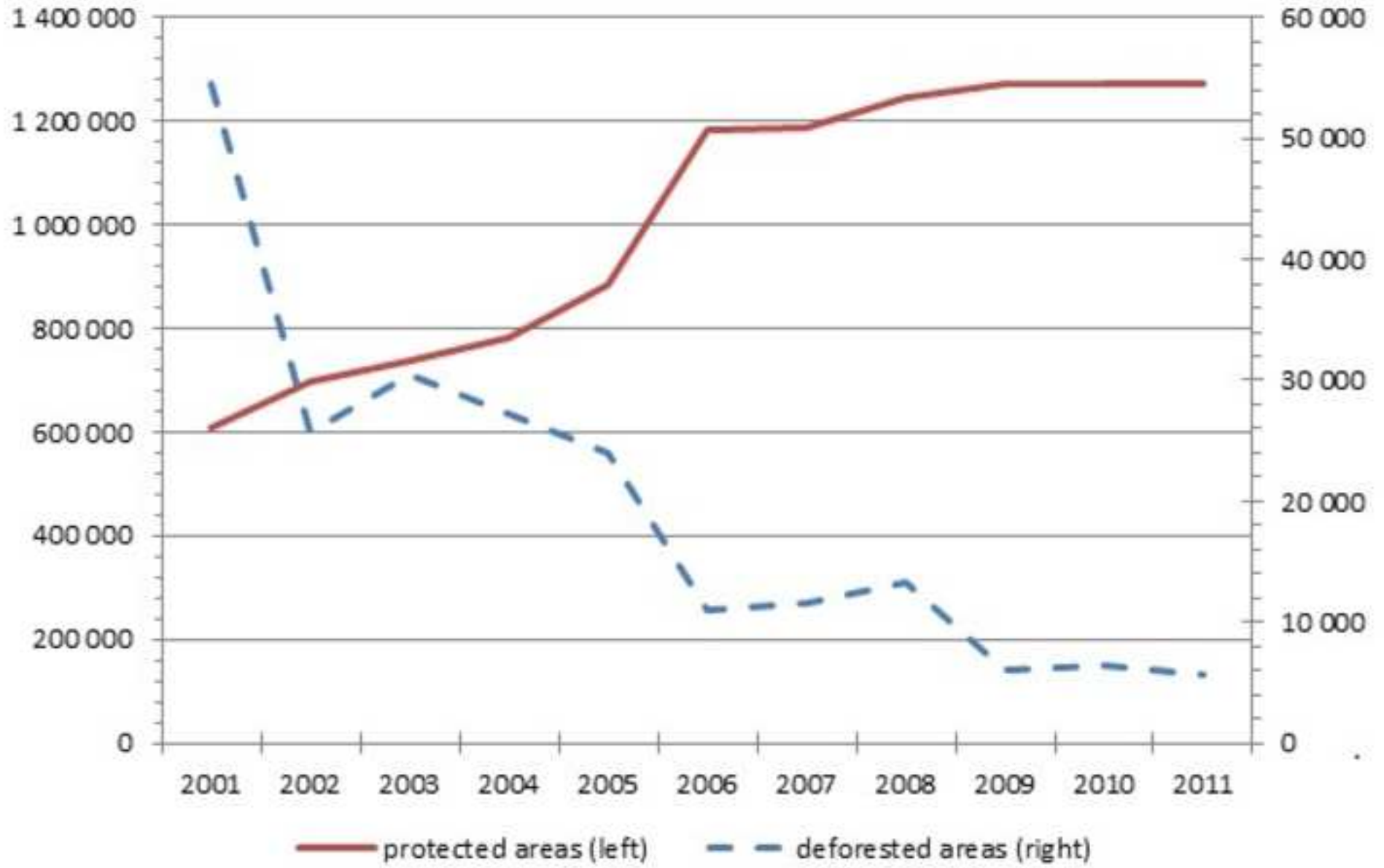
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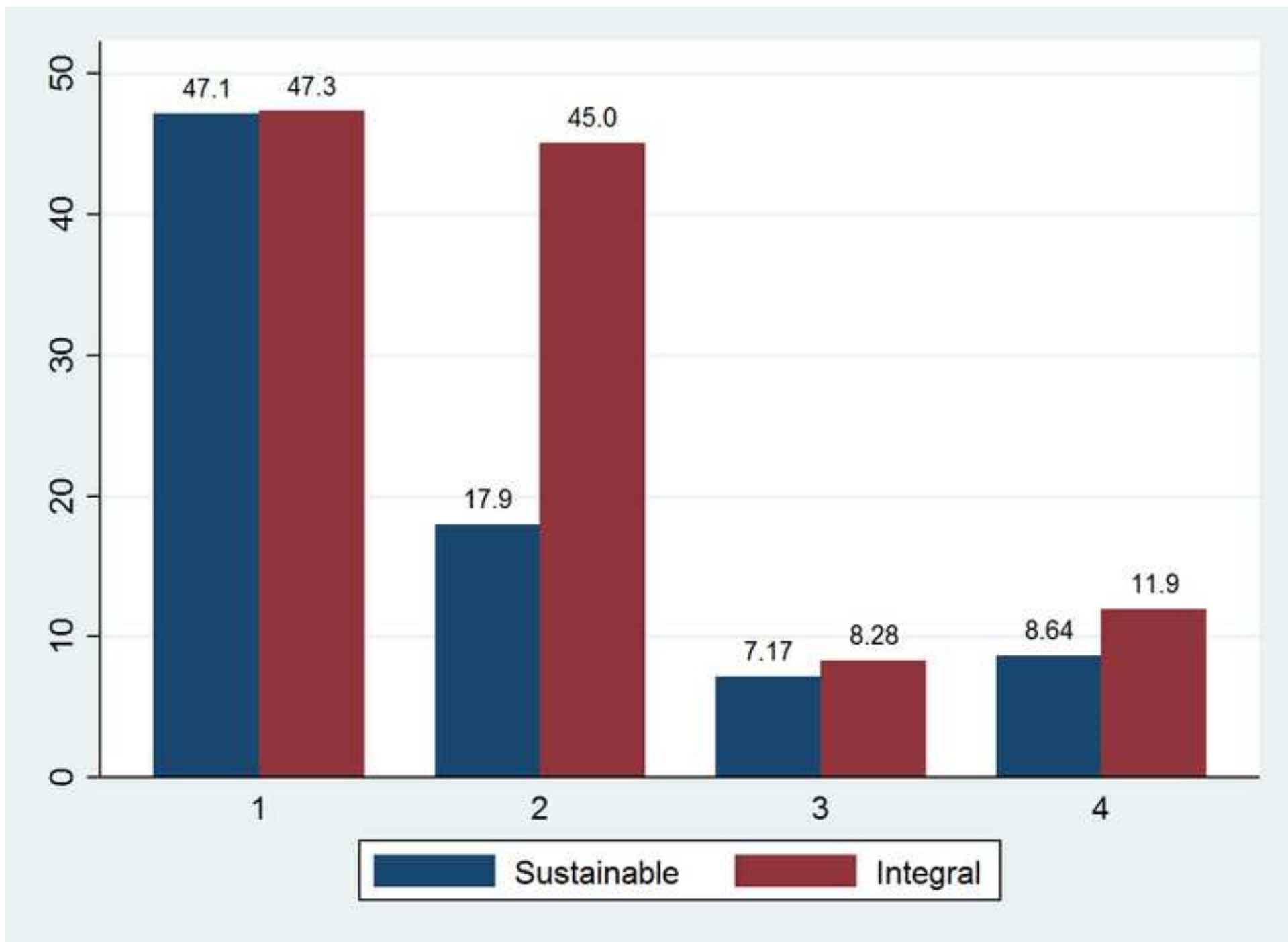
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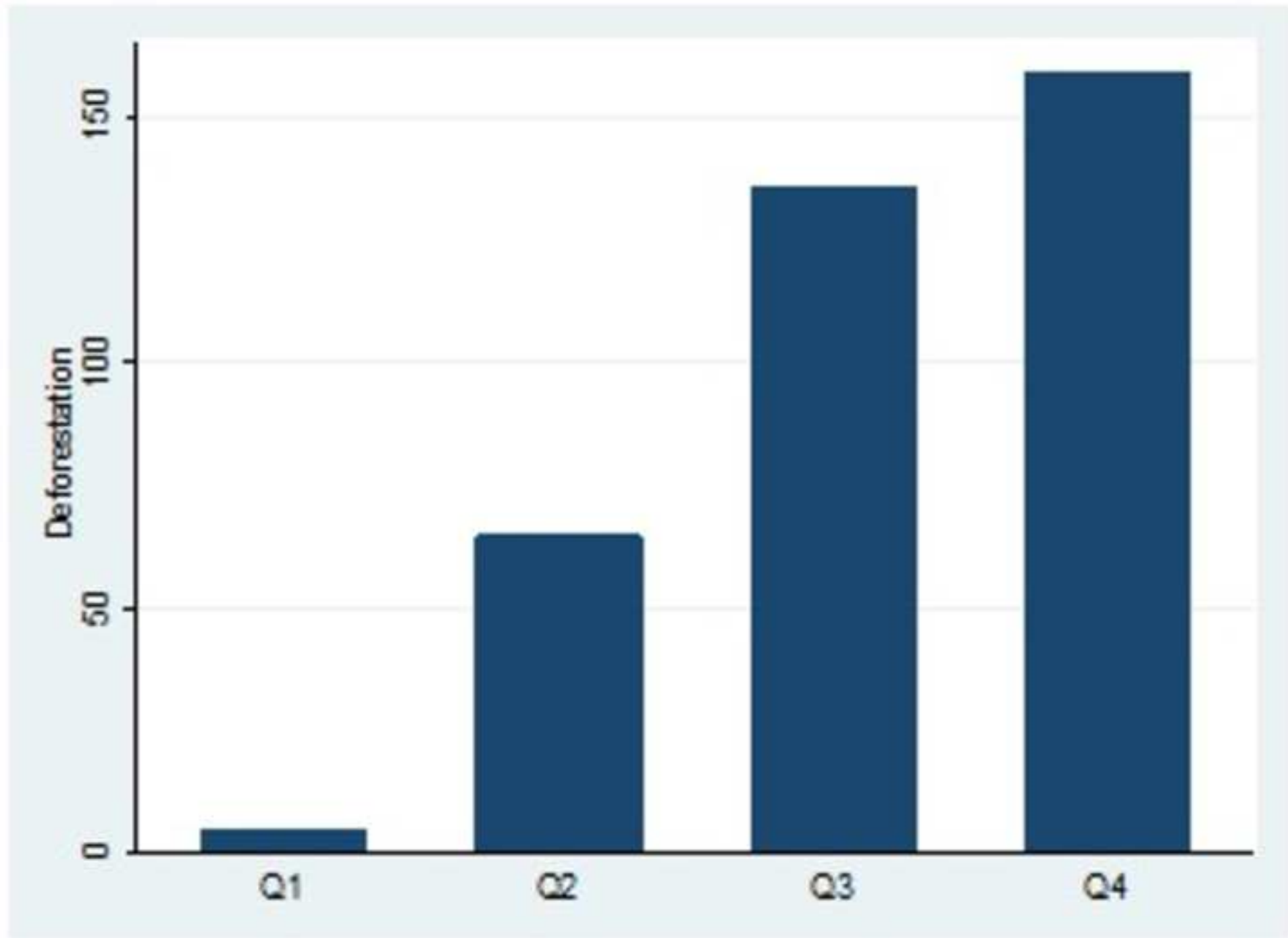


Figure 1

The scarcity effect

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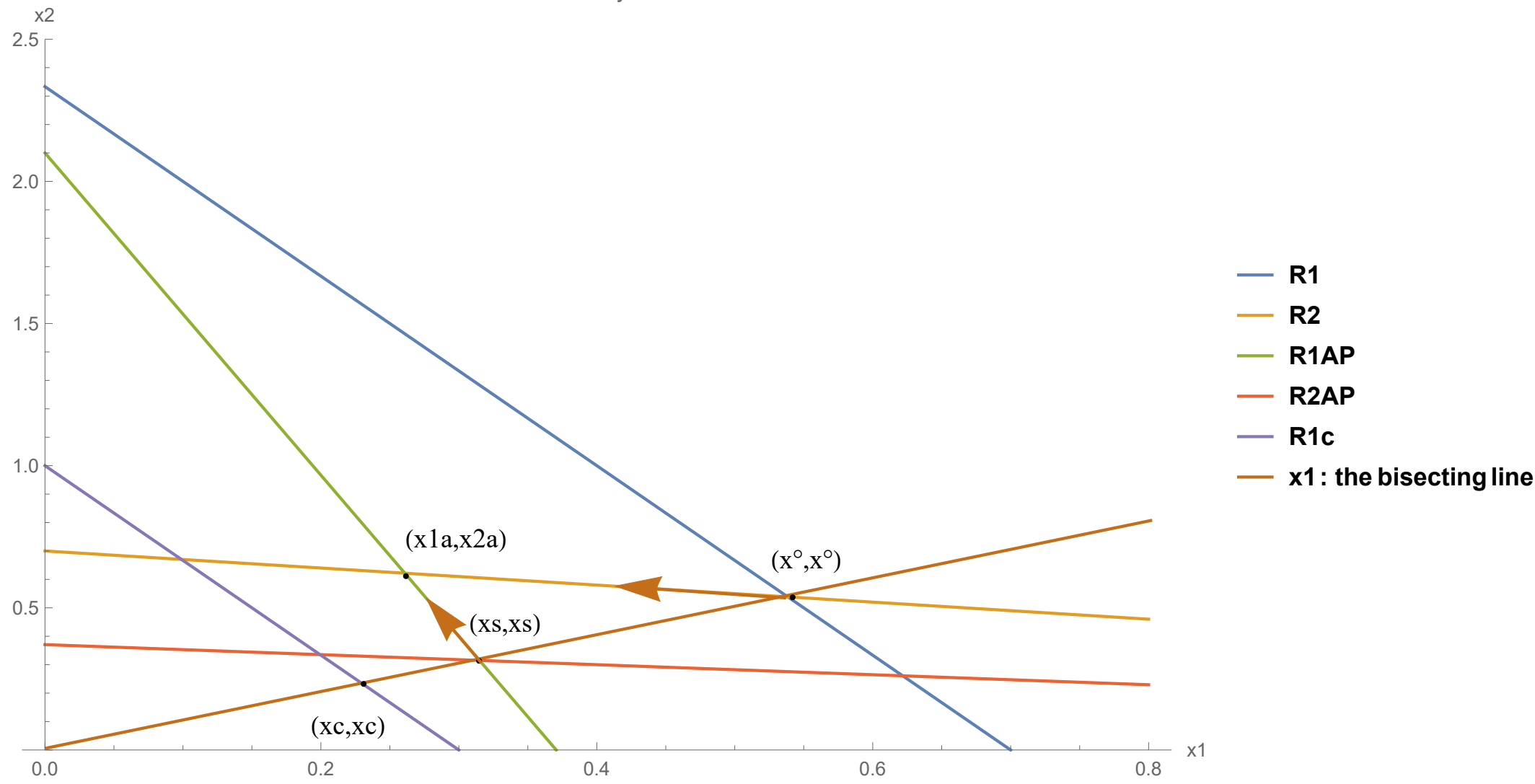


Figure 2

The infrastructure effect

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