

KEYWORDS

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DEFORESTATION, LEAKAGE AND AVOIDED DEFORESTATION POLICIES:

A SPATIAL ANALYSIS

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This paper analyses the impact of several avoided deforestation policies within a patchy forested landscape. Central is the idea that deforestation choices in one area influence deforestation decisions in nearby patches. We explore the interplay between forest landscapes comprising heterogeneous patches, localised spatial displacement, and avoided deforestation policies. Avoided deforestation policies at a landscape level are respectively: two Payments for Environmental Services (PES) policies, one focused on deforestation hotspots, the second being equally available to all agents; a conservation area; and, an agglomeration bonus. We demonstrate how the "best" policy, in terms of reduced leakage, depends on landscape heterogeneity. Agglomeration bonuses are shown to be more effective where there is less landscape heterogeneity, whilst conservation areas are most effective where there is more spatial heterogeneity

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1 Introduction

Deforestation and forest degradation continue to be of concern in many Low and Middle-Income Countries (LMICs). Over the past decades policy makers have adopted a broad range of programmes to try to reduce forest loss with varying levels of success. Conservation policies, such as National Parks, that relied on "*the heavy hand of the state*" excluded local communities from conservation areas (Agrawal and Gibson, 1999: 631), often without compensation. When such "*fence and fine*" actions failed to stem the continuing loss of forest, other approaches to forest management were introduced, such as Integrated Conservation-Development Projects (ICDPs) and various forms of participatory forest management. Though these initiatives have had some success, their frequent failure was attributed in part to their failure to create appropriate incentives for conservation by rural people (Hughes and Flintan, 2001, for a literature review; Ligon and Narain, 1999; Muller and Albers, 2004; Albers and Robinson, 2011). More recently, Payment for Ecosystem Services (PES) schemes have been introduced which explicitly link rewards to local communities in exchange for verifiable impacts on reducing the rate of deforestation of a specific forest.

Yet even where a particular initiative might be demonstrated to be successful in terms of reducing deforestation in a particular area, these initiatives were rarely implemented and evaluated in the context of a broader landscape. For example, there was no explicit consideration of whether the introduction of a protected area displaced extraction of forest resources into other less-protected areas, thus reducing its effectiveness (Oliveira et al. 2007; Ewers and Rodrigues 2008; Robinson et al., 2011). Indeed, many impact assessments continue to ignore such spatial displacement, that is leakage, in determining the effectiveness of a particular protected area on deforestation rates. Bruner et al.'s (2001) article, though now somewhat dated, is a case in point.

The growing role of REDD+ (Reduced Emissions from Deforestation and Forest Degradation) in global climate change negotiations, a mechanism that brings forest loss into climate discussions, has increased interest in understanding, predicting, and measuring leakage. Leakage is recognized in the Bali Action Plan - COP 13 as a "*displacement of emissions*" whereby a reduction in GHG emissions in one area (or activity) leads to higher emissions in another area (or activity). Such leakage can occur through a so-called "*activity-shifting leakage*", whereby individuals responsible for deforesting and forest degradation shift some or all of their activity from the more protected REDD forest to a less protected location (Aukland et al., 2003, van Oosterzee et al., 2012); or "*market or partial / general equilibrium leakage*" (Gan and McCarl, 2007; Meyfroidt and Lambin 2009; Rosendhal and Strand 2011; Carbone, 2013) in which the leakage is transmitted through markets, reflected

in changes in price for forest resources. Addressing leakage has been widely recognised as a major challenge when designing climate mitigation policies that incorporate a REDD+ scheme (Wunder, 2008; Albers and Robinson, 2013). Focusing on contagion effects of deforestation, Robalino and Pfaff (2012) argue that "*interactions should be considered in predicting deforestation over space and time (...) when designing spatial incentive schemes.*".

In this paper, we assess the impact of several avoided deforestation policies within a patchy forested landscape.¹ We accommodate two explicitly spatial aspects of forest landscapes. First, forest patches are heterogeneous in terms of the returns to forestry that they offer. Second, adjacent patches are linked through localised spatial displacement - leakage - such that one "neighbour's" deforestation actions may impact the returns to deforestation to those around them. Although we keep this model generalizable and so do not specify a particular leakage mechanism, the interaction can be likened to what is termed "*activity-shifting leakage*". One possible mechanism for such localized leakage could be whereby reduced deforestation in one area results in less agricultural land than there would otherwise be and thus decreased demand for agricultural laborers in that area, leading to localized out-migration to adjacent areas which then experience a surfeit of agricultural laborers relative to the status quo, making agriculture more attractive and thus increasing deforestation. Alternatively, poorly functioning local timber markets resulting in relatively lower deforestation in one location could increase the local price of timber, leading to increased deforestation pressures in adjacent forest areas due to these localized increases in timber prices. Whatever mechanism might be envisaged, central to the model is the idea that deforestation choices in one area influence deforestation decisions in nearby patches.

We explore the implications of a number of policy aimed at reducing deforestation at a landscape level: two Payment for Environmental Services (PES) policies, that can be likened to REDD+ policies - one focused on deforestation hotspots, the second being equally available to all agents (Bond et al., 2009); the introduction of a conservation area (Amin et al., 2014); and, an agglomeration bonus that reduces fragmentation by rewarding adjacent patches of lower deforestation in spatially structured landscapes (Parkhurst and Shogren, 2008; Drechsler et al., 2010; Watzold and Drechsler, 2014). We determine the impact of each policy in terms of avoided deforestation and leakage levels. We assess leakage here as the additional spatial interaction due to the policy implementation over and above any spatial interactions that occur without the policy.

¹Though we recognize the importance of forest degradation for climate and REDD+, in this paper we restrict our analysis to deforestation.

To our best knowledge, only a small number of papers in the literature have developed explicitly spatial models of leakage. Murray et al. (2004) explore the impact of leakage from a reserve to a forested area outside a reserve through a "*price-induced supply response*". The presence of a reserve creates an excess demand for timber relative to the reduced supply, the price rises, and the excess demand is met from outside the reserve. Gan and McCarl (2007) develop a theoretical model of transnational leakage. Again, the mechanism is through prices, and the extent of leakage is determined by the price elasticities of supply and demand for forest products. Angelsen and Delacote (2013) propose an understanding of the pattern of shifting activities that may create leakage between agricultural expansion and forest products harvesting: when land and labor are complement in the net return function of the households, a policy aiming at reducing deforestation may indirectly enhance forest degradation. Robinson et al. (2011 and 2013), focusing on forest degradation rather than deforestation, demonstrate that the extent of leakage is driven in part by both labour and product markets. When markets are functioning efficiently there is little if any direct leakage, though there may be indirect leakage through nearby markets. In contrast, when markets are poorly functioning, considerable displacement of forest degrading activities is likely. Focusing on protected areas in Brazil, Amin et al. (2014) and Sauquet et al. (2014) present cases of spatial strategic interactions between municipalities, which can be considered as leakage in a situation of strategic substitutability.

In this paper, we explore the interplay between forest landscapes comprising heterogeneous patches, localised spatial displacement, and avoided deforestation policies. We demonstrate how the "best" policy, in terms of reduced leakage, depends on landscape heterogeneity. For example, agglomeration bonuses are shown to be more effective where there is less landscape heterogeneity, whilst conservation areas are most effective where there is more spatial heterogeneity.

The rest of the paper is organised as follows. In Section 2, we develop our explicitly spatial model that demonstrates how spatial patterns of deforestation evolve over time, depending on the heterogeneity of a forest landscape and the spatial interdependences between different forest patches within this landscape. In Section 3, we describe four possible policies that aim to reduce deforestation and consider their implications in terms of avoided deforestation and leakage. In Section 4, we compare those policy options in terms of avoided deforestation, leakage and costs of implementing each. We conclude in Section 5.

2 The model

2.1 A spatial model of deforestation and leakage

The model is set up in the following way. We consider an $n \times n$ grid comprising a finite number of adjacent forest patches. Our analysis can be considered at different scales. A forest patch might be an area of forest belonging to one particular farmer in a rural community; a community forest landscape in a particular region; or even forestland across a specific country. Whatever the scale, deforestation decisions are made by representative agents at the level of the individual forest patch. At the beginning of each period, each agent chooses how much of their forest patch to deforest, so as to maximise their net present returns to deforesting.² A particular agent's payoff in a specific period is a function of its own chosen deforestation level D_{it} ; the exogenous characteristics of that agent's forest patch X_{it} ; and, the agent's neighbours' previous-period deforestation decisions on the adjacent forest patches in the landscape D_{jt-1} combined with the distance (or intensity of interaction) α_{ij} from those neighbours.

We focus on forest patch heterogeneity within the forest landscape. However, X_{it} could also be a function of the agent, or distance to markets. For example, relatively high values of X_{it} could be due to highly profitable timber harvests in that particular patch due to a particular species of tree being prevalent there; or to low outside opportunities for the particular agent, relative to the other agents. The neighbour previous-period choices, D_{jt-1} , combined with an interaction parameter which measures the intensity of the interaction, α_{ij} , determine the size of the spatial externality. This externality is a recursive relationship between agent i 's current deforestation and its neighbour j 's previous-period deforestation. We refer to this externality as leakage, using the language common in the literature on climate change and REDD+, which occurs if a decrease in one agent's level of deforestation results in an increase in the marginal payoff of their neighbours. Thus agent i 's marginal profit negatively depends on the agent's neighbours' previous period deforestation levels D_{jt-1} and the distance (or intensity of interaction) α_{ij} with those neighbours: $\frac{\partial^2 \pi_{it}}{\partial D_{it} D_{jt-1}} < 0$; $\frac{\partial^2 \pi_{it}}{\partial \alpha_{ij} D_{it}} < 0$.

Any deforestation is permanent (such as conversion to agriculture), and so there is no forest regeneration term. However, an agent could choose to actively reforest, in which case the forest cover would increase, and would be indicated by a negative deforestation term. Further, only direct neighbours' choices over deforestation influence agent i 's payoff. Thus, $\alpha_{ij} \in [0; 1]$ if i and j are

²Note that agents are not forward looking in our setting.

direct neighbours, $\alpha_{ij} = 0$ if they are not. α_{ij} close to 0 indicates relatively small interactions whilst, α_{ij} close to 1 indicates relatively large interactions.

We thus construct the model so that the optimal per-period level of deforestation for any particular agent will only change over time due to the neighbour interaction term α_{ij} . That is, with no interaction each agent deforests at a constant rate over time, allowing us to isolate the impact of spatial interdependence as leakage in REDD+ parlance.

Every period t , each agent chooses its level of deforestation to maximize its payoff:

$$\max_{D_{it}} \pi_{it}(D_{it}, X_{it}, \sum_{j \neq i} \alpha_{ij} D_{jt-1}) \quad (1)$$

The payoff obtained from deforestation is increasing and concave: $\frac{\partial \pi_{it}}{\partial D_{it}} > 0$; $\frac{\partial^2 \pi_{it}}{\partial D_{it}^2} < 0$.

The first-order conditions of problem (1) implicitly gives the optimal level of deforestation D_i^* of agent i , which depends on its own characteristics and its neighbours' previous optimal deforestation levels D_{jt-1}^* :

$$D_{it}^* = D_{it}(X_{it}, \sum_{j \neq i} \alpha_{ij} D_{jt-1}^*) \quad (2)$$

Using this model we can therefore define spatial interactions at time t as the difference between total deforestation at time t for $\alpha > 0$ and deforestation for $\alpha = 0$. The aggregate level of net deforestation at time t across the landscape is given by:

$$D_t = \sum_i D_{it} \quad (3)$$

2.2 Specification and benchmark

To provide more concrete insights, we specify functional forms and calibrate the model. We make a number of simplifying assumptions that allow us to ensure clarity of the model whilst not losing any of the key elements that need to be captured. First, we assume for simplicity that $X_{it} = X_i$ at any time period t . In other words, we do not consider potential retroactions between deforestation and the patch characteristics. Second, we let there be two types of forest patch. If $X_i = \bar{X}$, agent i gets high direct benefits from deforestation in a forest patch, whether due to highly profitable deforestation and/or low outside opportunities; if $X_i = \underline{X}$, agent i gets low direct benefits from deforestation. Third, only direct neighbours' choices over deforestation influence agent i 's payoff. Thus, $\alpha_{ij} \in [0; 1]$ if i and j are direct neighbours, $\alpha_{ij} = 0$ if not. Fourth, we allow for two levels of interaction low ($\underline{\alpha}$) and high ($\bar{\alpha}$). Finally, we consider two contrasting patterns

of *ex ante* spatial heterogeneity that we term "*clustered*" and "*dispersed*". These patterns are set for a 5 x 5 grid of 25 adjacent forest patches. Each cell corresponds to one forest patch which is controlled by one agent. In a clustered case, adjacent forest patches tend to be of the same type. In contrast, in a dispersed case, adjacent forest patches tend to be of different types. The dispersed case could be a proxy for a highly heterogeneous landscape which has some forest patches where the potential returns to agriculture are high, making deforestation more attractive, and others where the returns are low, perhaps driven by varying elevation, access to water, or access to markets.

These two extreme spatial distributions allow us to emphasize the role of spatial homogeneity and heterogeneity in determining the pattern and extent of leakage.

We consider a simple recursive quadratic payoff function of the form:

$$\pi_{it}(D_{it}, X_{it}, \sum_{j \neq i} \alpha_{ij} D_{jt-1}) = (\beta X_{it} - \sum_{j \neq i} \alpha_{ij} D_{jt-1}) D_{it} - \frac{1}{2} D_{it}^2 \quad (4)$$

Thus revenues from deforestation D_{it} in the absence of any spatial interaction effects are simply equal to the forest patch type X_{it} multiplied by some parameter β ,³ multiplied by the level of deforestation D_{it} . The costs of deforestation are quadratic, increasing in D_{it} . This non-linearity drives the result that agents typically do not deforest their full forest patch in the first period, but rather we have an interior solution. The presence of the interaction term α_{ij} potentially changes the returns to deforestation, depending on the size of α_{ij} and the actions of an agent's neighbours. This is what leads to the spatial externality - leakage. If an adjacent forest patch has a positive level of deforestation in the period $t - 1$ then the returns to agent i are reduced relative to there being no adjacent deforestation. Consequently, the neighbours' previous-period choices will impact negatively the agent's payoff.

Assuming an interior solution, the first-order condition of Equation (4) gives the optimal level of deforestation D_i^* for agent i :

$$D_{it}^* = \beta X_{it} - \sum_{j \neq i} \alpha_{ij} D_{jt-1}^* \quad (5)$$

We choose this specification such that, for any patch, any change in the rate of deforestation from the period one level is due to spatial interactions with neighbouring patches, the only dynamic parameter. Time $t = 0$ defines the initial conditions without spatial interactions. Thus deforestation at time $t = 0$ is given by $D_{i0}^* = \beta X_{i0}$, and this is the steady level of deforestation that each agent

³With $\beta > 0$.

would experience each period (until no forest in their patch remained) if $\alpha_{ij} = 0$, that is, if there were no spatial interactions.

We run the model for 10 periods to design Business-As-Usual (BAU) scenarios (Figure 1). We distinguish four potential cases that can be compared with the benchmark of no leakage, depending on whether similar patches are clustered (C) or dispersed (D), and whether there is high (H) or low (L) interaction: Clustered/Low-interaction (C/L), Clustered/High-interaction (C/H), Dispersed/Low-interaction (D/L), Dispersed/High-interaction (D/H). The results are given in terms of rates of deforestation for each patch each period.⁴ Parameters for the simulation analysis are given in Appendix A.1.⁵

⁴Note that if our modeling was adapted to address forest degradation, these deforestation rates could be reinterpreted as indicators of degradation intensity.

⁵Parameters were chosen here so that the agents in \bar{X} -patches have positive rates of deforestation in the BAU, while those in \underline{X} -patches have negative rates (meaning they choose to reforest). This choice is made for presentation purpose, as it is easier to distinguish each type on our landscape deforestation maps. It has no implication on the nature of our results, which would be the same if both types of agents deforest in the BAU.

Figure 1: BAU deforestation dynamics

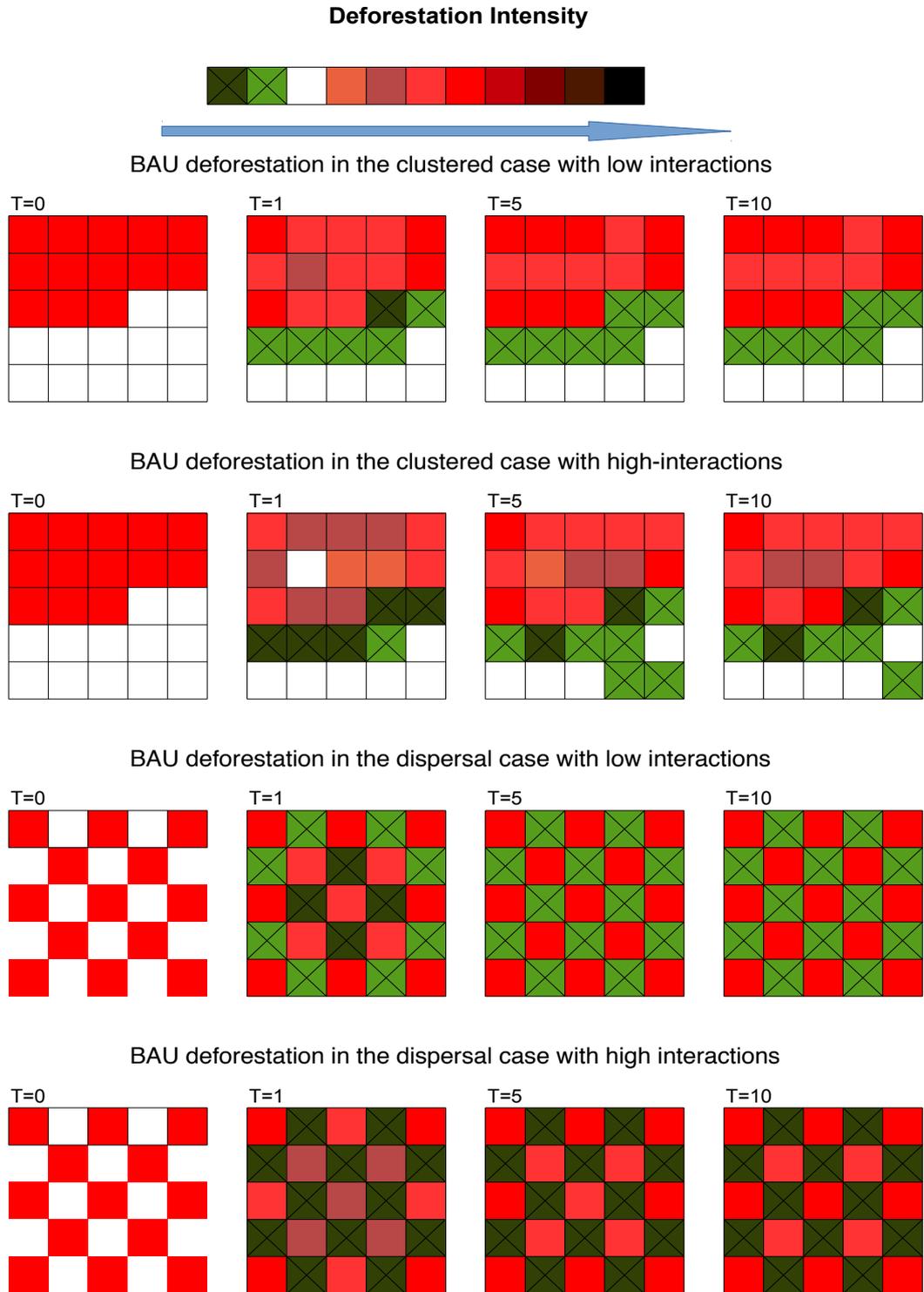


Figure 1 can be understood in the following way. *Ex ante*, all forest patches of type \overline{X} are identical, and all of type \underline{X} are identical. In the first period, because there is no prior deforestation, all \overline{X} agents make the same deforestation choice, as do all \underline{X} agents. There are two types of edge effects. One is imposed by the topology of the simulation model which has a finite number of forest patches such that some patches are at the model landscape boundary and others are not. As such there are edge effects imposed by the spatially finite model structure (we can imagine some notional land outside the grid where $\alpha_{ij} = 0$, where there is no scope for deforestation or reforestation, perhaps an urban landscape, or perhaps a fully protected area of forest). However, of particular interest in this paper are the edge effects that come from forest patches being adjacent to other forest patches where there are agents making active deforestation decisions.

From Figure 1, we can observe a number of dynamic transitions to different deforestation rates stabilization depending on the assumptions over spatial heterogeneity. In the C/L case, the stabilisation is reached after 5 periods. Agents on \overline{X} -patches all deforest at the same rate, whether they are adjacent to an edge, another \overline{X} -patch, or a \underline{X} -patch. The choices of agents on \underline{X} -patches differ however depending on whether they are adjacent to at least one \overline{X} -patch, in which case they reforest; or only \underline{X} -patch or an edge in which case they deforest. The reforestation occurs because there is negative spatial interactions from adjacent \overline{X} -patches. This reforestation creates a spatial interaction into \underline{X} -patches at the bottom of the grid which are adjacent either to other \underline{X} -patches or to a boundary. In the C/H case, the stabilisation is reached after 10 periods and is similar to the C/L case, though the equilibrium reflects a more complex pattern of interactions. In the D/L case, the stabilisation is reached after 5 periods with patches of reforestation alternating with patches of deforestation. Finally, in the D/H case, the stabilisation is reached after 5 periods as well; the pattern remains similar but with higher rates of deforestation and higher rates of reforestation.

Differences in aggregate net deforestation D_t are driven almost entirely by the forest patch type, rather than the spatial distribution of forest patches. This result is driven by our model assumption of homogenous and linear interactions between adjacent \overline{X} - and \underline{X} -patches. Though the distribution of deforestation is different in the two spatial cases, clustered and dispersed, the aggregate deforestation is much closer. Higher interactions tend to decrease deforestation for both types of agent whilst lower interactions reduce the variability of deforestation in time. More generally, higher spatial interactions increase deforestation variability.

3 Avoided deforestation policies and leakage

We assess policy options for reducing deforestation in our spatial setting. Policies are implemented at $t = 1$ and the model runs for 10 periods. With regards to each policy option, the aggregate Avoided Deforestation (AD) at time t is measured in the following way:

$$AD_t = D_t^{BAU} - D_t^{Pol} \quad (6)$$

D_t^{BAU} and D_t^{Pol} are respectively the aggregate deforestation level in the BAU scenario and the aggregate deforestation level with a policy option. Aggregated avoided deforestation is determined for each of the four cases that we address: C/L, C/H, D/L, D/H.

We explicitly take account of the impact of the policy both on the specific forest patches where the policy is implemented, but also on the total avoided deforestation so that we can analyse the impact of the policy setting on leakage. We consider leakage in our analysis as the additional spatial interaction due to the policy implementation over and above any spatial interactions that occur without the policy.

Spatial interactions are recursive in our model, and they are the only source of dynamics. Therefore there is no policy-induced leakage in the first year of policy implementation AD_1 . Our measure of leakage (L) is composed of the difference between the avoided deforestation at time $t > 1$ and the avoided deforestation at time $t = 1$:

$$L_t = AD_t - AD_1 \quad (7)$$

We focus on four policy options.⁶ These policies are respectively:

- A Payment for Environmental Services (PES) that focuses on deforestation hotspots, a "hotspot PES policy" (PESh);
- A PES applied to all agents, a "full PES policy" (PESf);⁷
- A Conservation Area policy (CA);
- An Agglomeration Bonus policy (AB).

⁶The policy calibration for each of the policy option is provided in Appendix A.2.

⁷We may underline that in our setting the PES is implemented also in patches where agents reforest effectively. In this case, the PES takes the form of a reforestation incentive.

3.1 Hotspot payment for environmental services policy

The hotspot PES policy (PESh) focuses on patches where there are higher deforestation rates (\bar{X} -patches). On these patches, the policy maker offers a price p_h to each agent per unit of avoided deforestation. Agent i 's payoff thus becomes:

$$\max_{D_{it}} \pi_{it}(D_{it}, \bar{X}_{it}, \sum_{j \neq i} \alpha_{ij} D_{jt-1}) + p_h(D_{BAUit} - D_{it}), \forall i \in [\bar{X}] \quad (8)$$

$$\max_{D_{it}} \pi_{it}(D_{it}, \underline{X}_{it}, \sum_{j \neq i} \alpha_{ij} D_{jt-1}), \forall i \in [\underline{X}] \quad (9)$$

Where D_{BAUit} is the deforestation level for agent i in the BAU scenario associated with one of the potential four cases (C/L, C/H, D/L, D/H), and p_h is the hotspot PES incentive.

In our specified framework, agent i 's deforestation is thus:

$$D_{it}^{PESh} = \beta \bar{X}_{it} - \sum_{j \neq i} \alpha_{ij} D_{jt-1}^{PESh} - p_h, \forall i \in [\bar{X}] \quad (10)$$

$$D_{it}^{PESh} = \beta \underline{X}_{it} - \sum_{j \neq i} \alpha_{ij} D_{jt-1}^{PESh}, \forall i \in [\underline{X}] \quad (11)$$

Equation (10) makes clear that agents with \bar{X} -patches will decrease their deforestation D_i^{PESh} when there is a hotspot PES payment p_h compared to BAU. This deforestation in turn changes the level of leakage compared to the BAU case. Specifically, lower deforestation in the \bar{X} -patches due to a PES payment results in greater deforestation in adjacent patches, whatever the patch type, relative to no PES payments. There is leakage if agent i is adjacent to any \bar{X} -patches (clustered case). Indeed, the decrease in the neighbours' deforestation will have a tendency to increase agent i deforestation. From Equation (11), we see that a type- \underline{X} patch surrounded by \bar{X} -patches (dispersed case) tends to increase deforestation compared to the BAU.

The aggregate avoided deforestation following the PESh policy is then:

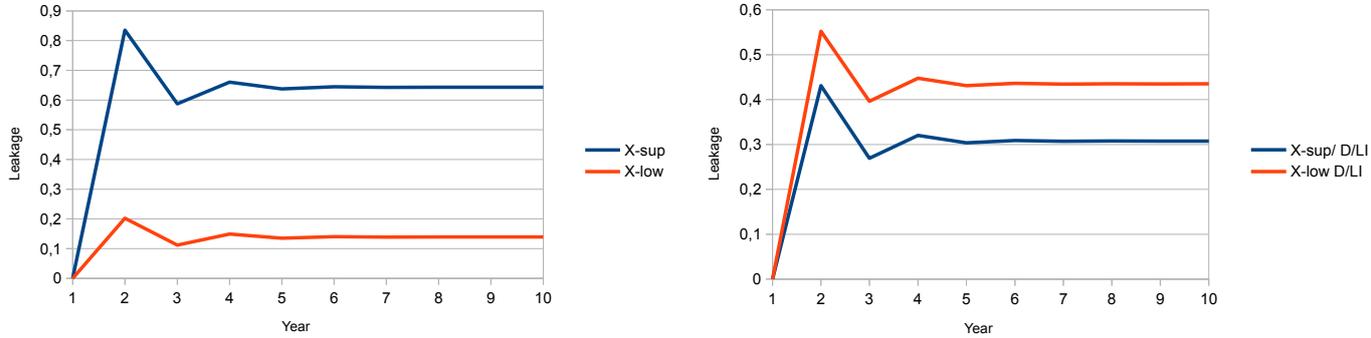
$$AD^{PESh} = \sum_{i \in \bar{X}} p_h - \sum_i [\sum_{j \neq i} \alpha_{ij} (D_{jt-1}^* - D_{jt-1}^{PESh})] \quad (12)$$

The first part of the right hand-side of Equation (12) represents the direct effect of the hotspot PES on deforestation, while the second part is related to leakage.

This leads to the following proposition:

Proposition 1: *Under a PES implementation on deforestation hotspots, leakage is stronger when agents are surrounded by neighbours with higher deforestation rates. It follows that leakage is stronger for \bar{X} -agents in a clustered case, while it is stronger for \underline{X} -agents in a dispersed case. Finally, leakage is more important in a high-interaction case.*

Figure 2: Leakage is stronger for \overline{X} -agents in a clustered case (left), and for \underline{X} -agents in a dispersed case (right) with low-interactions



Proof: see Appendix B.1.

An illustration of Proposition 1 is given in Figure 2 with low-interactions. We can see that leakage from \overline{X} -agents is more than 4 times the one of \underline{X} -agents in the clustered case. In the dispersed case, leakage from \underline{X} -agents is about 1.5 times stronger than the one of \overline{X} -agents.

3.2 Full payment for environmental services policy

Under this full PES policy (PESf), we consider a PES that is offered to every agent (both \bar{X} and \underline{X}), which brings:

$$\max_{D_{it}} \pi_{it}(D_{it}, X_{it}, \sum_{j \neq i} \alpha_{ij} D_{jt-1}) + p_f(D_{BAUit} - D_{it}), \forall i \in [\underline{X}, \bar{X}] \quad (13)$$

Where D_{BAUit} is the deforestation level for agent i in the BAU scenario associated with one of the potential four cases (C/L, C/H, D/L, D/H), and p_f is the full PES incentive.

In our specified framework, agent i deforestation is thus:

$$D_{it}^{PESf} = \beta X_{it} - \sum_{j \neq i} \alpha_{ij} D_{jt-1}^{PESf} - p_f, \forall i \in [\underline{X}, \bar{X}] \quad (14)$$

When the full PES p_f is effective, it is straightforward to see that \underline{X} -agents reduce their deforestation D_{it}^{PESf} (or increase their reforestation). Therefore, agents surrounded by those agents will increase their deforestation compared to the hotspot PES case.

The aggregate avoided deforestation following the PESf policy is then:

$$AD^{PESf} = \sum_i [p_f - (\sum_{j \neq i} \alpha_{ij} (D_{jt-1}^* - D_{jt-1}^{PESf}))] \quad (15)$$

In this case, the direct effect of the PES is higher as all agents are offered the payment compared to solely hotspot \bar{X} -agents as seen in the first part of the right hand-side of Equation (15). The second part is stronger for \underline{X} -agents and weaker for \bar{X} -agents.

This leads to the following proposition:

Proposition 2: *Under a full PES policy, agents reduce their deforestation. However, agents surrounded by \underline{X} -agents increase their deforestation compared to the hotspot PES case. It follows that leakage is stronger for \underline{X} -agents (resp. weaker for \bar{X} -agents) in the full PES case than in the hotspot PES case. The net effect depends on spatial distribution: leakage is stronger (resp. weaker) in the full PES case than in the hotspot PES case when agents are dispersed (clustered).*

Proof: see Appendix B.2.

Figures 3 and 4 illustrate Proposition 2, for a low interaction case.⁸

⁸Note however that the difference in terms of leakage is very small in our simulations. This is due to the fact that we assume homogenous and linear interactions between \bar{X} - and \underline{X} -agents. The result would be different if we assumed for instance stronger leakage between high-deforestation agents.

Figure 3: Leakage is stronger for \underline{X} -agents (resp. weaker for \overline{X} -agents) in the full PES case than in the hotspot PES case

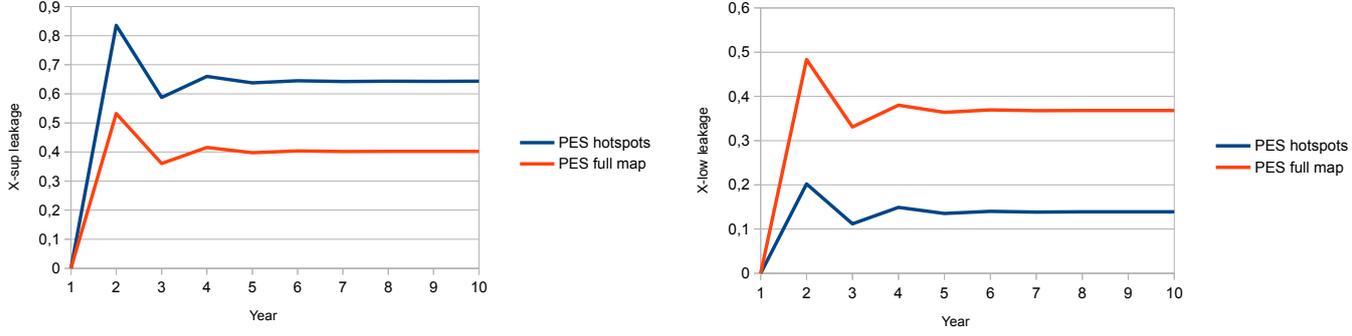
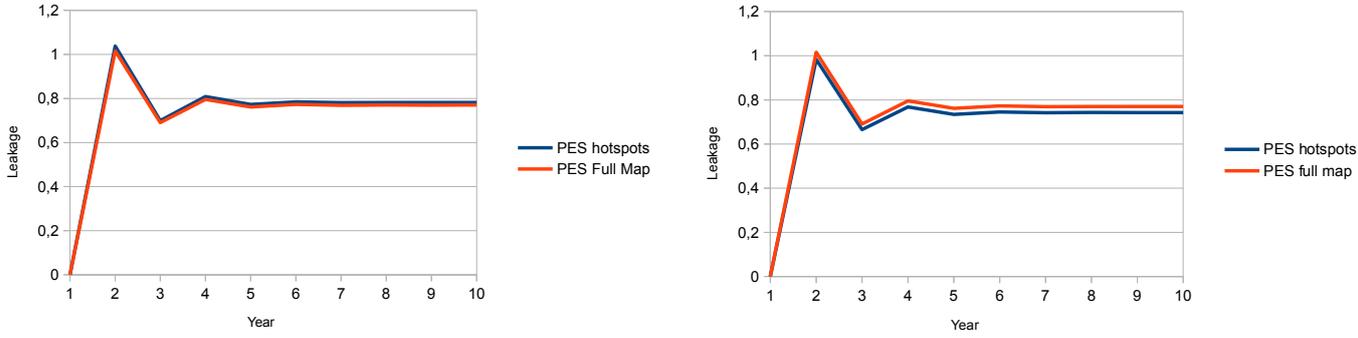


Figure 4: Leakage is stronger (weaker) under a hotspot PES than under a full PES in a clustered (dispersed) case (resp. left and right)



3.3 Conservation area policy

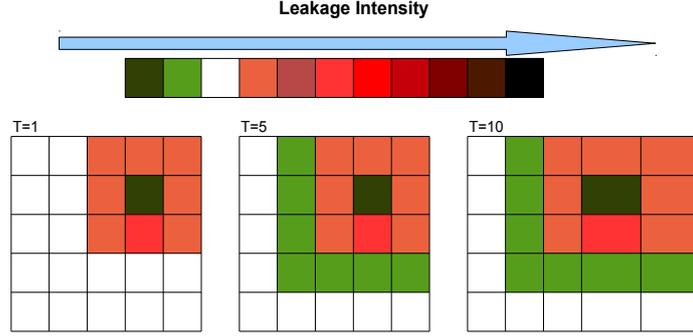
We now turn to the Conservation Area (CA) policy case whilst considering that the policy maker rents the land from one particular agent \tilde{i} (paying the opportunity cost of this land), and freezes the land as a reserve so that no deforestation occurs. In this case, leakage from policy implementation is limited in the sense that only one agent is source of leakage: only neighbours to agent \tilde{i} are subject to leakage.

Deforestation in this case takes the form:

$$D_{\tilde{i}t}^{CA} = 0, \forall i = \tilde{i} \quad (16)$$

$$D_{it}^{CA} = \beta X_{it} - \sum_{j \neq i} \alpha_{ij} D_{jt-1}^{CA}, \forall i \neq \tilde{i} \quad (17)$$

Figure 5: Leakage is concentrated around the conservation area (C/LI case)



The aggregate avoided deforestation following the CA policy is then:

$$AD^{CA} = D_{it}^* - \sum_i [\sum_{j \neq i} \alpha_{ij} (D_{jt-1}^* - D_{jt-1}^{CA})] \quad (18)$$

This leads to the following proposition:

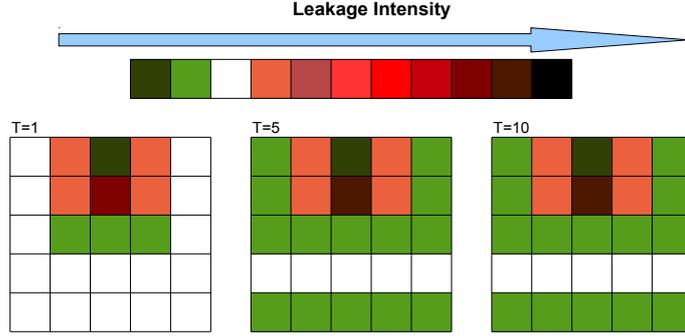
Proposition 3: *With a CA policy, the reserve patch is the sole source of leakage. It follows that leakage is concentrated around the reserve. Leakage will therefore be more geographically concentrated than under hotspot and full PES schemes.*

Proof: see Appendix B.3.

As seen in Figures 5 and 6,⁹ leakage is concentrated around the CA. It may also happen that positive feedback takes place as a second order effect: the conservation area increases deforestation in the "first belt" around; this belt may have in turn a spatial feedback on the "second belt", which may decrease its deforestation.

⁹Note that we use mapping here in the same manner as in Figure 1 to represent the impact of CA in terms of leakage. This is more straightforward to figure out leakage in the CA case, and leakage is expressed in deforestation intensity.

Figure 6: Leakage is concentrated around the conservation area (D/LI case)



3.4 Agglomeration bonus policy

The introduction of an Agglomeration Bonus (AB) policy may be of interest in dealing with adjacent patches whilst providing a joint incentive between agents. The AB policy takes the form of a two-part PES payment: a payment for individual avoided deforestation, a ; and, a payment that is proportional to previous deforestation in the neighbourhood, b . For simplicity, we focus here on the hotspot PES, and therefore a is equal to p_h .¹⁰ This AB can thus counterbalance leakage that was described in the hotspot PES policy case.

The AB policy is then set from:

$$\max_{D_{it}} \pi_{it}(D_{it}, \bar{X}_{it}, \sum_{j \neq i} \alpha_{ij} D_{jt-1}) + a(D_{BAUit} - D_{it}) + b(\sum_{j \neq i} \alpha_{ij} D_{jt-1}) D_{it}, \quad \forall i \in [\bar{X}] \quad (19)$$

$$\max_{D_{it}} \pi_{it}(D_{it}, \underline{X}_{it}, \sum_{j \neq i} \alpha_{ij} D_{jt-1}), \quad \forall i \in [\underline{X}] \quad (20)$$

In our specified framework, agent i deforestation under the AB is thus:

$$D_{it}^{AB} = \beta \bar{X}_{it} - (1 - b) \sum_{j \neq i} \alpha_{ij} D_{jt-1}^{AB} - a, \quad \forall i \in [\bar{X}] \quad (21)$$

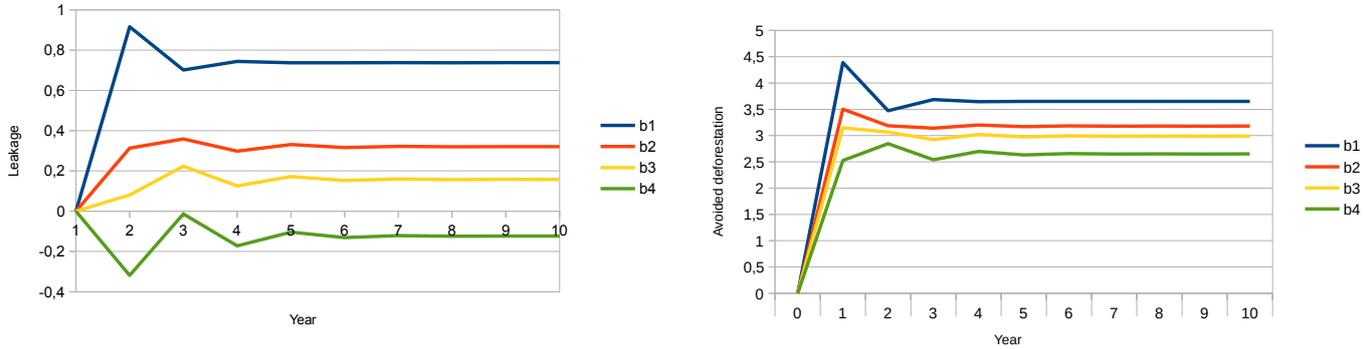
$$D_{it}^{AB} = \beta \underline{X}_{it} - \sum_{j \neq i} \alpha_{ij} D_{jt-1}^{AB}, \quad \forall i \in [\underline{X}] \quad (22)$$

The aggregate avoided deforestation following the AB policy is then:

$$\begin{aligned} AD^{AB} &= \sum_{i \in \bar{X}} [a - (\sum_{j \neq i} \alpha_{ij} (D_{jt-1}^* - D_{jt-1}^{AB}) - b D_{jt-1}^{AB})] \\ &\quad - \sum_{i \in \underline{X}} [\sum_{j \neq i} \alpha_{ij} (D_{jt-1}^* - D_{jt-1}^{AB})] \end{aligned} \quad (23)$$

¹⁰For simulation purposes in Section 4, we set different values for p_h and a .

Figure 7: Leakage and avoided deforestation decreases with the AB: $b_1 < b_2 < b_3 < b_4$



One can see here that increasing b indeed reduces leakage (by reducing the interactions between neighbours). It is essential, however, to note that it also reduces the aggregate avoided deforestation.

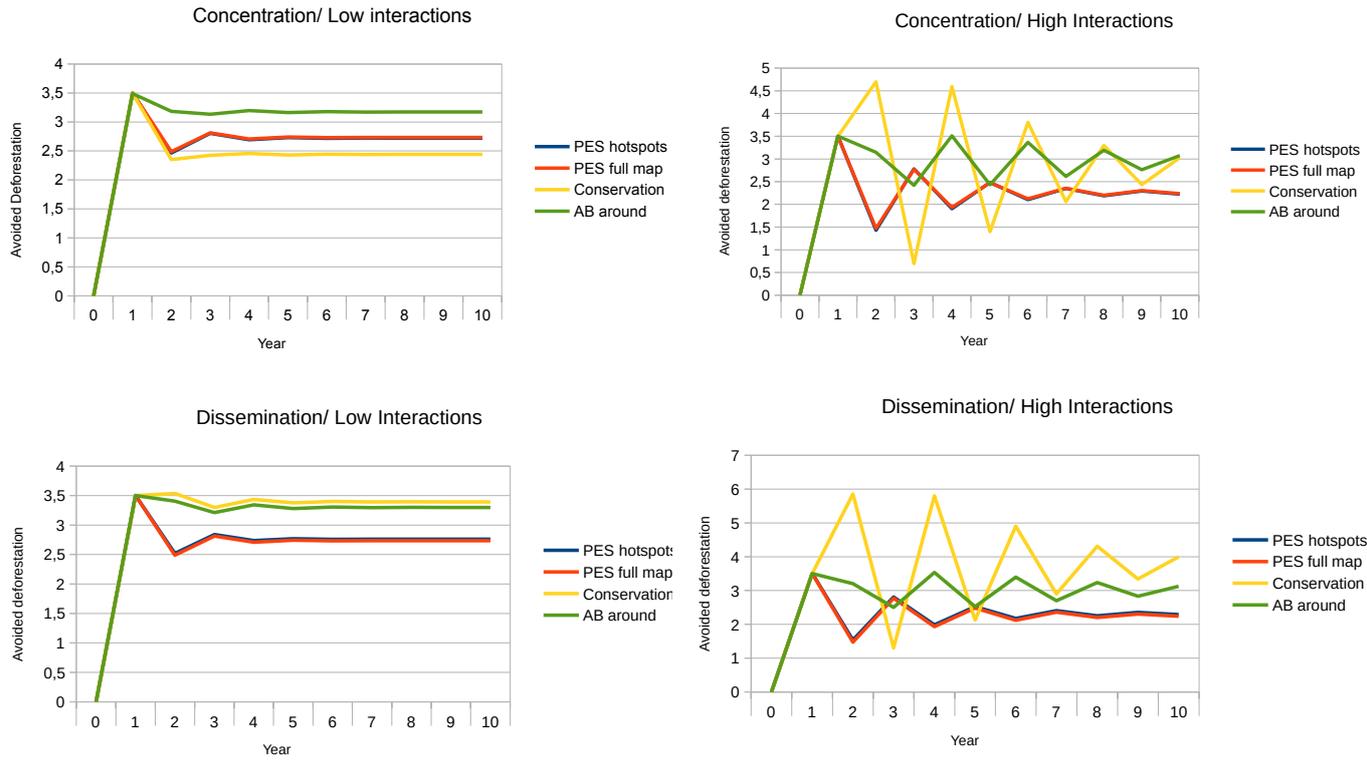
Proposition 4: *Leakage is decreasing in the AB policy. Leakage may even become negative for sufficiently high b . However, the agglomeration bonus also decreases avoided deforestation.*

Proof: see Appendix B.4.

Overall, indeed, the level of the agglomeration bonus b is negatively correlated to agent i neighbours' deforestation: the bonus thus performs as expected and reduces leakage. However, in order to be effective, the agglomeration bonus also has to be positively related to agent i 's own deforestation: it thus creates an incentive to increase deforestation. This negative effect can be outweighed by increasing the direct payment a , which is done at the expense of a higher total cost.

It follows that reducing leakage through an agglomeration bonus is made at the expense of reducing avoided deforestation. The tradeoff has to be considered carefully when implementing such type of scheme.

Figure 8: Aggregate Avoided Deforestation



4 Policy comparison

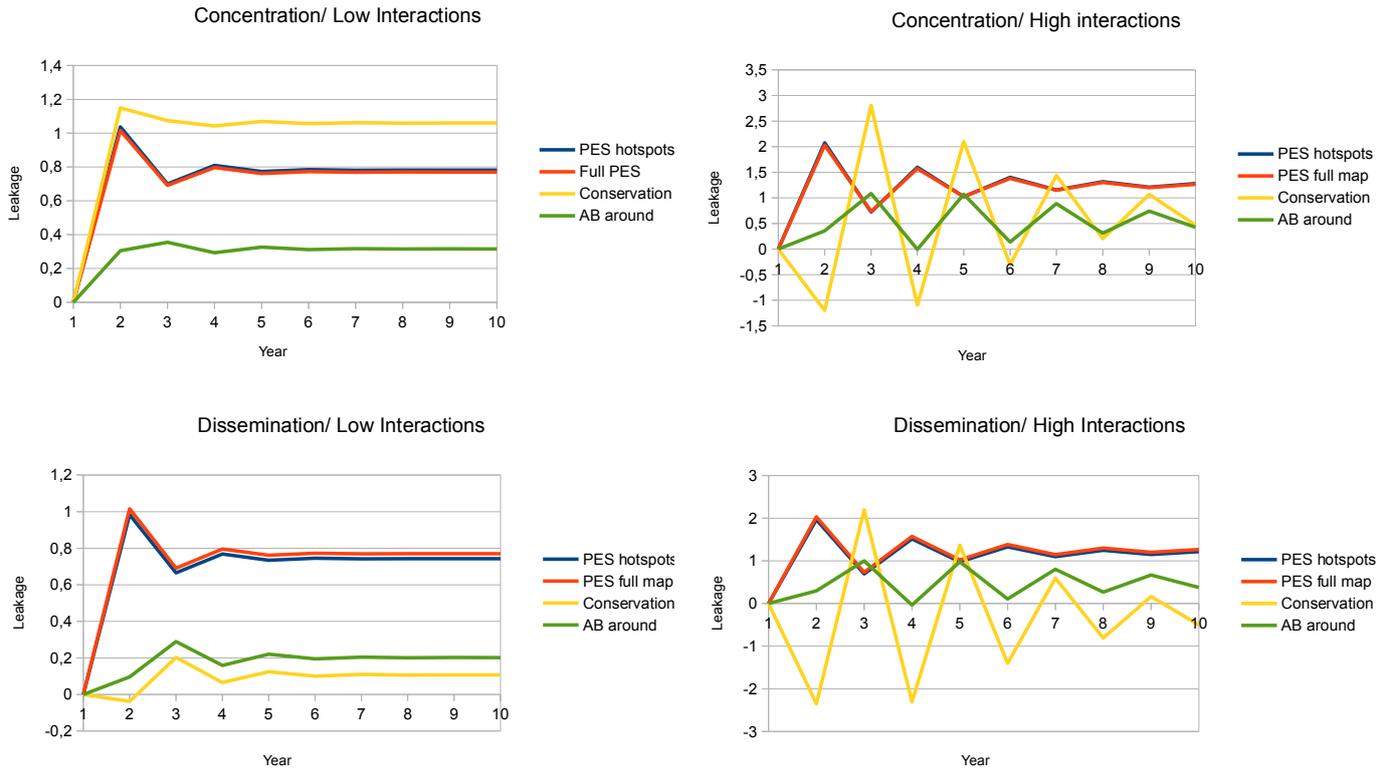
In this section, we focus on comparing the four policies presented in the previous section, that is CL, C/H, D/L, D/H.

As stated before, all policies are calibrated in order to generate the same avoided deforestation at period $t = 1$. The only dynamic parameter of the model is leakage. Therefore, the following comparison cannot be considered as an assessment of policy options *per se*, but only of their implications in terms of leakage.

4.1 Avoided deforestation and aggregate leakage

The respective aggregate Avoided Deforestation (AD) and Leakage (L) at the landscape scale are displayed in Figure 8 and Figure 9.

Figure 9: Aggregate Leakage



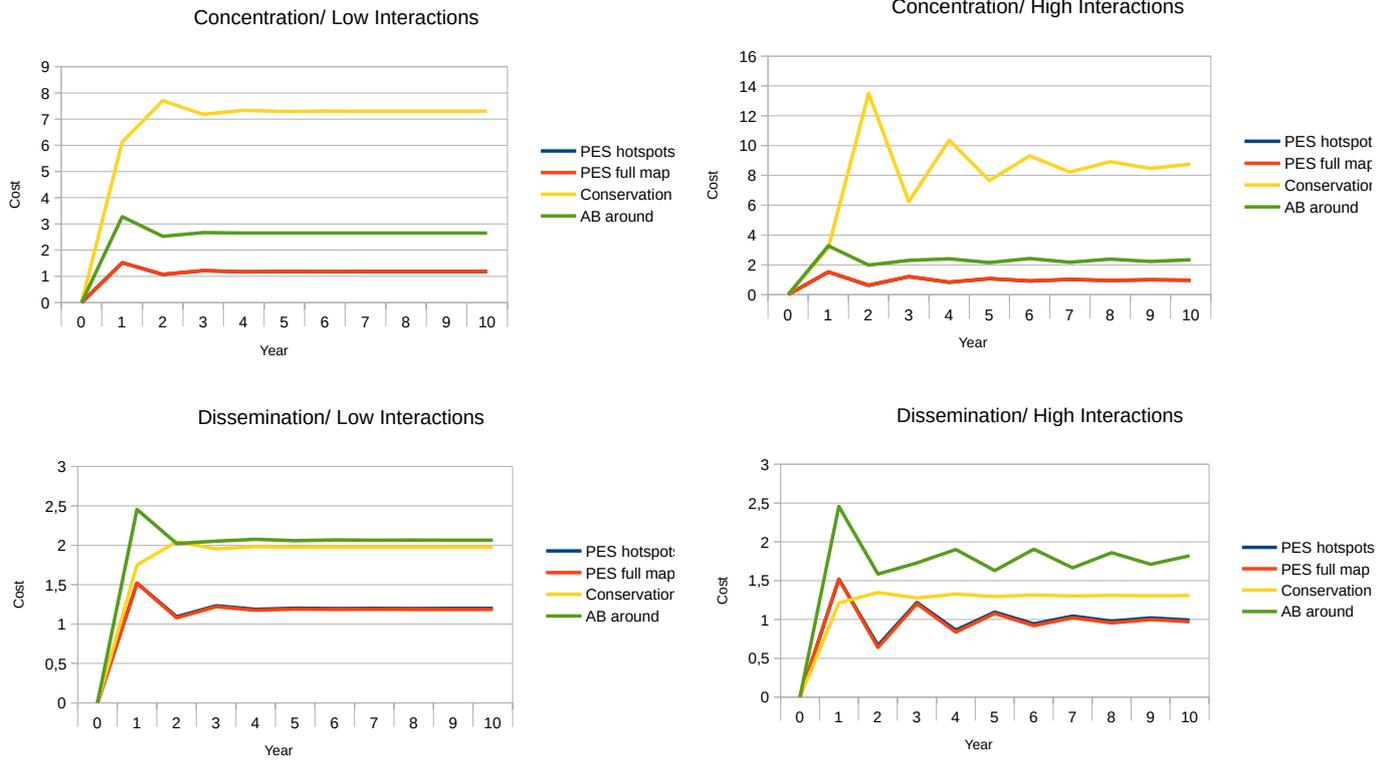
Note first that the ranking of policy effectiveness depends on the spatial distribution that we consider (Figure 8).¹¹ When considering clustered cases, the AB policy is the most effective tool in terms of aggregate AD . Hotspot and full PES policies bring intermediate results, while the CA policy is the less effective policy instrument. In contrast, in the dispersed cases, the CA policy becomes the most effective tool followed by the AB policy. Hotspot and full PES policies are the less effective policy options. Finally, we may underline stronger interactions increase the variability of avoided deforestation in time, especially for the CA policy case.

Looking at L corroborates our findings. L is the most important for the CA policy in a clustered case, while the AB policy is the most efficient. In contrast, in dispersed cases, the CA policy becomes the most effective tool in terms of L . Hotspot and full PES schemes are the one generating the largest amount of L .

This variability of the effectiveness of the CA policy with respect to spatial distribution can be explained by the spreading potential of the neighbours. In a clustered case, the neighbours to the reserve are also deforestation hotspots, and therefore very sensitive to leakage. In a dispersed case,

¹¹It is important to note here that the results from the AB policy are using the same bonus calibration.

Figure 10: Costs



the neighbours to the reserve are low-deforestation type agents. Those neighbours therefore play as buffer zones when it comes to leakage.

We may also stress that the two kinds of PES schemes that we consider bring very similar results in terms of AD and L . This is due to the linear form of our specified deforestation function expressed in Equation (5).

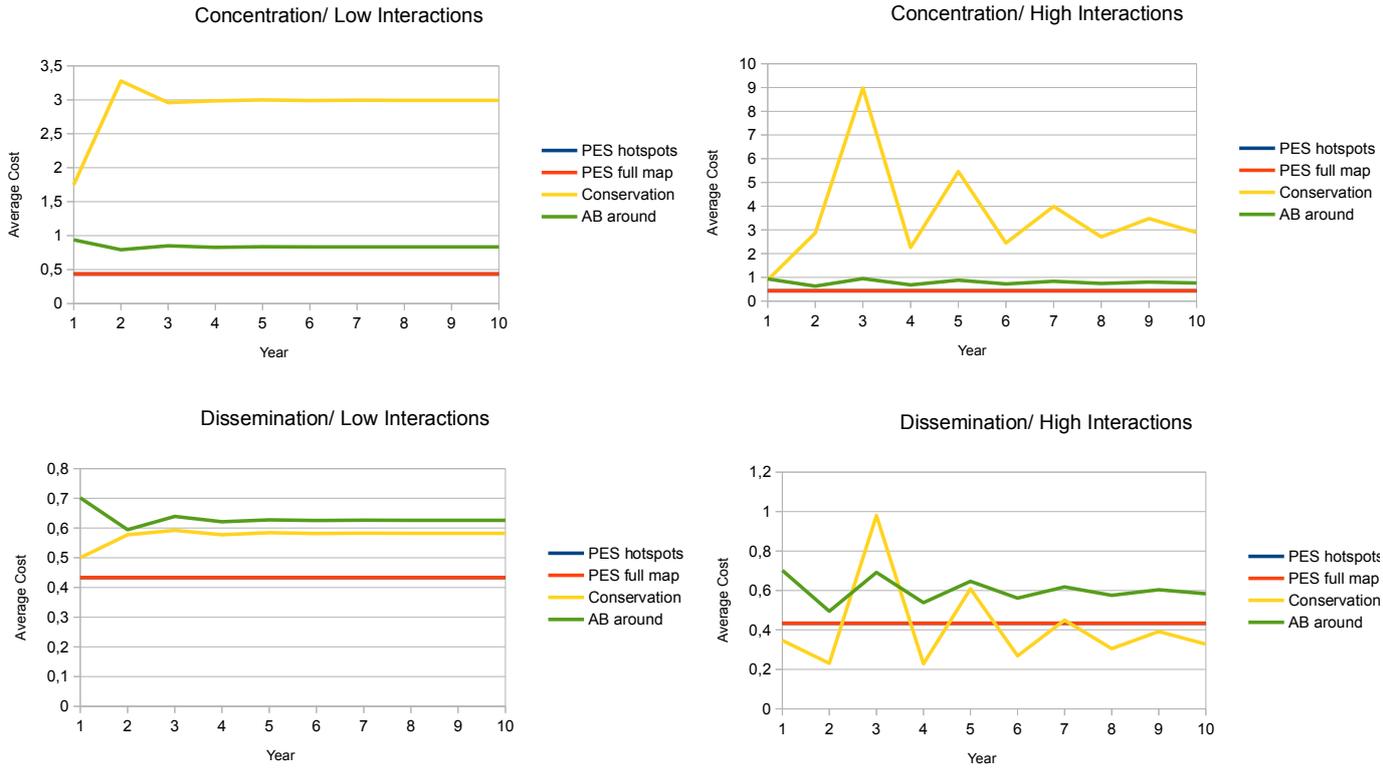
4.2 Policy costs and average costs

The costs of the policies are set as follows:

- Hotspot PES policy (PESh): $C^{PESh} = \sum_{i \in \bar{X}} p(D_{it}^* - D_{it}^{PESh})$.
- Full PES policy (PESf): $C^{PESf} = \sum_{i \in (\underline{X}, \bar{X})} p(D_{it}^* - D_{it}^{PESf})$
- Conservation Area policy (CA): $C^{CA} = \pi_{it}$
- Agglomeration Bonus policy (AB): $C^{AB} = \sum_{i \in \bar{X}} (a(D_{it}^* - D_{it}^{AB}) + b(\sum_{j \neq i} D_{jt-1}^{AB})) D_{it}$

Total costs and average costs are displayed in respectively Figure 10 and Figure 11.

Figure 11: Average Costs



It is interesting to note here that hotspot and full PES schemes are always the least cost options.¹² In a clustered case, the CA policy is the most costly option. This can be explained by the fact that the CA policy requires to compensate the agent for its whole payoff in order to conserve its land, while hotspot and full PES schemes are implemented on a voluntary basis, therefore distributing the cost of the policy more efficiently.

In a dispersed case, the AB policy is the most costly policy option. Indeed, leakage essentially concerns \underline{X} -agents (as seen in Proposition 1), which are not concerned by the PES. It follows that controlling leakage is more costly in this case, since the bonus is focused on \overline{X} -agents. Moreover, stronger interactions increase the variability of the results across time.

As a supplementary result, we propose in Appendix C. the comparison with the same first year cost for each policy.

¹²We focus here on direct costs, and avoid to consider transaction costs, which may be very high for PES implementation.

5 Conclusion

Governments in LMICs that engage in REDD+ typically undertake avoided deforestation and forest degradation policies that may directly or indirectly influence the drivers of forest loss. A key concern that has been extensively voiced is that efforts to reduce forest loss in one location may result in deforestation and forest degradation being displaced to another location, that is leakage.

Leakage is a frequently mentioned as a shortcoming of REDD+ implementation, both at the local and the international levels. In this paper, we consider several avoided deforestation policy options, and assess their implications in terms of leakage, avoided deforestation and costs. We apply our analysis to different spatial features. Though we model a spatial analysis of deforestation with localized leakage, the analysis is relevant to any public good provision with spatial interactions in which the action of an agent has a direct impact on their neighbours' payoff. Note that our model overlooks potentially important REDD+ topics. For instance, we assume here perfect monitoring of deforestation. We also assume homogenous interactions from low-deforestation agents and high-deforestation agents, which may not be true in real life. Nevertheless, several interesting findings can be found from our model.

First, leakage is sensitive to the spatial distribution of forests patches through agents' deforestation actions. When they are clustered in the same area, a CA policy through a reserve implementation will have the worst outcome in terms of leakage. In contrast, this policy will have the most effective outcome if agents are dispersed over the area. Under a hotspot PES policy, leakage strikes different agents depending on the spatial distribution. If agents of same type are clustered in the same area, then leakage will strike high deforestation agents. In contrast, leakage will strike more low deforestation agents in a dispersed case. Although setting a full PES policy on all agents should reduce leakage, we show that this reduction of leakage is only marginal. Increasing the scale of the PES indeed creates some new sources of leakage. The implementation of a AB policy can be an interesting tool to reduce leakage, although this policy option happens to be more costly.

Second, hotspot and full PES policy schemes appear to be the least cost option for reducing deforestation. Moreover, they appear to be the most effective tool in terms of avoided deforestation under a fixed budget. It follows that if the policy maker sets its short-term objective in terms of an aggregate level of avoided deforestation to achieve and a lower level of leakage, respectively AB and CA policies respectively in a clustered case and a dispersed case can be the preferred options. However, more classic PES schemes are relevant when the policy maker aims at minimizing costs, regardless of leakage.

Finally, we showed that the intensity of the interactions unambiguously tend to increase the variability of the aggregate avoided deforestation. This result gives the insight that avoided deforestation policies should be assessed in the long run, with sufficiently long periods of observation, in order to avoid focusing on short-term episodes, particularly when interactions happen to be strong.

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Appendix A. Simulation parameters

Appendix A.1. Parameter values

Parameter	Value
β	1
\bar{X}	5
\underline{X}	0
$\underline{\alpha}$	0.05
$\bar{\alpha}$	0.1

Appendix A.2. Policy calibration: same avoided deforestation at $t = 1$

Parameter	C/L	C/H	D/L	D/H
p_h	0.327	0.295	0.3654	0.3465
p_f	0.17	0.14	0.19	0.18
a	0.409	0.443	0.433	0.433
b	0.0059	0.0059	0.0059	0.0059
b_1	0.003			
b_2	0.00586			
b_3	0.007			
b_4	0.009			

Appendix B. Proofs

Appendix B.1. Proposition 1

Under a hotspot PES policy, only \bar{X} -type agents are targeted. Thus, they are the only agents experiencing a direct decrease of their BAU deforestation. It follows that leakage only comes from those agents in the first place. Then, given our spatial setting, leakage impacts more \bar{X} -type agents in a clustered case, and \underline{X} -type agents in a dispersed case.

Appendix B.2. Proposition 2

Under a full PES, \underline{X} -agents reduce directly their deforestation. They are therefore source of leakage for their neighbours. In contrast, \bar{X} -type agents are source of weaker leakage for their neighbours compared to the hotspot PES case as they receive a lower payment: the payment has indeed to be lower, since the policy is calibrated to achieve the same level of avoided deforestation after the first year. We directly obtain that leakage is stronger (resp. weaker) in the full PES case than in the hotspot PES case when agents are dispersed (clustered).

Appendix B.3. Proposition 3

If the CA policy leads to a reserve in one part of the map only, it is straightforward that leakage will be concentrated around that particular area.

Appendix B.4. Proposition 4

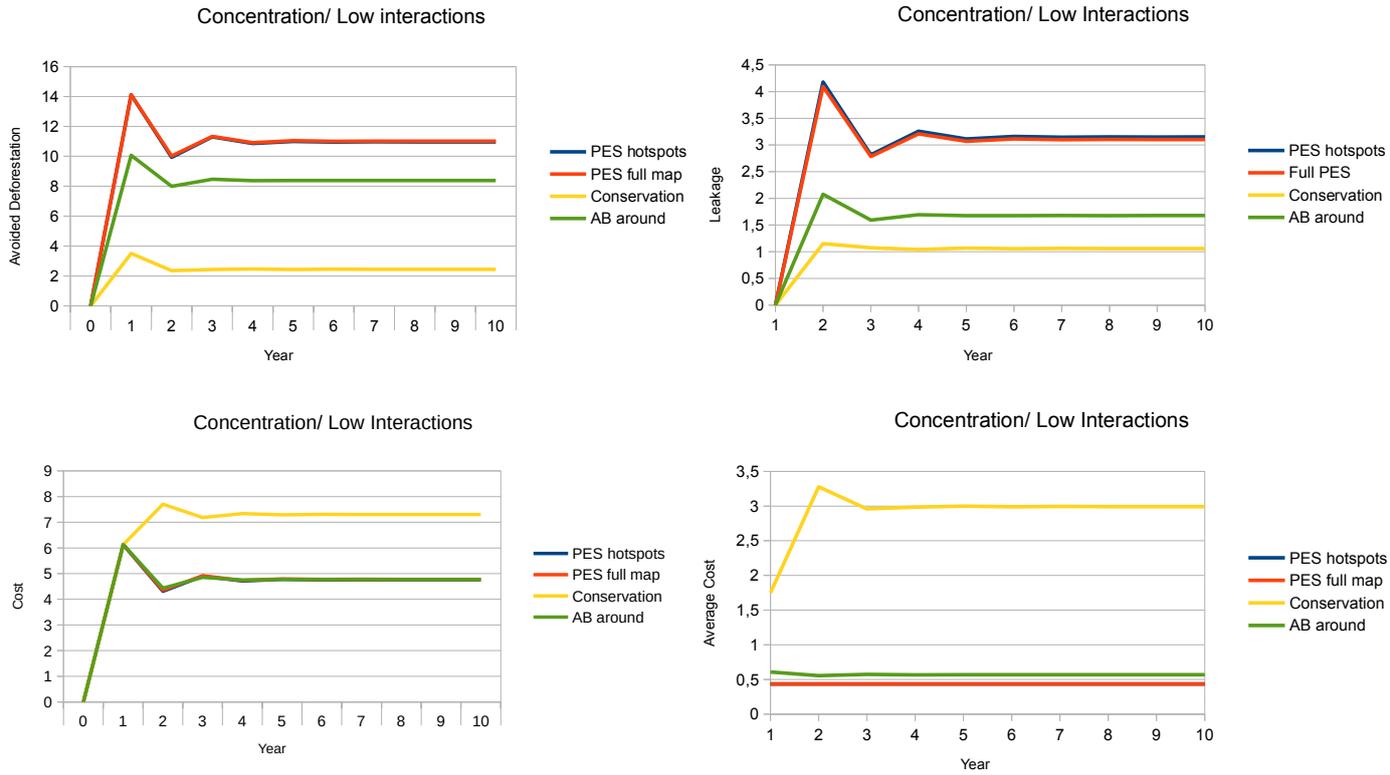
The payment proportional to previous deforestation in the neighbourhood, b , decreases the impact of the spatial interaction from the neighbours. Leakage is thus decreasing in b . However, deforestation under the PES with a bonus is increasing in the level of b :

$$\frac{\partial D_{it}^{AB}}{\partial b} = \sum_{j \neq i} \alpha_{ij} D_{jt-1}^{AB} > 0 \quad (24)$$

Appendix C. Policy calibration and comparison with the same first-year costs

In order to get complementary results, we run the model calibrated so that the four policies bring the same costs at the first year. We consider the C/L case through the parameters below

Figure 12: Policies with the same first-year costs



and Figure 12.

Parameter	C/L
p_h	1.086
p_f	0.565
a	0.915
b	0.0059

In this case, one can see that PES (hotspot and full) become the most effective tool in terms of avoided deforestation, but also bring the largest amount of leakage. Yet, it remains the least cost option.

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