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To cite this version:

François Bareille, Raphaël Soubeyran. Individual vs. collective agglomeration bonuses to conserve biodiversity. 2024. hal-04454553

HAL Id: hal-04454553

https://hal.inrae.fr/hal-04454553

Preprint submitted on 13 Feb 2024

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CEE-M Working Paper 2024-03

INDIVIDUAL VS. COLLECTIVE AGGLOMERATION BONUSES TO CONSERVE BIODIVERSITY

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February 8, 2024

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Abstract

Agglomeration bonuses (AB) are payments conditional on the contiguity of landowners' conservation areas. It is widely accepted that, by encouraging landowners to cooperate, ABs promote more cost-effective biodiversity conservation than homogeneous payments. This article challenges this conclusion by studying the impact of different AB designs, which may or may not encourage cooperation. Specifically, we show that differentiating the bonus between internal (within-landholding) and external (between-landholdings) boundaries affects AB cost-effectiveness. Using an economic-ecological model and game theory, our simulations on realistic landscapes show that the most cost-effective ABs are those presenting relatively larger internal bonuses. Conversely, ABs with relatively larger external bonuses are less cost-effective, despite fostering cooperation between landowners.

Keywords: Biodiversity; Coalition; Collective scheme; Cooperative management.

JEL Code: Q57

1 Introduction

Effective biodiversity conservation often requires spatial connectivity of conserved land (Fahrig, 2003). As the plots constituting a landscape are scattered across several landholdings, it has been suggested that regulators should move away from voluntary instruments targeting individual landowners – such as the homogeneous payments used in most countries – in favor of voluntary collective instruments, encouraging coordinated landscape-level conservation efforts by cooperating individual landowners (Nguyen et al., 2022) – such as the agglomeration bonus (AB), which adds a bonus to a homogeneous payment for each conserved plot adjacent to another such plot. However, cooperation incurs additional costs for landowners (Banerjee et al., 2021), and the question of whether agglomeration of conservation efforts can be achieved without cooperation has been overlooked.

We address this issue by examining AB schemes providing differentiated bonuses for the conservation of adjacent plots belonging to the same landholding (henceforth *internal bonus*) or to different landholdings (*external bonus*). Indeed, because landholdings are usually spatially concentrated (Chabé-Ferret and Enrich, 2021), it can make sense to differentially shape incentives to conserve adjacent plots depending on their owner (Parkhurst and Shogren, 2007). In particular, although both internal and external bonuses have the potential to agglomerate conserved plots, the former do not require cooperation between landowners unlike the latter. We ask whether internal and external bonuses are *substitutes* – i.e., only one of them is required – or *complements* – i.e., both are required together.

We adopt the perspective of a regulator wishing to maximize biodiversity for a given budget by choosing levels of internal and external bonuses. Landowners respond to this set of incentives by playing a two-stage game, first deciding individually with whom to cooperate, then cooperatively choosing their conservation efforts. We solve this game using numerical simulations for a large range of internal and external bonuses using a set of realistic landscapes.

Our results show that the two types of bonus are generally substitutable, with internal bonuses outperforming external ones. However, when the regulator's budget is tight, external bonuses can complement internal bonuses. In all cases, habitat agglomeration can be achieved cost-effectively *without* or *with only little* cooperation between landowners.

The intuitions behind our results are not straightforward. Our first main result – that in most cases the two bonuses are substitutes, with the internal bonus outperforming the external one – can be explained as follows. First, the internal bonus alone can work for a plot not forming a boundary between two different landholdings. Second, internal bonuses make compensation between plots easier to achieve than external bonuses, since an internal bonus allows compensation involving only two plots from the same landowner, whereas a similar bonus targeting external boundaries often requires more complex agreements between two landowners (involving at least two plots each).[1] For many plots, the regulator will save money by encouraging their conservation using internal rather than external bonuses.

Our second main result, that there are cases where the two bonuses are complementary, stems from the fact that internal bonuses do not allow compensation to occur between plots belonging to different landholdings, whereas external bonuses do. Complementarity between the two bonuses is more likely when the regulator's budget is tight, as in this case internal bonuses alone cannot induce the conservation of a large number of plots – especially of those located on landholding boundaries. Instead, adding external bonuses may be more cost-effective in this case than increasing the internal bonuses to encourage the conservation of those specific plots as they provide additional targeted incentives for them.

We contribute to the AB literature in two ways. First, we contribute to reflections on the very design of AB schemes. While the literature has commonly investigated the combination of flat payment and bonus that maximizes AB cost-effectiveness (e.g. Wätzold and Drechsler, 2014), we are unaware of any study analyzing the impacts of differentiated internal and external bonuses on AB cost-effectiveness. Such differentiated bonuses have already been considered by Parkhurst and Shogren (2007) in a lab experiment, not to study their cost-effectiveness, but to show that they can encourage landowners to reach some given spatial configurations.[2] We thus contribute to the literature with this first analysis. Second, we show that cooperation is generally not necessary – indeed not even desirable – to reach cost-effective landscape conservation. This departs from the common belief that collective schemes are more cost-effective than individual instruments because they induce cooperation (Westerink et al., 2017; Kotchen and Segerson, 2020; Nguyen et al., 2022). This result is obtained using a model in which cooperation between landowners is endogenous and

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[1] Only two adjacent plots are needed to make an internal bonus work. Indeed, if the sum of the opportunity costs of two adjacent plots from the same landholding are lower than two internal bonuses, a rational landowner will enroll the two plots within the AB scheme. This works even if the opportunity cost of one plot is lower than the bonus, because only the total payment for both plots is important, not the payment per plot. That is, compensation occurring between the two plots would be enough here to enroll the two plots within the scheme. By comparison, an external bonus will not work where the opportunity cost of one of the two plots is lower than the bonus, as in the absence of side-payments between landowners, the owner of the plot with the highest opportunity cost will not agree to conserve it. That is, the regulator needs to pay larger external payments or landowners have to find more complex agreements – involving four plots for instance – for the external bonus to work in this case.

[2] Other types of differentiated payments have been considered in experiments, such as combinations of ABs with network targeting (Fooks et al., 2016).

involves frictions, which contrasts with the standard assumption found in the literature that all landowners cooperate within the grand coalition (e.g. Wätzold and Drechsler, 2014).[3] We model the landowner coalition formation process as in Bareille et al. (2023), and add to this paper by considering flexible AB schemes that can differentially encourage cooperation (via the proportion of internal and external bonuses).

The paper is organized as follows. Section 2 develops our methodology. Section 3 describes the simulation results. Section 4 discusses and concludes.

2 Methods

Our aim is to study how the proportion of internal and external bonuses affects AB cost-effectiveness, that is, biodiversity level and total payments from the regulator to landowners. We detail hereafter the main features of our ecological-economic game (Section 2.1), before presenting our simulation procedure (Section 2.2).

2.1 Ecological-economic game

Biodiversity. Consider a landscape composed of contiguous plots subdivided across a set $\mathbf{I}$ of I landowners.[4] Assume that each landowner i owns a subset $\mathbf{K}_i$ of these plots, $i_k \in \mathbf{K}_i$ denoting plot k of landowner i (with $\bigcup_{i \in \mathbf{I}} \mathbf{K}_i \equiv \mathbf{P}$), for which they can either undertake productive ($x_{i_k} = 0$, e.g. agriculture) or conservation activities ($x_{i_k} = 1$). Denoted $B(\mathbf{x})$, the biodiversity level within the landscape depends on the whole vector of conservation efforts – denoted $\mathbf{x}$, with $\mathbf{x} = (x_{i_k})_{i_k \in \mathbf{P}}$, such that:

$$B(\mathbf{x}) = \sum_{i_k \in \mathbf{P}} \sum_{\substack{j_l \in \mathbf{P} \\ j_l \neq i_k}} x_{i_k} x_{j_l} \mathrm{e}^{-d_{i_k j_l}/D}, \tag{1}$$

where $d_{i_k j_l}$ is the distance between plots i_k and j_l and $D > 0$ is the dispersal rate of the considered species. Inspired by Wätzold and Drechsler (2014), equation (1) shows that biodiversity increases with the number of conserved plots. Yet, because D is positive, biodiversity is greater when the conservation efforts are more spatially clustered *ceteris paribus* (the larger D, the smaller the benefits of habitat agglomeration for biodiversity).

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[3] Such frictions are notably due to communication costs that landowners face when jointly enrolling in an AB scheme (Albers et al., 2008; Banerjee et al., 2017), which grow increasingly as coalition size increases (Banerjee et al., 2021). For another kind of friction, see Drechsler (2017) who introduces fairness considerations.

[4] Bold elements indicate vectors henceforth. For example, $\mathbf{I}$ is the vector of landowners, such that $i \in (1, ..., I)$.

Agglomeration bonus schemes. AB schemes typically consist of two elements: (i) a flat payment p to landowners for each conserved plot and (ii) a bonus q if this conserved plot stands next to another conserved plot. We assume that landowners only receive the bonus for plots within the same conservation project (Huber et al., 2021). In other words, they receive the bonuses only if the boundaries within two adjacent conserved plots belong to landowners cooperating *within the same coalition* (denoted by a vector $\mathbf{S}$ indicating the composition of a given coalition of size $|\mathbf{S}|$). The regulator can exploit landholding demarcations within the landscape to offer relatively greater – or lesser – rewards to *internal boundaries* (those between two plots belonging to the same landowner) or *external boundaries* (those between two plots belonging to different landowners), formulating respectively q^I (internal bonus) and q^E (external bonus). This distinction between internal and external bonuses translates into the individual payoff u_i of landowner i belonging to coalition $\mathbf{S}$ such that:

$$u_i(\mathbf{x_S}, |\mathbf{S}|) = \sum_{i_k \in \mathbf{K}_i} (p x_{i_k} + c_{i_k}(1 - x_{i_k})) + \sum_{i_k \in \mathbf{K}_i} (q^I \phi^I_{i_k} x_{i_k} + q^E \phi^E_{i_k} x_{i_k}) - \mathbb{1}_{|\mathbf{S}| \geq 2} C|\mathbf{S}|, \tag{2}$$

where $\mathbf{x_S}$ is the set of conservation decisions implemented by the landowners within $\mathbf{S}$ for their plots (i.e. $\mathbf{x_S} = (x_{i_k})_{i_k \in \mathbf{K}_i, i \in \mathbf{S}}$), c_{i_k} is the opportunity cost of conserving plot i_k and C is the individual coordination cost parameter when i cooperates within a coalition of size $|\mathbf{S}|$ (for $|\mathbf{S}| \geq 2$). The two remaining elements $\phi^I_{i_k}$ and $\phi^E_{i_k}$ respectively count the number of internal (within-landholding) and external (between-landholdings) boundaries to adjacent conserved plots belonging to the same conservation project.[5]

Coalition formation. We assume that landowners respond to the set of AB incentives by endogenously forming coalitions in which they sign up to conservation projects in common (Bareille et al., 2023). Formally, they play a two-stage game in which they choose both (i) with whom to cooperate, and (ii) which plots to conserve (within their coalition). The game's outcomes are the set of conservation decisions within stable coalition structures, i.e. the set of landowner partitions within mutually exclusive coalitions where no landowner wants to change coalition or is not accepted into another coalition.[6]

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[5] A landowner must conserve two adjacent plots to receive an internal bonus. Because they receive q^I for each plot, they get $2q^I$ in total for this boundary. If the first plot is also adjacent to a third conserved plot in the same landholding, then the landowner receives two additional bonuses (one for the first plot, another for the third plot). By comparison, two adjacent conserved plots belonging to two different landowners from the same coalition lead the two landowners to receive q^E each. Section 3.3 details how the payments are framed in alternative ABs based on fictitious examples.

[6] Note that we assume that landowners do not make side payments. Indeed, while side payments are implicitly authorized in the literature when maximizing the aggregated utilities of landowners within the grand coalition

Solving the problem by backward induction, the landowners choose their conservation efforts in the second stage to maximize the aggregated utility of all the landowners in the coalition that they belong to, that is:

$$\max_{\mathbf{x_S} \in \{0,1\}^{|\mathbf{S}|}} \sum_{i \in \mathbf{S}} u_i(\mathbf{x_S}, |\mathbf{S}|). \tag{3}$$

The solution of equation (3), denoted $\mathbf{x}^*_{\mathbf{S}}$, is the vector of conservation efforts over all the coalition's plots that maximize the coalition members' aggregate utility. Plugging $\mathbf{x}^*_{\mathbf{S}}$ back into equation (2) provides the set of individual payoffs for all landowners within coalition $\mathbf{S}$.

While the second stage consists of a cooperative game, the first stage consists of a non-cooperative game where landowners simultaneously decide whether and with whom to cooperate, anticipating the conservation decision they will take cooperatively within their coalition in the second stage. Coalition formation decisions depend on the comparison of the payoffs that each landowner can get in any coalition (Hart and Kurz, 1983). As a solution concept, we use the *internal and external stability conditions* (Barrett, 1994), adjusted to the exclusive membership case (Carraro and Marchiori, 2002). Formally, a coalition structure $\boldsymbol{\pi}$ is internally stable if none of the members of all the coalitions within $\boldsymbol{\pi}$ want to split off (and to act individually) nor want another member of their coalition to split off (and act individually). Formally, the internal stability condition states that $\forall \mathbf{S} \in \boldsymbol{\pi},\ \forall i, j \in \mathbf{S},\ j \neq i$:

$$u_i\left(\mathbf{x}^*_{\mathbf{S}}, |\mathbf{S}|\right) > u_i\left(\mathbf{x}^*_{\{i\}}, |\{i\}|\right) \text{ and } u_i\left(\mathbf{x}^*_{\mathbf{S}}, |\mathbf{S}|\right) > u_i\left(\mathbf{x}^*_{\mathbf{S}\setminus\{j\}}, |\mathbf{S}\setminus\{j\}|\right). \tag{4}$$

The external stability condition states that, for any coalition and any landowner external to it, either the landowner is unwilling to join the coalition or at least one member of the coalition is unwilling to accept this landowner as a new coalition member. Formally, the external stability condition states that $\forall \mathbf{S}, \mathbf{S}' \in \boldsymbol{\pi},\ \mathbf{S}' \neq \mathbf{S},\ \forall i \in \mathbf{S}'$:

$$u_i\left(\mathbf{x}^*_{\mathbf{S}'}, |\mathbf{S}'|\right) > u_i\left(\mathbf{x}^*_{\mathbf{S}\cup\{i\}}, |\mathbf{S}\cup\{i\}|\right) \text{ or } \exists\ j \in \mathbf{S} \text{ s.t. } u_j\left(\mathbf{x}^*_{\mathbf{S}}, |\mathbf{S}|\right) > u_j\left(\mathbf{x}^*_{\mathbf{S}\cup\{i\}}, |\mathbf{S}\cup\{i\}|\right). \tag{5}$$

Solving for equations (4) and (5) provides a set of stable coalition structures $\boldsymbol{\pi}$. Coupled with equations (1) to (3), the associated conservation decisions within the coalitions of the same

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(Wätzold and Drechsler, 2014; Drechsler, 2017), monetary side payments have not been formally observed in real-world AB applications (Nguyen et al., 2022). The most realistic hypothesis certainly lies somewhere in between, since landowners may decide to help each other other than financially. However, modeling of this aspect goes beyond the objective of this paper.

stable coalition structure allow us to compute the biodiversity level at the landscape scale and the regulator's total payments to landowners. The total payments for $\boldsymbol{\pi}$ are given by:

$$TP(\boldsymbol{\pi}) = \sum_{i_k \in \mathbf{K}_i, i \in \mathbf{S} \in \boldsymbol{\pi}} (px^*_{i_k} + q^I \phi^I_{i_k} x^*_{i_k} + q^E \phi^E_{i_k} x^*_{i_k}). \tag{6}$$

Regulator's problem. As there may be several stable coalition structures for a given landscape, we assume that the regulator focuses on the maximum average biodiversity level for a range of average total payments (covering all stable coalition structures). Formally, the regulator's problem can be written as follows:

$$\max_{q^I, q^E} \sum_{\boldsymbol{\pi} \in \boldsymbol{\Pi}} \frac{1}{|\boldsymbol{\Pi}|} B(\mathbf{x}^*), \tag{7}$$

such that:

$$\sum_{\boldsymbol{\pi} \in \boldsymbol{\Pi}} \frac{1}{|\boldsymbol{\Pi}|} TP(\boldsymbol{\pi}) \leq \overline{TP}, \tag{8}$$

where $\mathbf{x}^*$ is the vector of binary conservation decisions for coalition structure $\boldsymbol{\pi}$, $\boldsymbol{\Pi}$ is the set of stable coalition structures induced by q^I and q^E, and $\overline{TP}$ is a given budget available to the regulator constraining the total payments made to landowners.

2.2 Empirical implementation

We numerically solve the model previously described with mathematical programming. We apply the model to a set of fictitious grid landscapes composed of seven landowners owning seven plots each, the distance between the centroids of two adjacent plots being normalized to one. Figure 1 shows the structure of the type of landscapes generated.[7]

While simplistic, we believe that our hexagonal set-up provides a reasonable approximation to real landscapes. Indeed, although plots from the same landholding can be fragmented over space (Drechsler, 2023), most of them are usually agglomerated in large patches (e.g. Moravcová et al., 2017).[8] To represent the natural heterogeneity of real landscapes, we created 50 fictitious land-

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[7] See Appendix A1 for a discussion of the merits of this landscape structure over a squared landscape.

[8] To our knowledge, all AB studies but Drechsler (2023) have considered continuous landholdings made of contiguous plots (e.g. Parkhurst and Shogren, 2007; Panchalingam et al., 2019; Bareille et al., 2023). This notably reflects modern agricultural landscapes following land consolidation programs in the second half of the twentieth century (Philippe and Polombo, 2009; Moravcová et al., 2017; Chabé-Ferret and Enrich, 2021). As such, even Drechsler (2023) considers that landholdings usually present a higher proportion of internal than external boundaries and he thus showed that the AB is more cost-effective when dealing with continuous landholdings than fragmented ones.

scapes with randomized opportunity costs. Specifically, the plot-level opportunity cost c_{i_k} is drawn from a uniform distribution with values ranging from €110/plot to €250/plot while imposing a spatial cost auto-correlation at a Moran's index of 0.8. This latter value creates landscapes composed of clusters of plots with low opportunity costs and clusters with high opportunity costs, thus resembling the actual distribution of soil quality in real landscapes. Finally, we randomly apply landowner-level shifters of ±€45/plot to the generated landscapes to additionally represent the impacts of landowners' characteristics on opportunity costs (e.g. difference in landowners' knowledge, machinery, etc.). Figure 1 represents the average opportunity costs of all the plots within our 50 randomly generated landscapes.[9]

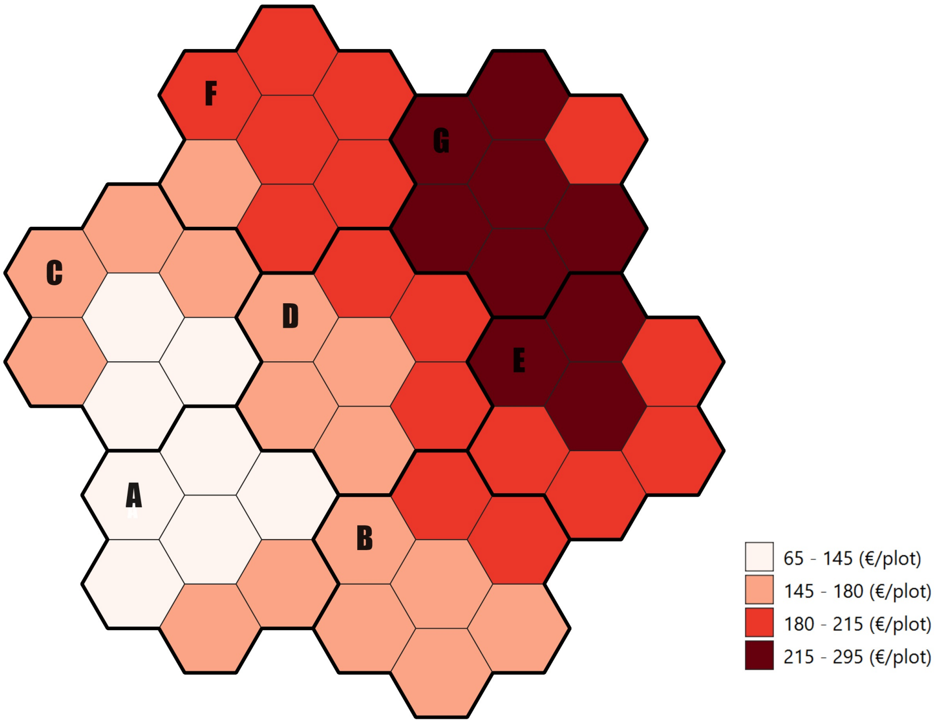

Figure 1: Landscape structure and average cost per plot.

NOTE. Plot colors indicate average plot opportunity cost across the 50 generated landscapes. White lines are the internal boundaries ($12 \times 7 = 94$ internal boundaries in total within the landscape). Black lines are landholding boundaries, of which a subset constitutes the external boundaries (36 in total within the landscape). Black letters are landowner identifiers.

To focus on the relative role of the internal and external bonuses, we set the flat payment to zero ($p = 0$). Setting $D = 2$ and $C = 0.5$, we run the models for varying levels of internal and external bonuses on the 50 landscapes, until the full landscape is covered by natural habitats. For sake of clarity, we note $AB(z, 100 - z)$ with $z = 100 \times q^I/(q^I + q^E)$ the AB scheme being made of

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[9] Figure A1 in the Supplementary Material shows the distribution of opportunity costs in four of the 50 generated fictitious landscapes. While the structure closely resembles the averages, the structure of each landscape is unique though they are all comparable.

$z\%$ internal bonuses and $(100-z)\%$ of external bonuses. For example, $AB(67,33)$ indicates an AB scheme that rewards internal bonuses around twice as much as external bonuses.

3 Results

This section first reports differences in cost-effectiveness across alternative AB schemes (Section 3.1). Section 3.2 investigates whether the differences in cost-effectiveness are linked to differences in cooperation levels between the alternative AB schemes. Section 3.3 focuses on the relative additionality of internal and external bonuses as a key mechanism explaining our results.

3.1 Cost-effectiveness

Figure 2 shows the biodiversity levels reached on average over all the stable coalition structures of the 50 landscapes as a function of total payments for five AB schemes with varying proportions of internal and external bonuses, from $AB(0,100)$ – where 100% of the payments are for external bonuses – to $AB(100,0)$ – where 100% of the payments are for internal bonuses. It clearly shows that increasing the proportion of internal bonuses (almost) always improves AB cost-effectiveness: for a given level of total payments from the regulator to the landowners, the biodiversity level increases as the proportion of internal bonuses increases.[10] Specifically, the least cost-effective AB scheme is $AB(0,100)$, followed by the $AB(20,80)$ and $AB(33,67)$, whatever the level of total payments.[11]

However, Figure 2 shows that the ranking of the two most cost-effective AB schemes – $AB(50,50)$ and $AB(100,0)$ – depends on the regulator's budget. Specifically, $AB(100,0)$ is the most cost-effective when total payments exceed €5,500 (where the two curves cross each other; see Figure A3 in Supplementary Material for a zoom).[12] On the contrary, $AB(50,50)$ is more cost-effective (up to +15% biodiversity compared to $AB(100,0)$) when total payments are smaller. This indicates that, while a regulator will prefer to reward internal bonuses only when their budget is larger than €5,500, they will prefer to reward internal and external bonuses equally for tighter budgets. Figure A4 in the Supplementary Material confirms this pattern. Specifically, it shows

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[10] This also works in the other direction: for a given biodiversity level, total regulator payments to landowners decrease as the proportion of internal bonuses increases.

[11] The maximum level of biodiversity in the $AB(0,100)$ scheme (about 0.17) is achieved for a budget of about €6,500. Increasing the budget does not increase biodiversity, as the remaining plots to conserve in $AB(0,100)$ are those along the internal boundaries. By comparison, scheme $AB(20,80)$ achieves a fully preserved landscape for a budget of about €24,500, while scheme $AB(33,67)$ requires about €21,000.

[12] Scheme $AB(100,0)$ leads to a fully conserved landscape for a budget of €13,500, whereas €15,500 is required for $AB(50,50)$.

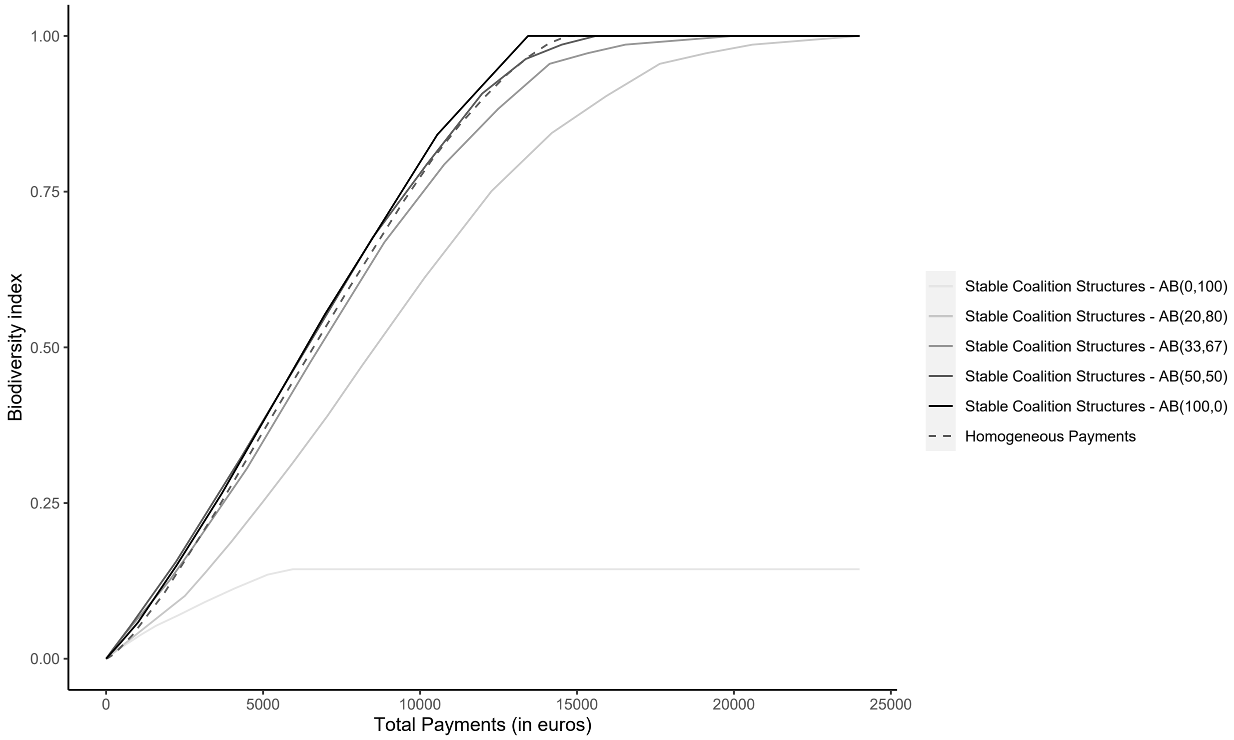

Figure 2: Cost-effectiveness of alternative AB schemes within stable coalition structures.

NOTE. The figure shows the normalized biodiversity level as a function of total payments for homogeneous payment schemes (dashed line) and for alternative AB schemes $AB(z, 100 - z)$ within the stable coalition structures (solid lines, ranging from light grey to black). The AB scheme $AB(z, 100 - z)$ with $z = 100 \times q^I/(q^I + q^E)$ denotes the AB rewarding the internal bonus $z/(1 - z)$ times more than the external bonus. The simulations were performed using $p = 0$, $D = 2$ and $C = 0.5$. The outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes.

that $AB(100, 0)$ is generally the most cost-effective AB scheme, except for small budgets, where $AB(67, 33)$ and $AB(80, 20)$ schemes can be more cost-effective. Although still relatively limited, the increase in biodiversity enabled by these two schemes expands over larger ranges of total payments: from €0 to €6,500 for $AB(67, 33)$ and from €0 to €8,500 for $AB(80, 20)$. Hence, if the budget is limited to €8,500, the regulator will prefer a scheme that couples internal bonuses with small external bonuses (about a quarter of the level of the internal bonus), rather than rewarding internal bonuses only.[13]

3.2 Cooperation

The greater cost-effectiveness of AB schemes that reward more internal than external bonuses raises questions about the extent of cooperation in these ABs. Indeed, while it is generally believed that

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[13] Confirming our results, Table A1 in the Supplementary Material provides more detailed information on changes in biodiversity levels and total payments depending on *internal* and *external bonus values*. It also provides detailed information on AB cost-effectiveness, computed as the ratio of biodiversity over total payments.

ABs are more cost-effective than homogeneous payments because they encourage landowners to decide cooperatively which adjacent plots to conserve (unlike homogeneous payments, for which conservation decisions are made individually), our results in Section 3.1 suggest a different pattern. Specifically, they show that the most cost-effective ABs are those with little or no external bonuses, which does not inherently encourage the formation of coalitions in which landowners cooperate.[14] To explicitly investigate how cooperation among landowners changes across the alternative AB schemes, Figure 3 shows changes in average coalition size within the stable coalition structures as a function of total payments for the alternative AB schemes.

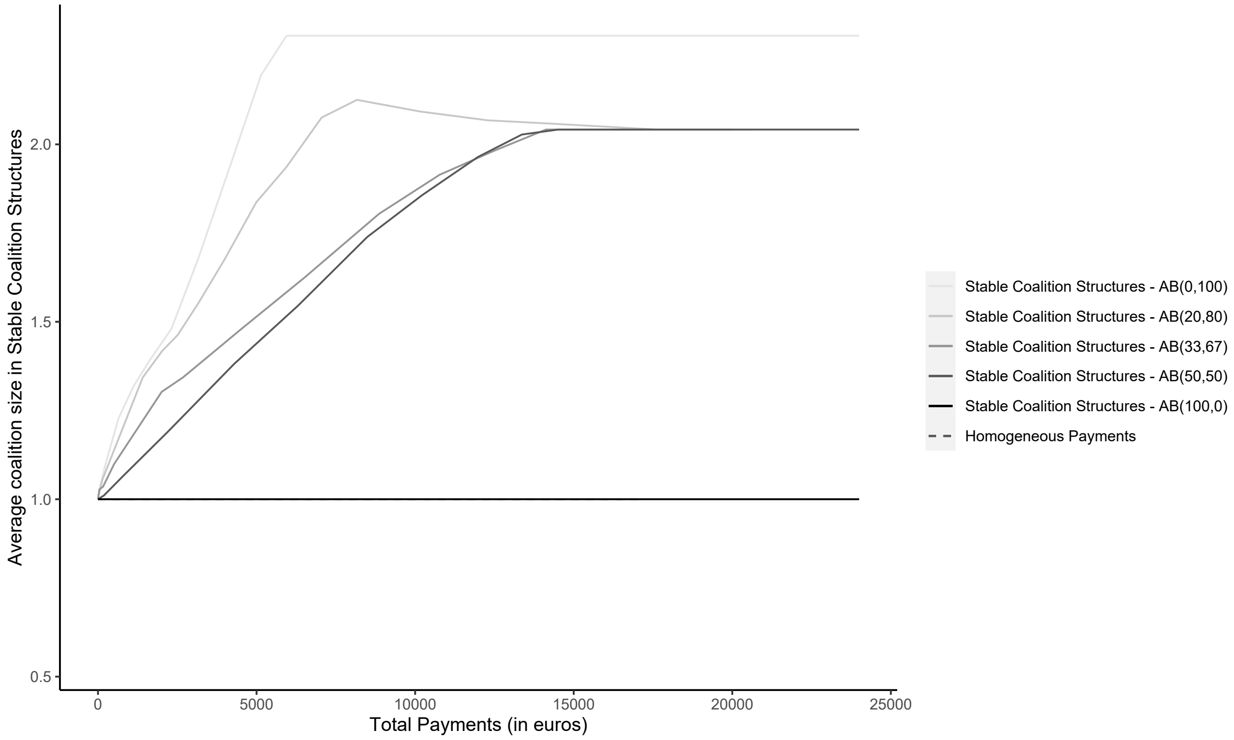

Figure 3: Coalition size within stable coalition structures responding to alternative AB schemes.

NOTE. The figure shows average coalition size within stable coalition structures as a function of total payments for alternative AB schemes $AB(z, 100 - z)$ (solid lines, ranging from light grey to black) and homogeneous payment schemes (dashed line). AB scheme $AB(z, 100 - z)$ with $z = 100 \times q^I/(q^I + q^E)$ denotes the AB rewarding internal bonuses $z/(1 - z)$ times more than external bonuses. The simulations were performed using $p = 0$, $D = 2$ and $C = 0.5$. Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes. An average coalition size of one – as for homogeneous payments and $AB(100, 0)$ – means that landowners enroll individually within the scheme.

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[14] For example, landowners will only apply individually to the $AB(100, 0)$ scheme, as it offers no benefits from cooperation. By comparison, landowners will only apply collectively to $AB(0, 100)$, as conserving plots with no external boundaries is unrewarded under this scheme. That is, landowners have incentives to conserve only plots along external boundaries with $AB(0, 100)$. Given that AB schemes considered first and second are respectively the most and least cost-effective ABs (see Figure 2), these two contrasting examples draw an intuitive pattern where AB cost-effectiveness and landowner cooperation are negatively linked.

Figure 3 confirms the intuition. For example, it shows that the least cost-effective AB scheme – $AB(0, 100)$ – is the one that allows the largest coalitions to be formed, and therefore most favors cooperation.[15] Figure 3 actually shows that the average coalition size decreases as the proportion of internal bonuses within the AB schemes increases. For a given budget, there are larger coalitions in $AB(0, 100)$ than in $AB(20, 80)$, which in turn has larger coalitions than $AB(33, 67)$, and so on. As long as both internal and external bonuses are rewarded, landowners in alternative AB schemes respond to high total payments by forming average stable coalition structures typically consisting of one three-landowner coalition, one two-landowner coalition and two singletons. However, when internal boundaries alone are rewarded, landowners apply individually to the AB scheme.

To sum up, we have two cases to distinguish, depending on the size of the regulator's budget: (i) if the budget is large enough (above €5,500 in Figure 2), the most cost-effective AB scheme is $AB(100, 0)$ where no landowner cooperates, vs. (ii) if the budget is tight (below €5,500 in Figure 2), the most cost-effective AB scheme is one where some landowners cooperate, but where the extent of cooperation remains limited – e.g. the $AB(50, 50)$ scheme in Figure 2, with an average coalition size below 1.25 (see Figure 3).

3.3 Mechanisms

To illustrate the mechanisms behind our main results, Figure 4 shows landowners' conservation (and cooperation) decisions in response to four contrasting AB schemes, with total payments held constant. Figure 4 specifically shows the landowners' decisions in two polar cases – $AB(100, 0)$ in (a) vs. $AB(100, 0)$ in (b) – and two interior cases. One of the latter has high external bonuses, $AB(25, 75)$, in (c) while the other has high internal bonuses, $AB(75, 25)$, in (d).[16] Here, we focus on the case where total payments are sufficiently low (specifically equal to €1,800), in order to illustrate the case where internal and external bonuses have some degree of complementarity (see Section 3.1). Since the four schemes lead to the same total payments, their cost-effectiveness ranking is the same as their biodiversity ranking.

Figure 4 illustrates the two advantages of internal over external bonuses. First, they can lead to conservation of plots located away from landholding boundaries, which is not the case with external bonuses. To illustrate this, let us compare the landowners' decisions under the scheme in (a) with

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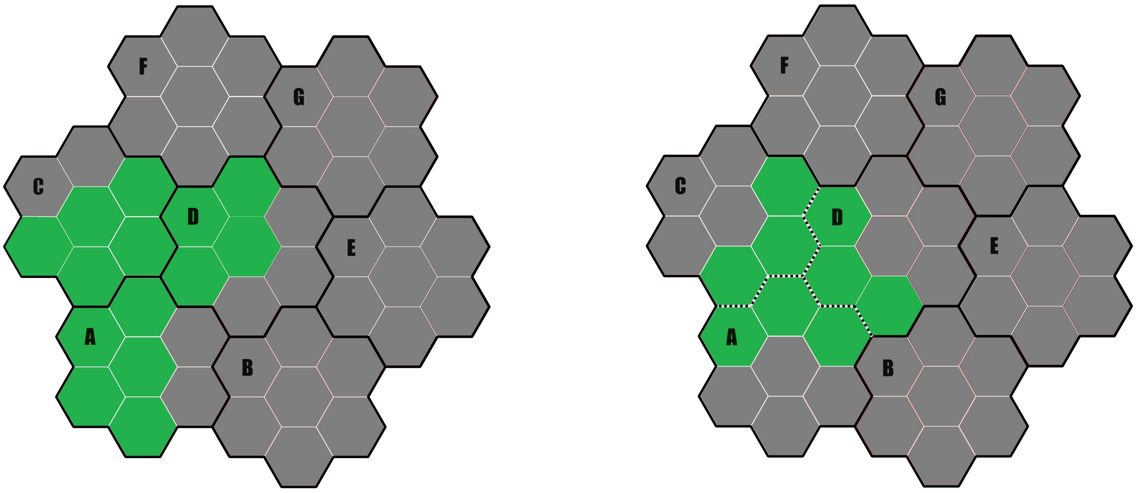
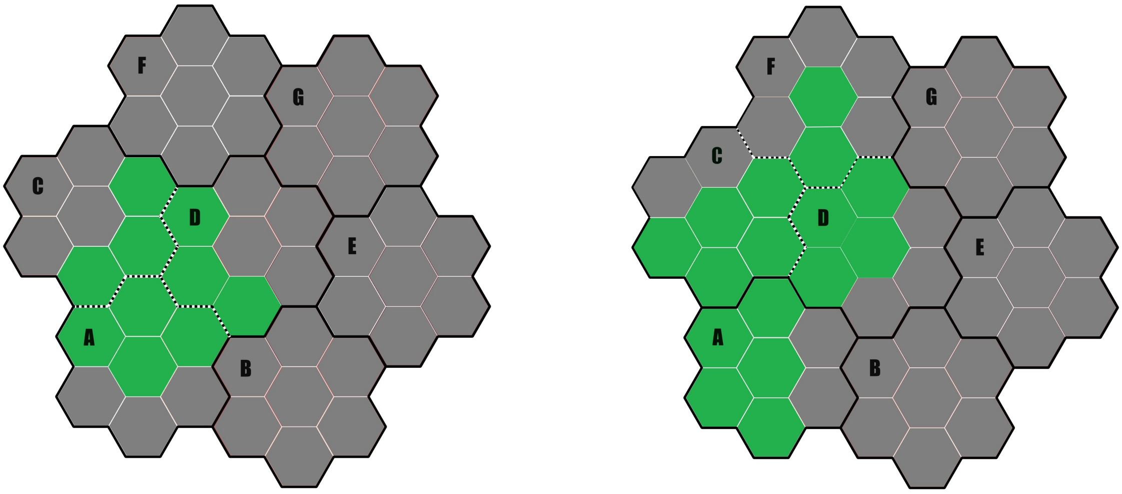
[15] In any case, coalition size remains limited. For large total payments, the average stable coalition structure in $AB(0, 100)$ consists of one three-landowner coalition and two two-landowner coalitions (for an average coalition size of 2.33). That is, landowners do not cooperate all together within the grand coalition, even when the rewards can be attained via external bonuses – and thus via cooperation only.

[16] The opportunity cost distribution corresponding to the decisions taken in Figure 4 are provided in Figure A6 in the Supplementary Materials.



(a) $AB(100,0)$
$q^{I} =$ €50 & $q^{E} =$ €0
Biodiversity= 0.14, Total payments=€1,800

(b) $AB(0,100)$
$q^{I} =$ €0 & $q^{E} =$€100
Biodiversity= 0.07, Total payments=€1,800



(c) $AB(25,75)$
$q^{I} =$ €25 & $q^{E} =$ €75
Biodiversity= 0.08, Total payments=€1,800

(d) $AB(75,25)$
$q^{I} =$ €45 & $q^{E} =$ €15
Biodiversity= 0.15, Total payments=€1,800

Figure 4: Conservation decisions in response to alternative AB schemes, at constant budget.

NOTE. The figure shows the conservation decisions (green for conserved plot; grey for productive plot) within stable coalition structures responding to alternative AB schemes. The alternative AB schemes are characterized by different internal and external bonuses (q^{I} and q^{E} respectively). To ensure comparability between the different AB schemes, all the cases represent the conservation decisions reached for total regulator payments to landowners of €1,800. An example of implicit opportunity costs across the landscape corresponding to the conservation decisions displayed in the figure is shown in Figure A6 in the Supplementary Material. Black letters are landowner identifiers. Black lines are landholding boundaries. Dashed lines between landholdings indicate coalitions. For example, in (b), landowners A, C and D form coalition $\{A,C,D\}$ in response to the $AB(0,100)$ scheme (there is no other coalition in this stable coalition structure). Note that the figures show, for each AB scheme, the conservation decisions within one stable coalition structure only (out of the many possible such structures) for one particular fictitious landscape. This is to facilitate results presentation, but there are other stable coalition structures for the AB schemes under consideration in the considered fictitious landscape (for which the conservation decisions can differ).

those in (b) in Figure 4. Moving from (a) to (b) means that the regulator switches from a 100% internal bonus of €50 to a 100% external bonus of €100, leaving total payments unchanged. In (b), no plots other than those located on landholding boundaries are conserved (but nine plots on the landholding boundaries of A, C and D are conserved), while six of those plots with internal boundaries only are conserved in (a) – as well as eight plots on landholding boundaries. Second, internal bonuses enable compensation to occur between a smaller number of plots (to be conserved) than external bonuses, so they are likely to lead to more conservation. To illustrate this, let us focus on landowner D. In (a), D conserves four plots individually,[17] whereas they need to cooperate with A and C in (b) to jointly decide to conserve (at least seven) plots with external boundaries within $\{A, C, D\}$, in order to conserve three plots in D's landholding.[18] Cooperation induced by external bonuses thus implies more complex compensation solutions between plots than can be achieved by landowners acting alone with internal bonuses.

Figure 4 also clearly illustrates how the internal and external bonuses interact. On the one hand, it illustrates the possible complementarity between the two bonuses. Indeed, the ranking of the different schemes, in terms of cost-effectiveness, is $(d) > (a) > (c) > (b)$ with corresponding biodiversity levels of 0.15, 0.14, 0.08 and 0.07 respectively, the best scheme being $AB(75, 25)$ with high internal bonuses and low external bonuses. On the other hand, it illustrates situations where the two bonuses are substitutable. Indeed, the second best scheme is that with internal bonuses alone in (a), far ahead of those in (c) with a high proportion of external bonuses and those in (b) with external bonuses only.

To understand how the complementarity between the two bonuses works, let us compare schemes in (a) and (d) in Figure 4. Moving from (a) to (d) means that the regulator decreases the internal bonus by €5 (from €50) and increases the external bonus by €15 (from €0), leaving the total payments unchanged. Landowners A, C and D do not change their conservation decisions. Landowner F is the only one to change their decision, conserving two plots in (d) thanks to their cooperation with C and D.[19] Landowner F does not conserve these two plots in (a) because their opportunity costs are above the internal bonuses they would receive for conserving them: the total opportunity

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[17] In this case, D receives a total of €400 of internal bonuses, for a total opportunity cost of €395.

[18] Here D receives €600 of external bonuses for a total opportunity cost of €367. That is, D' windfall benefits are greater in (b) than in (a). A similar pattern appears with landowners A and C, who respectively receive windfall benefits of €246 and €310 in (b), but only €161 and €158 in (a).

[19] Note that the stable coalition structure – with A on the one hand and $\{C, D, F\}$ on the other – is only one of the two possible stable coalition structures that emerge under the AB scheme in (d). Indeed, a coalition structure consisting of landowners A, C and D cooperating, with landowner F not applying to the scheme, is also stable. While it would lead to greater biodiversity than with the scheme in (a), such a stable coalition structure leads to greater total payments, and thus it is not a suitable candidate for our example.

costs for these two plots is €133=€66+€67 whereas the total internal bonuses would be only €100. By cooperating with C and D in (d), F conserves these two plots because they receive the two types of bonuses (with associated payments of $2\times q^I + 3 \times q^E =$ €135), which together exceed their aggregated opportunity cost. In a nutshell, combining external and internal bonuses here leads to increased conservation by landowner F without reducing conservation by the other landowners. As a consequence, it increases biodiversity without affecting total payments and thus improves AB cost-effectiveness.

To understand how the substitutability between the two bonus types works, let us compare schemes (a) and (c) in Figure 4. Moving from (a) to (c) means that the regulator switches from pure internal bonuses (of €50) to smaller internal bonuses (of €25) coupled with large external bonuses (of €75), again leaving total payments unchanged. In (a), all but one plot on the boundaries between the landholdings of A, C and D are conserved (i.e. eight plots) as well as six of their other plots. In (c), all nine plots on the boundaries between these three landholdings are conserved cooperatively, thanks to the large external bonuses, but only one other plot is conserved because the internal bonus is too low. Hence, there is not much difference between the two bonuses in their propensity to incentivize the conservation of plots on landholding boundaries, but the internal bonus enables the conservation of many more plots not on boundaries. In plain English, replacing a large proportion of internal by external bonuses means halving biodiversity for the same budget. From the regulator side, there is thus a possible substitution between internal and external bonuses, with the former having a clear advantage over the latter. As shown in (d), only when the regulator replaces a small proportion of internal with external bonuses does AB cost-effectiveness increase – i.e. internal and external bonuses are then complementary.

4 Conclusion

Scientists and policymakers are paying increasing attention to collective biodiversity conservation schemes (Westerink et al., 2017; Kotchen and Segerson, 2020; Arora et al., 2021; Nguyen et al., 2022). Initially proposed by Parkhurst et al. (2002), the AB is probably the best known of these collective instruments. Using a stylized model and simulations, we show in this paper that the most cost-effective agglomeration of conservation efforts can generally be achieved without (much) cooperation between landowners. Our results have obvious policy implications. They particularly indicate how better AB design can increase its cost-effectiveness. They strongly encourage the formulation of ABs specially targeting internal landholding boundaries when the regulator is not too financially constrained. They also suggest that complementing these internal bonuses with small external bonuses can improve AB cost-effectiveness when the regulator's budget is tightly constrained.

Given the high levels of heterogeneity in the problem under consideration, our results are grounded on numerical resolutions of a model of landowners' endogenous cooperation response to alternative sets of AB incentives on a set of realistic landscapes. Our results thus likely reflect rational and realistic landowners' responses to possible ABs that may be implemented in reality. They do however reflect some assumptions that we have made for simplicity, e.g. the absence of side-payments between landowners (Drechsler, 2017), the continuous structure of landholdings (Drechsler, 2023) and the rules governing coalition membership (Barrett, 1994; Carraro and Marchiori, 2002). Future research may investigate how the advantages of internal over external bonuses are affected when our assumptions relating to these aspects are weakened.

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Supplementary Material

A1 Hexagonal vs. squared landscape

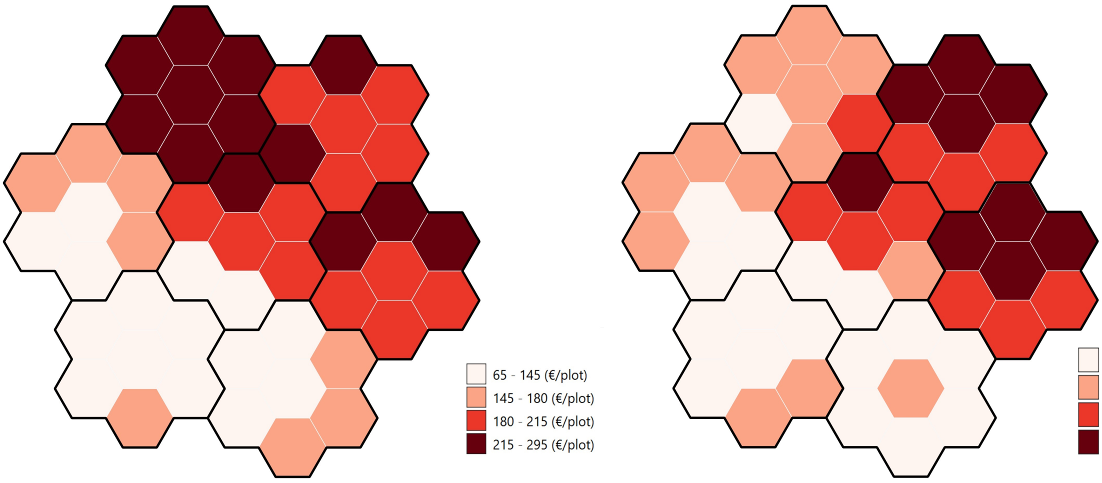
Our hexagonal landscape presents several advantages over a squared one (Bareille et al., 2023, considered a squared landscape made of 9 × 9 plots for example). First, it reduces the numerical resolution time. Indeed, while the number of coalition structures to consider is $Bell(9) = 21,147$ with nine landowners, there are only $Bell(7) = 877$ alternative coalition structures with seven landowners. The resolution of the program with seven landowners over all the cases that we consider in the following approximately takes about two days with the CPLEX 41.5.0 version of GAMS on a computer with an Intel(R) Core(TM) i9-12900H 2.50 GHz processor (64 Go of RAM). By comparison, the resolution of the program with the squared landscape made of 9 × 9 plots would take about ten days with the same computer.

Second, all the peripheral landowners (i.e. all landowners except landowner D, see Figure 1) present the same relative space compared to the central landowner (i.e. landowner D), thus all presenting the same numbers of internal and external boundaries. This is a sharp difference with the squared landscape, where peripheral landowners have a different number of external boundaries. That is, compared to a squared set-up, our hexagonal landscapes allow greater symmetry between landowners.

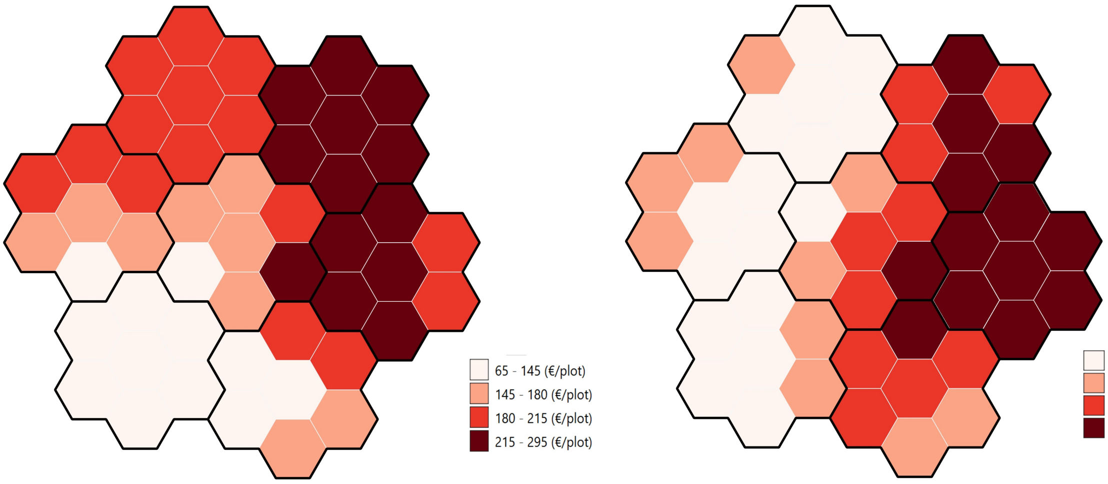
Three, the proportion of external boundaries is slightly larger. In total, our landscapes respectively present 84 and 36 internal and external boundaries, compared to 108 and 36 internal and external boundaries in a squared landscape of 9 × 9 plots. That is, hexagonal landscapes gives a more even proportion of internal and external boundaries within the landscape. The greater proportion of external boundaries in our set-up comes from the fact that hexagonal plots with external boundaries always have at least two external boundaries (three for the plots located on landholdings' corners), while squared plots have at most two external boundaries (for the plots that are located on the landholdings' corners).

A2 Landscape cost randomization

Figure A1 shows the distribution of the plots' conservation opportunity costs in €/plot across four generated landscapes that we use for our simulations (four out of 50 in total). All the landscapes are different, but have a similar type of distribution to represent coherent landscapes, comparable in terms of both geography and topography. Average opportunity cost distribution is displayed in the main text in Figure 1.



(a) Random landscape n°1 (b) Random landscape n°2



(c) Random landscape n°3 (d) Random landscape n°4

Figure A1: Examples of cost randomization for four landscapes.

NOTE. The figures display the average profitability of the productive activity (i.e.‘ opportunity costs of conservation) of the plots across the landscape for four fictitious landscapes – out of 50 – generated for the purpose of our simulation exercise.

A3 Cost-effectiveness: benchmark calibration

Figure A2 shows the cost-effectiveness of the AB scheme $AB(67, 33)$ within the grand coalition and stable structures compared to homogeneous payments.The x-axis shows total public payments and the y-axis the normalized biodiversity level – as depicted in equation (1) given the landscape structure $\mathbf{x}$ obtained under the modeled payments, and divided by the value of biodiversity in equation (1) when all plots are conserved.

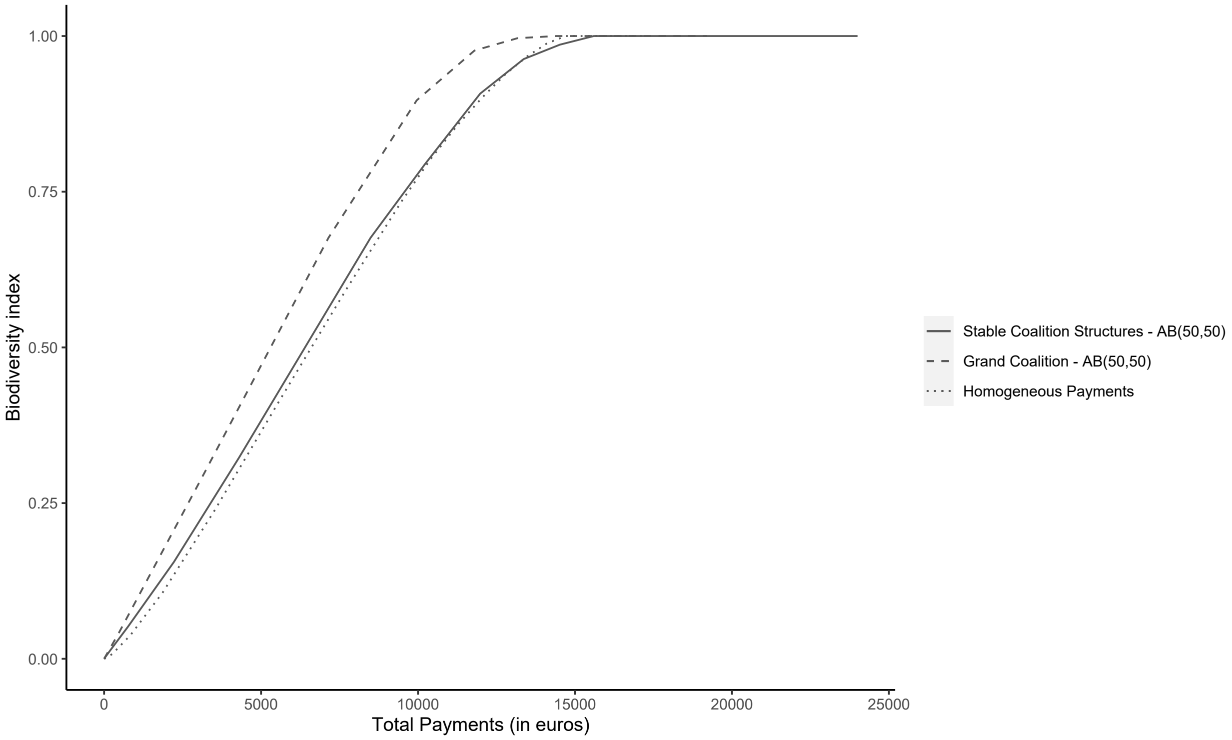


Figure A2: Cost-effectiveness of the AB scheme $AB(67, 33)$ within the grand coalition and stable coalition structures compared to homogeneous payments.

Note. The figure shows the normalized biodiversity level as a function of total payments for homogeneous payments for the AB scheme $AB(67, 33)$ within the grand coalition (exogenously assumed but not stable) and the stable coalition structures (endogeneously derived from the coalition formation game and thus stable). The simulations were performed using $p = 0$, $D = 2$ and $C = 0.5$. Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes.

Specifically, Figure A2 aims to reproduce the main figure in Bareille et al. (2023), who consider the case where $q^I = q^E$, but adapting it to our specific landscape structure. In other words, it provides a means of validating our calibration for the case where internal and external premiums are equal. Despite some minor differences, Figure A2 is very similar to the main result in Bareille et al. (2023). Specifically, it shows that, by assuming the stability of the grand coalition, the literature usually overestimates the cost-effectiveness of the AB. Compared to the landscapes formed by the grand coalition, the stable coalition structures that are endogenously formed in response to the AB lead to landscapes that are about 5% to 10% less cost-effective for biodiversity conservation. This is valid for the whole range of total payments. In line with Bareille et al. (2023), we also find that the homogeneous payments lead to landscapes that are globally less cost-effective than those endogenously reached in response to $AB(50, 50)$ for stable coalition structures, except for high levels of total payments. Though the difference in cost-effectiveness between the two schemes is smaller in our case, we find that our set-up is able to produce results similar to theirs. As such, the results obtained with $AB(50, 50)$ form the benchmark for the remainder of our analyses in Section 3 of the main text.

A4 Cost-effectiveness: zoom of Figure 2

Figure A3 zooms on Figure 2 for low budgets, highlighting the range of total payments where external bonuses can complement internal bonuses.

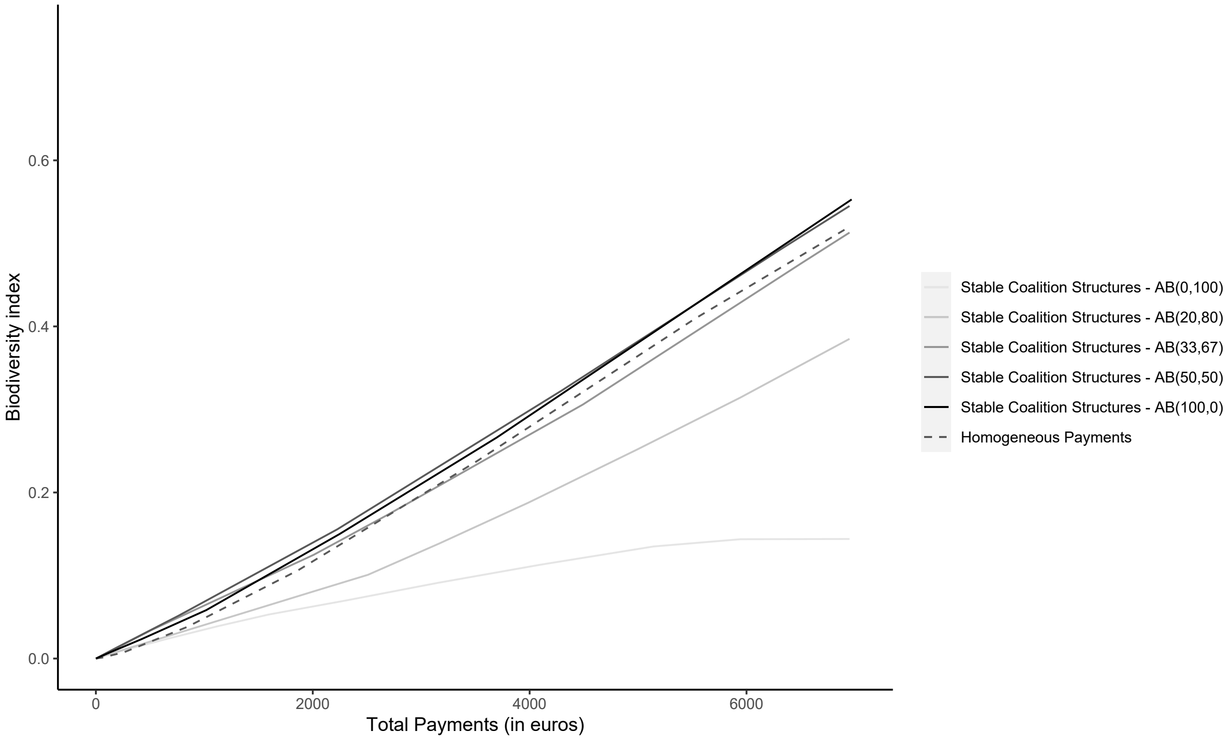


Figure A3: Cost-effectiveness of alternative AB schemes within stable coalition structures compared to homogeneous payments.

Note. The figure zooms on the normalized biodiversity level as a function of total payments (up to €7,000) for homogeneous payments and for the AB scheme $AB(z, 100 - z)$ within stable coalition structures. The AB scheme $AB(z, 100 - z)$ with $z = 100 \times q^I/(q^I + q^E)$ denotes the AB rewarding the internal $z/(1 - z)$ times more than the external bonus. The simulations were performed using $p = 0$, $D = 2$ and $C = 0.5$. Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes.

A5 Cost-effectiveness: additional results for alternative AB schemes

Figure A4 shows the cost-effectiveness of additional AB schemes than those presented in Figure 2. It shows that, for large budgets, $AB(100, 0)$ is the most cost-effective AB scheme, while, for smaller budgets, AB schemes that additionally (slightly) reward external bonuses can improve AB cost-effectiveness to a reasonable extent.

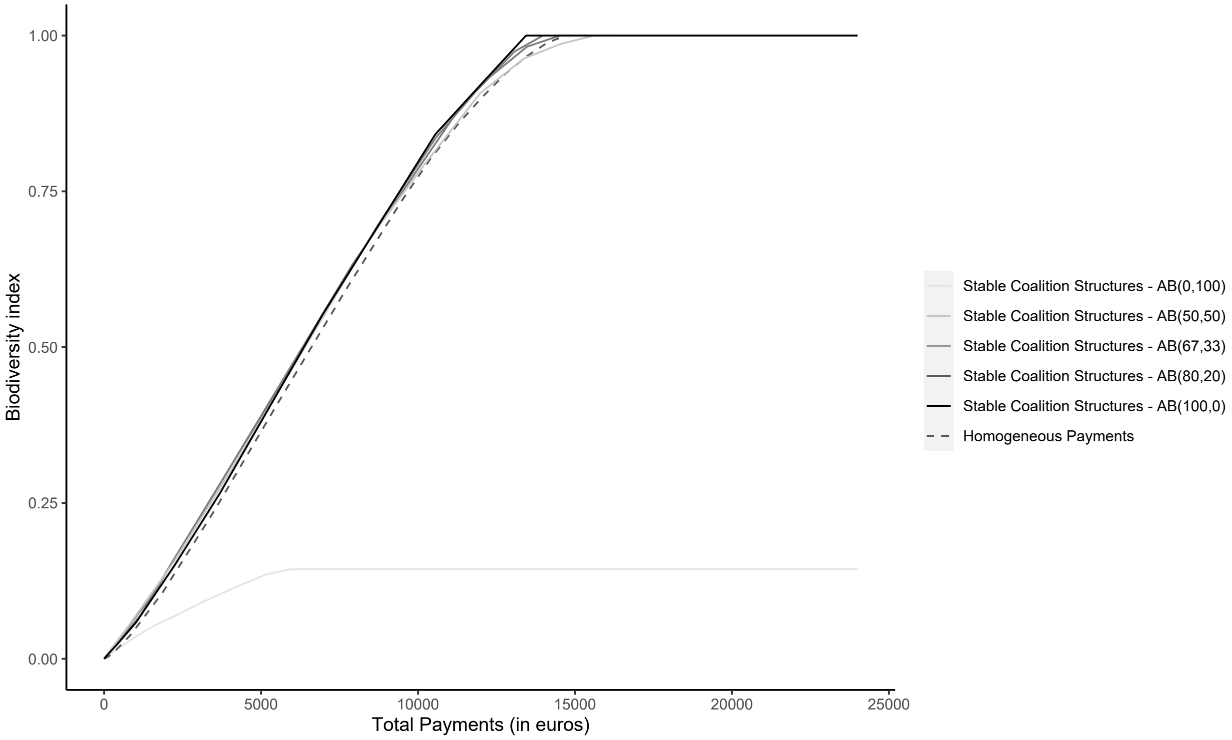


Figure A4: Cost-effectiveness of alternative AB schemes within stable coalition structures compared to homogeneous payments.

Note. The figure shows the normalized biodiversity level as a function of total payments for homogeneous payments for the AB scheme $AB(z, 100 - z)$ within stable coalition structures. The AB scheme $AB(z, 100 - z)$ with $z = 100 \times q^I/(q^I + q^E)$ denotes the AB rewarding the internal $z/(1 - z)$ times more than the external bonus. The simulations were performed using $p = 0$, $D = 2$ and $C = 0.5$. Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes.

A6 Cost-effectiveness: detailed outcomes by pairs of internal and external bonuses

Table A1 shows how AB cost-effectiveness (Panel C.) –computed here as the ratio of biodiversity over total payments– as well as its numerator (biodiversity, Panel A.) and denominator (total payments, Panel B.), change depending on internal and external bonuses. Each pair of q^I and q^E corresponds to a unique AB scheme. For example, a scheme pairing an internal bonus of €60 with an external bonus of €20 corresponds to a particular level of $AB(75, 25)$ scheme.

Table A1: Biodiversity, payments and cost-effectiveness depending on internal and external bonuses

		Internal bonus						
		0	**20**	**40**	**60**	**80**	**100**	**120**
		A. Biodiversity						
External bonus	**0**	0.00	0.00	0.06	0.55	1.00	1.00	1.00
	20	0.00			0.67			1.00
	40	0.00			0.75			1.00
	60	0.00	0.02	0.24	0.79	1.00	1.00	1.00
	80	0.02			0.84			1.00
	100	0.05			0.87			1.00
	120	0.07	0.09	0.40	0.88	1.00	1.00	1.00
		B. Total payments						
External bonus	**0**	0	0	1,018	6,970	13,440	16,800	20,160
	20	0			8,286			20,700
	40	0			9,356			21,240
	60	44	350	3,470	10,213	18,020	19,900	21,780
	80	648			11,159			22,320
	100	1,593			11,821			22,860
	120	2,314	2,919	6,320	12,491	19,640	21,520	23,400
		C. Cost-effectiveness						
External bonus	**0**	-	-	57.29	79.99	74.40	59.52	49.60
	20	-			80.86			48.31
	40	-			79.96			47.08
	60	40.54	52.01	70.17	77.72	55.49	50.25	45.91
	80	36.13			76.07			44.80
	100	33.26			73.25			43.74
	120	20.29	32.11	63.82	70.69	50.92	46.47	42.74

Note. The table shows the outcomes of alternative AB schemes, averaged over all stable coalition structures over the 50 landscapes, as functions of internal and external bonuses. The bonuses are expressed in euros/boundary. Panel A. provides the levels of biodiversity, normalized so that a value of 1.00 corresponds to a landscape where all plots are conserved. Panel B. presents the total payments made by the regulator to the landowners, expressed in euros. Panel C. presents the ratio of biodiversity levels to total payments (multiplied by 1,000,000 to facilitate reading), used as a measure of cost-effectiveness.

Panel A. of Table A1 shows that biodiversity is generally greater with an internal than with an external bonus. For example, while an internal bonus of €60 allows landowners to achieve a biodiversity level of 0.55, the same level of external bonus does not allow them to conserve any plots in most landscapes (i.e. biodiversity is zero). Furthermore, doubling the external bonus from €60 to €120/boundary only leads to a biodiversity level of 0.07. Thus, an internal bonus alone leads to higher levels of biodiversity than an external bonus alone. However, it obviously leads to greater levels of total payments (see Panel B. of Table A1).

Panel C. of Table A1 specifically provides the cost-effectiveness of the AB schemes, computed here as the ratio of the biodiversity level over total payments (values are multiplied by one million to facilitate reading). It shows that the maximal cost-effectiveness ratio (80.86) is achieved with an internal bonus of €60 and an external bonus of €20 (this corresponds to a $AB(75, 25)$ scheme), which confirms that there is a degree of complementarity between the two types of bonuses. This complementarity is however limited, since decreasing the external bonus to €0 leads to a decrease in the level of biodiversity by less than 1% (79.99).

A7 Cooperation: additional results for alternative AB schemes

Figure A5 shows changes in average coalition size within the stable coalition structures responding to AB schemes additional to those presented in Figure 3. It shows that ABs that present both positive internal and external bonuses lead to roughly similar cooperation outcomes. These outcomes are at intermediary levels compared to $AB(0, 100)$ – highest cooperation – and $AB(100, 0)$ – no cooperation.

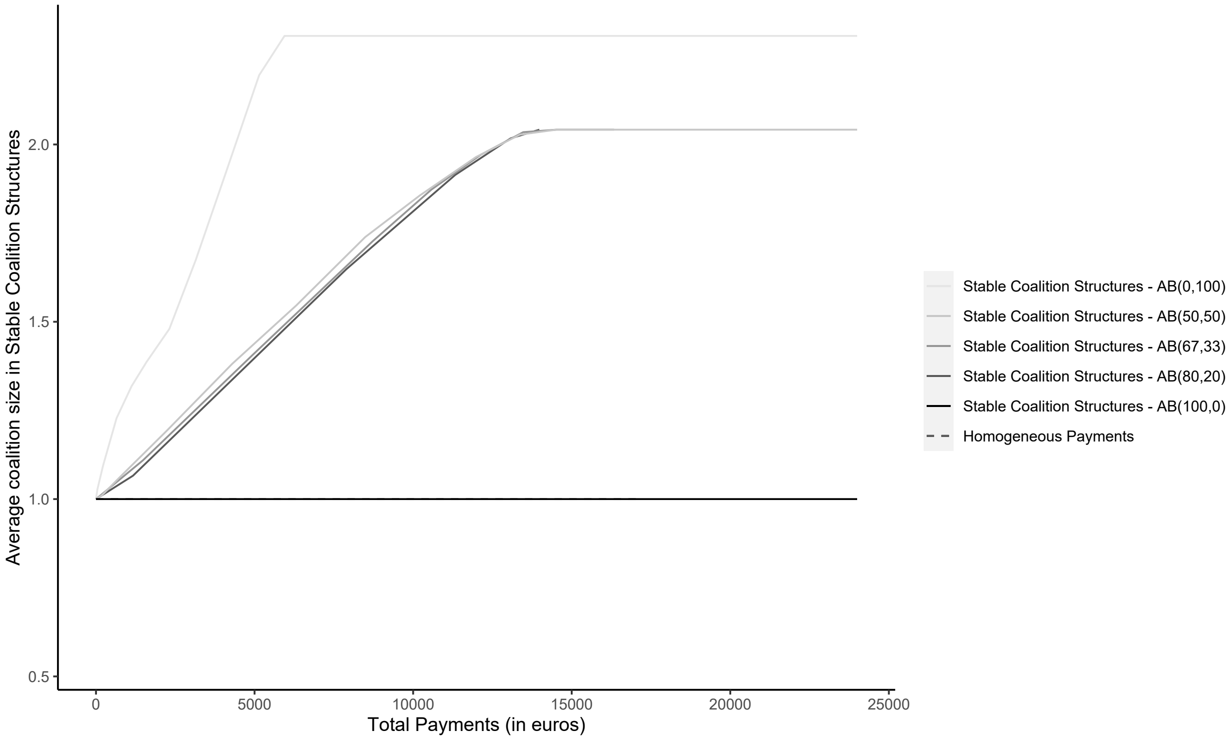


Figure A5: Average coalition size within the stable coalition structures responding to alternative AB schemes.

Note. The figure shows the average size of the coalitions within the stable coalition structures as a function of total payments for the AB scheme $AB(z, 100 - z)$ within the stable coalition structures. The AB scheme $AB(z, 100 - z)$ with $z = 100 \times q^I/(q^I + q^E)$ denotes the AB rewarding internal $z/(1 - z)$ times more than external bonuses. The simulations were performed using $p = 0$, $D = 2$ and $C = 0.5$. Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes.

A8 Distribution of opportunity costs for Section 3.3

Figure A6 shows the distribution of the opportunity costs across the landscape for the example given in Figure 4 of Section 3.3. These opportunity costs explain the enrollment of the different plots within the alternative AB schemes (differentiated by the proportion of internal and external bonuses).

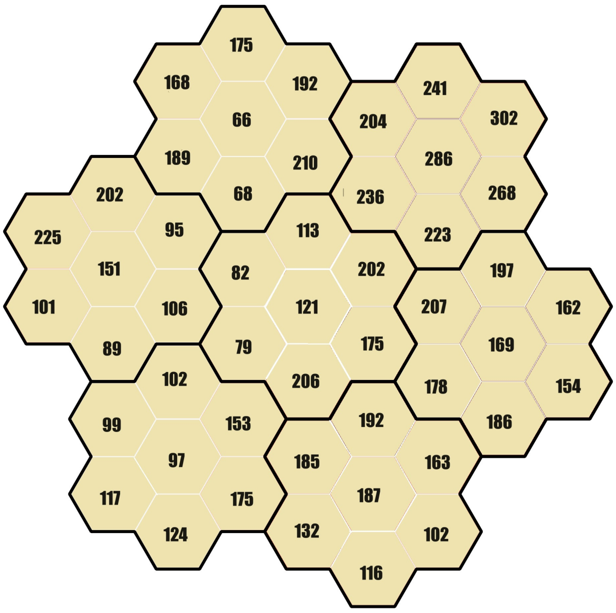


Figure A6: Distribution of opportunity costs in a random landscape.

Note. The figure shows the opportunity cost per plot across a landscape corresponding to the conservation decisions taken in Figure 4 in response to alternative AB schemes. Black lines are landholding boundaries.

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