



## Working Paper

# Individual versus group-level agglomeration bonuses to conserve biodiversity

François Bareille<sup>1</sup>, Raphaël Soubeyran<sup>2</sup>

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<sup>1</sup> University of Paris-Saclay, INRAE, AgroParisTech, Paris-Saclay Applied Economics, Palaiseau, France

<sup>2</sup> CEE-M, University of Montpellier, CNRS, INRAE, Institut Agro, Montpellier, France

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# INDIVIDUAL VERSUS GROUP-LEVEL AGGLOMERATION BONUSES TO CONSERVE BIODIVERSITY \*

François Bareille<sup>1</sup> and Raphaël Soubeyran<sup>2</sup>

November 2024

<sup>1</sup>*University of Paris-Saclay, INRAE, AgroParisTech, Paris-Saclay Applied Economics, Palaiseau, France.*

<sup>2</sup>*CEE-M, University of Montpellier, CNRS, INRAE, Institut Agro, Montpellier, France*

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## Abstract

Agglomeration bonuses (ABs) 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 instruments targeting landowners individually. This article challenges this conclusion by studying the impacts of different AB designs, some of which explicitly aim to enhance cooperation while others do not. Specifically, we study whether differentiating the bonuses 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 differentiating the two bonuses (in favor of internal ones) generally increases AB cost-effectiveness. The two bonuses are indeed largely substitutable, with internal outperforming external bonuses. However, when the regulator's budget is tight, external bonuses can complement internal ones at the margin. The complexity of compensation between plots belonging to different landholdings is a key element in explaining these patterns. Given this complexity, the most cost-effective schemes are characterized by little or no cooperation between landowners. Regarding policy, we conclude that differentiated ABs are cost-effective schemes that should be part of the regulators' toolbox.

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# 1 Introduction

Effective biodiversity conservation generally requires agglomerating habitats (Fahrig, 2003). As plots constituting a landscape are scattered across several landholdings, regulators are often advised to move away from voluntary instruments targeting individual landowners – such as the homogeneous payments used in most countries – in favor of voluntary *group-level* schemes encouraging coordinated landscape-level conservation efforts by cooperating individual landowners (Westerink et al., 2017; Kotchen and Segerson, 2019, 2020). Typical group-level schemes found in the literature relate to the agglomeration bonus (AB), which adds a bonus to a homogeneous payment (HP) for each conserved plot adjacent to another (Parkhurst et al., 2002), whether *on the same* or *different* landholding(s). First implemented in Switzerland in 2001 (Huber et al., 2021), ABs are now used in several countries (Nguyen et al., 2022). Yet, although the theoretical and experimental literature expects favorable AB outcomes (e.g., Albers et al., 2008; Banerjee et al., 2017, 2021), there is no evidence that ABs effectively encourage habitat agglomeration in practice (Häusler and Zabel, 2024).

This discrepancy may stem from the difficult cooperation processes that landowners face in real landscapes. Indeed, conserving adjacent plots from different landholdings requires landowners to collaborate within the same agglomeration project – and thus overcome incurred cooperation frictions – to get the bonuses (Banerjee et al., 2017, 2021; Bareille et al., 2023).<sup>1</sup> Until now, most of the literature has ignored the fact that landowners generally own several land plots (often arranged contiguously; see, e.g., Bareille et al., 2020), while habitat connectivity depends on conserving adjacent plots *between* but also *within* landholdings (i.e., the set of plots owned and managed by a landowner; see, e.g., Drechsler, 2023). Since conserving adjacent plots belonging to the same landowner does not require cooperation, differentiating the bonuses within and between landholdings could enable more cost-effective biodiversity conservation.

We address this question by examining ABs providing *differentiated bonuses* for conserving adjacent plots *within* the same landholding (henceforth “*internal bonuses*”) and *between* different landholdings (“*external bonuses*”). Although both bonuses can agglomerate conserved plots, they do not imply the same frictions for the landowners, such that differentiating them can improve AB

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<sup>1</sup>Such frictions refer to coordination costs landowners face when jointly enrolling in AB schemes (Albers et al., 2008), which increase with the number of cooperating landowners (Banerjee et al., 2021). They also arise from opposing interests among landowners (Zavalloni et al., 2019), inherently discouraging the formation of the grand coalition. This consideration departs from the literature’s standard assumption that all landowners cooperate together (Drechsler et al., 2010; Bamière et al., 2013; Wätzold and Drechsler, 2014; Drechsler, 2017). Other types of friction hindering cooperation exist (see, e.g., Drechsler, 2017, who introduces fairness considerations).

cost-effectiveness. We specifically investigate here whether internal and external bonuses should be equal (“*undifferentiated AB*”) or not (“*differentiated AB*”) and whether one of them should be favored.

We adopt the perspective of a regulator wishing to maximize biodiversity for a given budget by choosing internal and external bonuses. Landowners respond to these incentives by playing a two-stage game, first deciding individually with whom to cooperate, then cooperatively choosing their conservation efforts. There, landowners contract with the regulator on specific conservation choices, but cannot contract with each other on ex-post side-payments. We solve this game using numerical, spatially-explicit, ecological-economic simulations for a large range of internal and external bonuses, using parameter values calibrated with French data.

We show three main results. First, the two bonuses are generally substitutable, with internal bonuses outperforming external ones. Second, when the regulator’s budget is tight, external bonuses can complement internal bonuses at the margin. Third, in any case, habitat agglomeration can be achieved cost-effectively *without* or *with only little* cooperation between landowners. All in all, when budgets increase, regulators maximize AB cost-effectiveness by increasingly prioritizing internal bonuses over external ones, until a threshold beyond which only internal bonuses remain, encouraging landowners to pursue conservation individually.

The intuition behind our first result hinges on the common failure of simple agreements between potentially cooperating landowners to get the external bonuses. Indeed, only two adjacent plots are needed for an internal bonus to work; if their combined opportunity costs are lower than two internal bonuses, a rational landowner will enroll both within the AB – what matters here is the combined surplus from the two plots, not the surplus per plot. This is not the case for external bonuses. Indeed, an external bonus fails when one plot’s opportunity cost is lower than the bonus, as its owner will not agree to conserve it (at least in the absence of side-payments between landowners). To incentivize conservation of these adjacent plots, the regulator must raise the external bonus above each plot’s cost.<sup>2</sup> Hence, the regulator must spend more to encourage conservation of two adjacent plots owned by different landowners than two owned by a single landowner.

Our second result stems from the fact that, unlike external bonuses, internal bonuses lack targeted incentives for conserving adjacent plots from different landholdings. Complementarity between the two bonuses is more likely when the regulator’s budget is tight, as internal bonuses alone cannot induce the conservation of many plots in this context – especially those located on

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<sup>2</sup>Except in rare cases where landowners can reach more complex agreements – involving four plots, for example – allowing each landowner to compensate one plot’s net losses with another plot’s net gains.

landholding boundaries. In such cases, adding external bonuses may be more cost-effective than simply increasing the internal bonuses to conserve those specific plots.

We contribute to the AB literature in two ways. First, we contribute to *AB design* reflections by exploiting more realistic landscape structures. The literature has indeed generally assumed that *landowners have only one plot* (e.g., Drechsler et al., 2010; Wätzold and Drechsler, 2014; Banerjee et al., 2017, 2021; Arora et al., 2021), therefore overlooking the implications of differentiating internal and external bonuses.<sup>3</sup> Second, by considering interior borders, we show that cooperation is sometimes unnecessary – actually even undesirable – to reach cost-effective landscape conservation. This challenges the common belief that group-level schemes are more cost-effective than individual instruments due to induced cooperation (Westerink et al., 2017; Kotchen and Segerson, 2019, 2020; Nguyen et al., 2022). We show that what matters is actually agglomerating conservation efforts, not cooperation as such.

## 2 Methods

We aim to assess how bonus differentiation affects AB cost-effectiveness. We detail hereafter our ecological-economic game (Section 2.1), before presenting our simulations (Section 2.2).

### 2.1 Ecological-economic game

**Biodiversity.** Consider a landscape of contiguous plots subdivided among a set  $\mathbf{N}$  of  $N$  landowners.<sup>4</sup> 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  $\bigcup_{i \in \mathbf{N}} \mathbf{K}_i \equiv \mathbf{P}$ ), on which they can either undertake productive ( $x_{i_k} = 0$ , e.g., agriculture) or conservation activities ( $x_{i_k} = 1$ ). The landscape’s biodiversity level  $B(\mathbf{x})$  depends on the whole vector of conservation efforts – denoted  $\mathbf{x}$ , with  $\mathbf{x} = (x_{i_k})_{i_k \in \mathbf{P}}$  – such that:

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

where  $d_{i_k j_l}$  is the distance between plots  $i_k$  and  $j_l$  in meters and  $D > 0$  is the considered species’s dispersal rate. Increasing with both habitat size and connectivity, biodiversity index (1) is com-

<sup>3</sup>With only few exceptions (Parkhurst and Shogren, 2007; Panchalingam et al., 2019; Bareille et al., 2023; Drechsler, 2023), previous studies have only considered one plot per farm and no studies have ever looked at the impact of bonus differentiation on AB cost-effectiveness. Only Parkhurst and Shogren (2007) considered such differentiated bonuses to demonstrate their performance in encouraging the conservation of any desired spatial configurations (rather than studying AB cost-effectiveness as we do).

<sup>4</sup>Bold elements indicate vectors; e.g.,  $\mathbf{N}$  is the vector of landowners, such that  $i \in (1, \dots, N)$ .

monly used to assess habitat agglomeration over space (Wätzold and Drechsler, 2014). As further explained in Appendix A1, such a function generalizes a standard model of species’ dispersal between habitat patches – a good predictor of the species’ survival probability within the landscape (Hanski, 1999). With  $D > 0$ , equation (1) is ideal for measuring the abundance of *territorial* species, such as butterflies, small mammals or woodland birds (Hanski et al., 2013, 2017).<sup>5</sup>

**Agglomeration bonus schemes.** ABs typically include two elements: (i) a HP  $p$  for each conserved plot and (ii) a bonus  $q$  if the plot stands next to another conserved plot. In response to these incentives, landowners can contract together with the regulator on their conservation efforts, receiving bonuses only for plots *within the same conservation project* – a condition that fits the Swiss AB (Krämer and Wätzold, 2018; Huber et al., 2021; Häusler and Zabel, 2024). That is, bonuses are awarded only if the adjacent conserved plots belong to landowners cooperating *within the same coalition* (denoted by  $\mathbf{S}$ , indicating the composition of a coalition of size  $|\mathbf{S}|$ ) – but not if they belong to landowners in different coalitions.<sup>6</sup> The regulator can exploit landholding demarcations to differentiate bonuses between *internal boundaries* (within the same landholding’s plots) and *external boundaries* (between different landholdings’ plots), formulating respectively  $q^I$  (internal bonus) and  $q^E$  (external bonus). This differentiation affects the individual payoff  $u_i$  of landowner  $i$  in coalition  $\mathbf{S}$  as follows:

$$u_i(\mathbf{x}_{\mathbf{S}}, |\mathbf{S}|) = \sum_{i_k \in \mathbf{K}_i} (px_{i_k} + c_{i_k}(1 - x_{i_k})) + \sum_{i_k \in \mathbf{K}_i} (q^I \phi_{i_k}^I x_{i_k} + q^E \phi_{i_k}^E x_{i_k}) - \mathbf{1}_{|\mathbf{S}| \geq 2} C|\mathbf{S}|, \quad (2)$$

where  $\mathbf{x}_{\mathbf{S}}$  is the set of conservation decisions by landowners in  $\mathbf{S}$  (i.e.,  $\mathbf{x}_{\mathbf{S}} = (x_{i_k})_{i_k \in \mathbf{K}_i, i \in \mathbf{S}}$ ) and  $c_{i_k}$  is the plot  $i_k$ ’s opportunity cost. Landowners thus have incentives to initially conserve plots with the lowest costs before facing higher costs for remaining plots.<sup>7</sup>  $C|\mathbf{S}|$  is the coordination cost for  $i$  within a coalition of size  $|\mathbf{S}|$  (for  $|\mathbf{S}| \geq 2$ ). Such coordination costs include the time spent on communication (Banerjee et al., 2017), but may also take more explicit forms (e.g., hiring consultants to assist landowners’ conservation decisions; see Krämer and Wätzold, 2018).  $\phi_{i_k}^I$  and

<sup>5</sup>Not considered here,  $D < 0$  would change the situation into an “agglomeration malus” problem where positive bonuses are turned negative to conserve *non-territorial* species like bustards (Bamière et al., 2013).

<sup>6</sup>Most conservation schemes worldwide work similarly (whether group-level or not), with regulators contracting with landowners based on their declared efforts *ex ante* and setting the payments accordingly. An alternative scheme could relax this constraint, providing external bonuses *even across different coalitions*. Yet, this would generate additional costs for regulators, which would have to monitor all the plots to verify the actual conservation decisions taken to implement them. By comparison, our model avoids these monitoring costs (as in the aforementioned practical cases), such that this constraint does not necessarily lower AB cost-effectiveness.

<sup>7</sup>While acknowledging our static modeling and linear utility functions, this is consistent with the observation that landowners often face increasing opportunity costs on remaining plots as conservation efforts increase.



$\phi_{i_k}^E$  respectively count the number of internal and external boundaries to adjacent conserved plots in the same conservation project.

**Coalition formation.** We assume that landowners respond to the AB by endogenously forming coalitions in which they sign up to joint conservation projects (as in Bareille et al., 2023). They play a two-stage game, first choosing coalition partners, and then plots to conserve. 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.<sup>8</sup>

Reasoning backward, landowners choose their conservation efforts in the second stage to maximize the aggregated utility of all the landowners of their coalition,<sup>9</sup> i.e.:

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

The solution of problem (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  $\mathbf{x}_{\mathbf{S}}^*$  into equation (2) yields the individual payoffs for each landowner within  $\mathbf{S}$ .

While the second stage is a cooperative game, the first stage is a non-cooperative game where landowners simultaneously decide whether and with whom to cooperate, anticipating their coalition’s conservation decisions in the second stage. Coalition formation decisions depend on the comparison of each landowner’s payoffs across all potential coalitions (Hart and Kurz, 1983). As a solution concept, we use the *internal* and *external stability conditions* (Barrett, 1994), adjusted for exclusive membership (Carraro and Marchiori, 2002). Formally, a coalition structure  $\boldsymbol{\pi}$  is internally stable if no one wants to leave the coalition *and* no one wants another member to leave the coalition. Formally, the internal stability condition states that  $\forall \mathbf{S} \in \boldsymbol{\pi}, \forall i, j \in \mathbf{S}, j \neq i$ :

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

<sup>8</sup>We assume that landowners can contract on conservation efforts, but not on side-payments. Although side-payments are *implicitly* authorized in previous studies maximizing the aggregated landowners’ utilities within the grand coalition (e.g., Wätzold and Drechsler, 2014), no one has ever observed formal monetary side-payments in real AB applications (Nguyen et al., 2022).

<sup>9</sup>This assumption is common to most endogenous coalition formation studies, whether applied to group-level conservation schemes (Gengenbach et al., 2010; Zavalloni et al., 2019; Bareille et al., 2021, 2023), international environmental agreements (Barrett, 1994; Carraro and Marchiori, 2002; Finus et al., 2024) or cartels (d’Aspremont et al., 1983).

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

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

Solving equations (4) and (5) provides a set of stable coalition structures resulting from the AB. Corresponding conservation decisions from the second stage – i.e., problem (3) – yield the biodiversity index (1) and regulator’s total payments for each stable coalition structure. The total payments, for the coalition structure  $\pi$ , are:

$$TP(\pi) = \sum_{i_k \in \mathbf{K}_i, i \in \mathbf{S} \in \pi} (px_{i_k}^* + q^I \phi_{i_k}^I x_{i_k}^* + q^E \phi_{i_k}^E x_{i_k}^*). \quad (6)$$

**Regulator’s problem.** As there may be several stable coalition structures for a given landscape, we assume that the regulator aims to maximize the average biodiversity level with a limited budget. Formally, the regulator’s problem is:

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

such that:

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

where  $\mathbf{x}^*$  is the vector of binary conservation decisions corresponding to  $\pi$ ,  $\Pi$  denotes the set of stable coalition structures induced by  $q^I$  and  $q^E$  and  $\overline{TP}$  is the regulator’s budget.

## 2.2 Empirical implementation

We solve the model above with mathematical programming.

**Landscape structure.** We apply the model to fictitious grid landscapes with seven landowners, each owning seven one-hectare hexagonal plots, where the distance between the centroids of adjacent plots is normalized to one. Figure 1 illustrates this landscape structure with respectively 84 and 36 internal and external boundaries.<sup>10</sup> While simplistic, we believe that our setup reason-

<sup>10</sup>Considered fixed in the model, the ownership structure could yet endogenously change via land markets in response to ABs. However, data suggests this is unlikely; e.g., the average Swiss payment is about €500/ha, while farmland

ably approximates real landscapes. Indeed, although plots within a landholding can be spatially fragmented (Drechsler, 2023), they are usually clustered in large patches (Moravcová et al., 2017; Bareille et al., 2020). Appendix A2 further discusses the merits of this landscape structure.

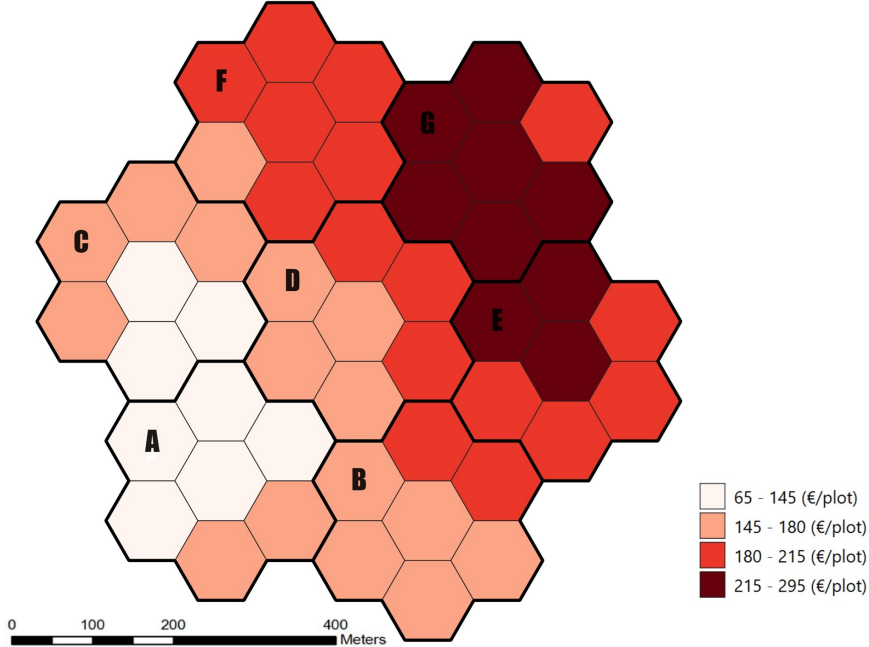


Figure 1: Landscape structure and average cost per plot.

NOTE. Plot colors indicate average plot opportunity cost across the 50 generated landscapes. Each plot covers one hectare, such that the distance between the centroids of two adjacent plots is 107.5 m, a representative distance that we normalize to one when computing the biodiversity index with equation (1). Thin lines are the internal boundaries ( $12 \times 7 = 84$  internal boundaries in total within the landscape). Bold lines are landholding boundaries, of which a subset constitutes the external boundaries (36 in total within the landscape). Black letters are landowner identifiers.

**Taking the model to the data.** Our model can be applied to various conservation problems, provided that data on opportunity costs and targeted species’ dispersal rate are available for calibration.

We collected such data for the common hamster in *Alsace*, the only endemic French region where this species remains (Limbach and Rozan, 2023). Whereas Alsace was trending towards maize monoculture landscapes (in which hamsters cannot survive; see Marquet, 2014), the French government began encouraging farmers to collectively conserve large patches of non-maize habitats (i.e., soft wheat, sunflowers and other more marginal crops in which hamsters can nest). Plot opportunity costs are calibrated using crop profitability data from Alsace, with values ranging from

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prices are around €100,000/ha. Given transaction costs and uncertainties associated with the short-term duration of ABs (between one to five years in Europe; see, e.g., Westerink et al., 2017), it is unlikely that land markets adjust to ABs.

€110/ha to €250/ha.<sup>11</sup> We create fifty fictitious landscapes with randomized plot opportunity costs  $c_{i_k}$  drawn from a uniform distribution in this range, while imposing a spatial cost autocorrelation at a Moran’s index of 0.8 (a value as measured in real agricultural landscapes; see Pasher et al., 2013) – creating plot clusters with low vs. high opportunity costs. We then randomly apply landowner-level shifters of  $\pm\text{€}45/\text{plot}$  to additionally represent the impacts of landowners’ characteristics on opportunity costs (e.g., difference in knowledge or machinery). Figure 1 shows the average plot opportunity costs within the fifty landscapes (Appendix A3 explores the heterogeneity behind such average values). Finally, we calibrate the dispersal rate to mimic the male hamsters’ territorial behavior, which move up to 300 m/year on average (i.e., over about one quarter of our landscape; see Marquet, 2014). This dispersal behavior corresponds to a value of  $D = 2$  (see Appendix A1 for more details).

**Analyses.** Setting  $p = 0$ , our preferred analyses run the model for varying levels of internal and external bonuses across the fifty landscapes until fully covered by suitable habitats. For clarity, we note  $AB(z, 100 - z)$  with  $z = 100 \times q^I / (q^I + q^E)$  the AB consisting of  $z\%$  internal bonuses and  $(100 - z)\%$  of external bonuses. For example,  $AB(67, 33)$  indicates a scheme rewarding internal bonuses twice as much as external bonuses. We compare the AB outcomes to those of standard HPs, with  $p > 0$  but where  $q^I = q^E = 0$  in equation (2).<sup>12</sup> Finally, we follow Bareille et al. (2023) and assume low levels of opportunity costs ( $C = 0.5$ ), amounting in total to between 0.1% and 1% of the individual payoffs. Table 1 summarizes our preferred values and the alternatives used for sensitivity analyses.

### 3 Results

This section first reports differences in cost-effectiveness between alternative ABs (Section 3.1). Section 3.2 explores whether these differences are linked to cooperation levels. Section 3.3 analyses the relative additionality of internal and external bonuses as a key mechanism behind our results. Section 3.4 explores the robustness of our results.

<sup>11</sup>Courty et al. (2023) indicate a maize profitability of respectively €730/ha and €950/ha on average for non-irrigated and irrigated plots in France between 2017 and 2021, while those of soft wheat and sunflower were respectively of 710€/ha and €560/ha during that period. Weighting the maize profitability by the proportion of irrigated maize in Alsace (about 40% according to AGRESTE, 2024) leads to opportunity costs of between €110/ha and €250/ha. Note additionally that we could not have used the Swiss case for the calibration because it rewards permanent grasslands, a type of area for which it is difficult to know the exact profitability (only used to provide part of the feeding for various livestock), ultimately preventing us from calibrating realistic opportunity costs for our simulations in this case.

<sup>12</sup>Note that  $q^I + q^E$  and  $p$  are the single free parameters for our AB and HP simulations, respectively.

Table 1: Overview of the calibrated parameter values for the simulations

	Preferred values	Alternative values	Sources
A. FIXED LANDSCAPE CHARACTERISTICS			
Number of generated landscapes	50	–	–
Number of landowners	7	–	–
Number of plots per landowner	7	–	Bareille et al. (2020)
Size of the plots <sup>a</sup>	1 ha	–	Häusler and Zabel (2024)
Average opportunity costs (& confidence interval)	€180/ha (± €70/ha)	–	Limbach and Rozan (2023), Courty et al. (2023) and AGRESTE (2024)
B. OTHER CALIBRATED PARAMETERS			
Spatial correlation of the opp. costs <sup>b</sup>	0.8	{0.4}	Pasher et al. (2013)
Homogeneous payment ( $p$ )	€0/ha	{€20/ha}	–
Coordination costs ( $C$ )	0.5	{0.05, 5, 50}	Bareille et al. (2023)
Targeted species' dispersal rate ( $D$ )	2	{1,4}	Gutiérrez and Thomas (2000), Marquet (2014) and Limbach and Rozan (2023)

<sup>a</sup>: the distance between the centroids of two adjacent plots is normalized to one (specifically equal to 107.5 m).

<sup>b</sup>: the spatial correlation of opportunity costs is computed using Moran's index on the landscapes'  $49 = 7 \times 7$  plots.

NOTE. The table sums up the values of our model parameters as calibrated for our preferred analyses (first column), and our sensitivity analyses (second column), along with corresponding sources justifying our choices. Panel A. provides justifications for our fixed landscape characteristics. Panel B. provides justifications for the other parameters, whose specific effects are further tested in sensitivity analyses. Our preferred values are expected to mimic the Swiss AB performance as if applied in Alsace for the conservation of common European hamsters. Appendix A4 shows that this calibration typically reproduces standard results of the AB literature for the  $AB(50, 50)$  case – the single AB investigated by the literature so far.

### 3.1 Cost-effectiveness

Figure 2 shows average biodiversity levels across all stable coalition structures of the fifty landscapes as a function of budgets for five ABs with different internal and external bonuses proportions, from  $AB(0, 100)$  to  $AB(100, 0)$ . It shows that increasing the proportion of internal bonuses often improves AB cost-effectiveness. Specifically, the least cost-effective scheme is  $AB(0, 100)$ , followed by  $AB(20, 80)$  and  $AB(33, 67)$ , whatever the budgets.<sup>13</sup>

However, Figure 2 shows that the ranking of the two most cost-effective AB schemes –  $AB(50, 50)$  and  $AB(100, 0)$  – depends on budgets. Specifically,  $AB(100, 0)$  is more cost-effective than  $AB(50, 50)$  when budgets exceed €5,500 (where the two curves intersect; see Figure A3 in Supplementary Material for a zoom). In contrast,  $AB(50, 50)$  is more cost-effective when budgets are smaller. This indicates that, while regulators prefer to reward internal bonuses only when their budgets exceed €5,500, they prefer to reward internal and external bonuses equally for tighter budgets. Figure A4 confirms this pattern, but for *partial* differentiation. Specifically, it shows that

<sup>13</sup>Maximum biodiversity (about 0.15) is achieved with about €6,500 in  $AB(0, 100)$ . Increasing the budget does not increase biodiversity, as the remaining plots to conserve are those along the internal boundaries. By comparison,  $AB(20, 80)$  achieves a fully preserved landscape with about €24,500, while  $AB(33, 67)$  requires about €21,000.

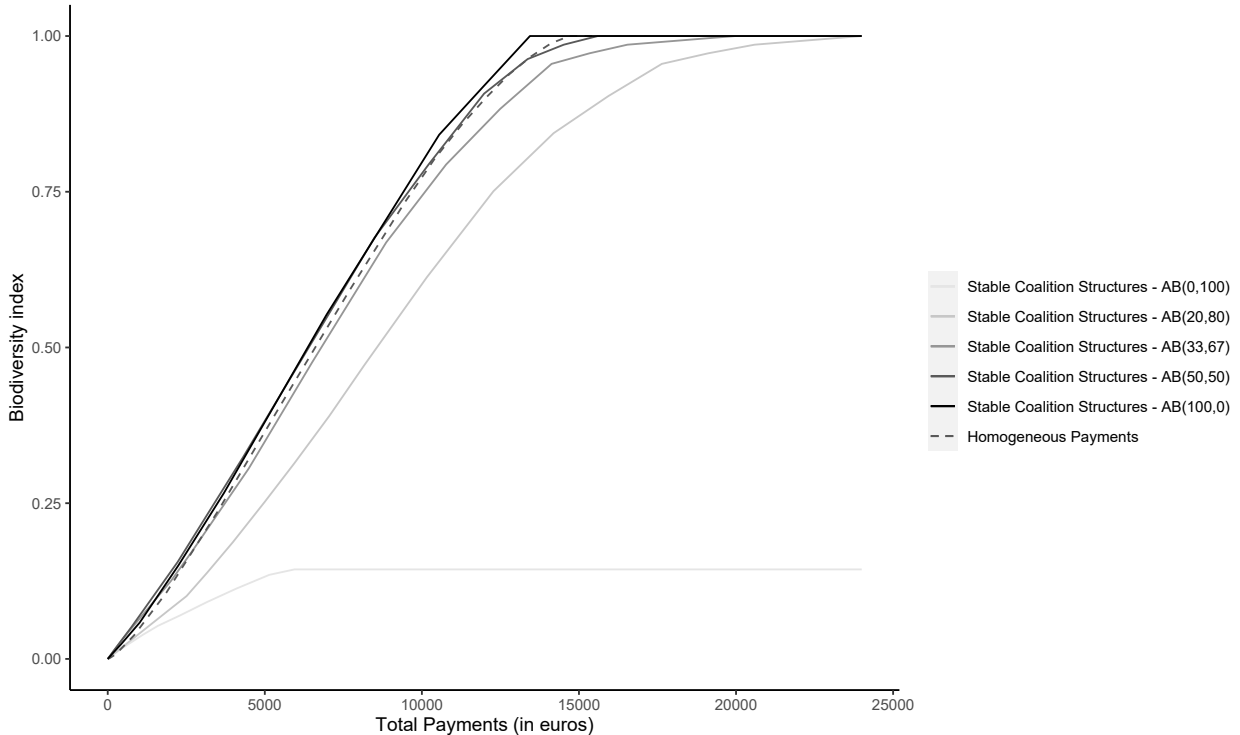


Figure 2: Cost-effectiveness of alternative AB schemes within stable coalition structures.

NOTE. The figure shows the normalized biodiversity level as a function of budgets for HP 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 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  $C = 0.5$ . Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8).

$AB(100, 0)$  is the most cost-effective scheme for large budgets, but  $AB(67, 33)$  and  $AB(80, 20)$  are the most cost-effective schemes for medium budgets.

Summarizing these AB performances, Table 2 shows that the most cost-effective scheme increasingly favors internal bonuses as budgets increase: the most cost-effective AB is undifferentiated for low budgets, partially differentiated for medium budgets and fully differentiated for large ones.<sup>14</sup> Figure A5 in Supplementary Material suggests that, because  $AB(100, 0)$  always generates the largest conserved areas (although with minimal differences for HP and AB schemes as long as  $z \geq 50$ ), the complementarity provided by external bonuses for low and medium budgets is due to their role in agglomerating conservation efforts at landholding boundaries.

<sup>14</sup>Confirming our results, Table A2 in Supplementary Material provides more information on biodiversity and budget levels as functions of *internal* and *external bonuses* levels. Note moreover that the results in Table 2 have a dual interpretation. Using a biodiversity conservation goal rather than a budget constraint to determine the most cost-effective scheme, Table 2 shows that the higher the biodiversity conservation goal, the more differentiated the scheme needs to be.

Table 2: Most cost-effective scheme per budget level

	€2,000	€4,000	€6,000	€8,000	€10,000	€12,000	€14,000
<b>Most cost-effective scheme</b>	(50, 50)	(67, 33)	(80, 20)	(80, 20)	(100, 0)	(100, 0)	(100, 0)
Habitat area (%)	0.20	0.41	0.59	0.75	0.85	0.93	1.00
Biodiversity	0.15	0.29	0.48	0.67	0.79	0.91	1.00

NOTE. The table shows the average outcomes for the most cost-effective scheme, averaged over all stable coalition structures over the 50 landscapes, depending on the budget level. This level corresponds to the total payments made to all seven landowners in the landscape. The first line provides the most cost-effective scheme depending on the size of the budget, among pure HPs,  $AB(0, 100)$ ,  $AB(20, 80)$ ,  $AB(33, 67)$ ,  $AB(50, 50)$ ,  $AB(67, 33)$ ,  $AB(80, 20)$  and  $AB(100, 0)$ . For instance, with a €6,000 budget, regulators prefer  $AB(80, 20)$  – that couples external with four times larger internal bonuses – rather than any other AB. The second line provides the corresponding habitat size (as a proportion of the landscape). The third line provides the corresponding value of biodiversity, normalized so that a value of 1.00 corresponds to a landscape where all the plots are conserved.

Finally, Figure 2 shows that  $AB(100, 0)$  is always more cost-effective than HPs with our preferred calibration. This sharply contrasts with previous literature (e.g., Bareille et al., 2023), which finds that HPs are more cost-effective than undifferentiated ABs for large budgets – as connections between the numerous conserved plots automatically appear. While confirming that undifferentiated ABs are less cost-effective than HPs when budgets are large (above €13,000), Figure 2 shows that fully differentiated ABs consistently outperform HPs, *even for large budgets*.

### 3.2 Cooperation

The greater cost-effectiveness of ABs rewarding more internal than external bonuses raises questions about the extent of cooperation there. Indeed, while ABs are generally believed to be more cost-effective than HPs because they encourage cooperative conservation decisions (unlike HPs, which only encourage individual conservation decisions), our results in Section 3.1 suggest otherwise. Specifically, the most cost-effective ABs are those with few or no external bonuses, apparently not incentivizing coalition formation.<sup>15</sup> To investigate how cooperation changes across ABs, Figure 3 shows changes in average coalition size within stable coalition structures as a function of budgets for alternative ABs.

Figure 3 confirms this intuition. It shows that the least cost-effective AB –  $AB(0, 100)$  – is the one that allows the largest coalitions to be formed, and therefore most favors cooperation.<sup>16</sup> Figure 3 shows that average coalition sizes decrease as the proportion of internal bonuses increases. For a

<sup>15</sup>For example, landowners only apply individually to  $AB(100, 0)$  as it offers no benefits from cooperation. By comparison, landowners only apply collectively to  $AB(0, 100)$ , as conserving plots with no external boundaries is unrewarded. As these two schemes are the most and least cost-effective ABs respectively (at least for large budgets; see Figure 2), they draw an intuitive pattern in which AB cost-effectiveness and landowner cooperation are negatively linked.

<sup>16</sup>In any case, coalition size remains limited. For large budgets, 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 all cooperate together within the grand coalition, even when the rewards can be attained via external bonuses – and thus via cooperation only.

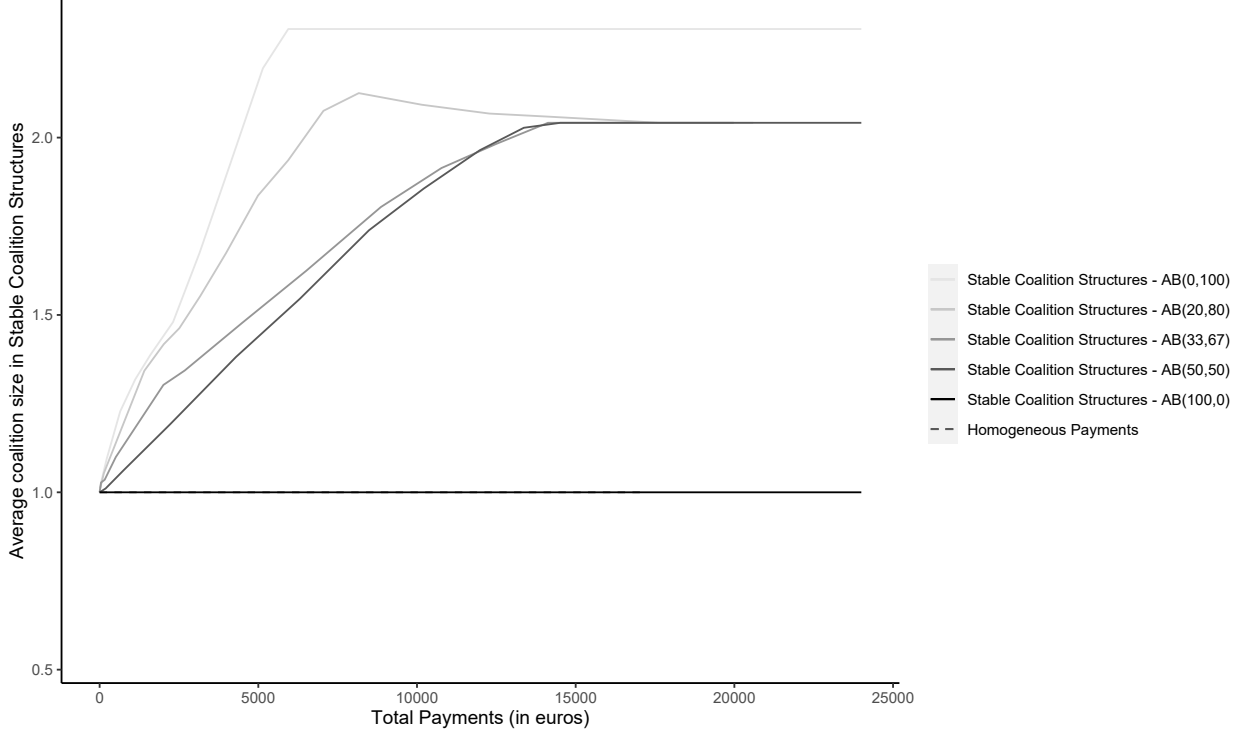


Figure 3: Coalition size within stable coalition structures responding to alternative AB schemes.

NOTE. The figure shows average coalition size within stable coalition structures as a function of total payments for alternative AB (solid lines, ranging from light grey to black) and HP schemes (dashed line). The 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 (with a Moran's index of 0.8). An average coalition size of one – as for HP and  $AB(100, 0)$  – means that landowners enroll individually within the scheme. Hidden by the  $AB(100, 0)$  curve, HPs lead to one-landowner coalitions by definition.

given budget,  $AB(0, 100)$  has larger coalitions than  $AB(20, 80)$ , which in turn has larger coalitions than  $AB(33, 67)$ , and so on. When both internal and external bonuses are rewarded, landowners in alternative ABs respond to high total payments by forming stable coalition structures typically consisting of one three-landowner coalition, one two-landowner coalition and two singletons (a robust result for alternative ABs; see Figure A6 in Supplementary Material). However, when only internal bonuses are rewarded, landowners apply to the AB individually.

In summary, we identify two cases based on the regulator's budget: (i) if the budget is large enough (e.g., above €5,500 in Figure 2), the most cost-effective 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 to only a small extent (as shown by an average coalition size below 1.25 in  $AB(50, 50)$  for these budgets).



### 3.3 Mechanisms

To illustrate the mechanisms behind our results, Figure 4 shows landowners' conservation and cooperation decisions in response to four contrasting ABs, with total payments held constant. It specifically depicts two polar cases –  $AB(100, 0)$  in (a) vs.  $AB(100, 0)$  in (b) – and two interior cases with high vs. low external bonuses –  $AB(25, 75)$  in (c) vs.  $AB(75, 25)$  in (d). We focus below on the case of low budgets – specifically €1,800 – to illustrate how internal and external bonuses can be complementary (Section 3.1).

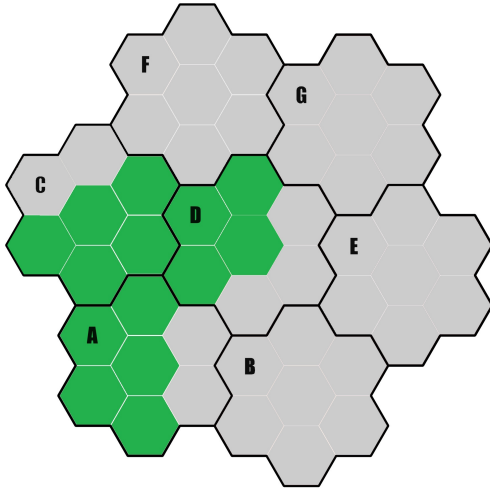
Figure 4 illustrates the two intrinsic advantages of internal over external bonuses. First, they encourage the conservation of plots located away from landholding boundaries, unlike external bonuses. At constant budget, we indeed see that switching from a 100% external bonus of €100 to a 100% internal bonus of €50 shifts conservation from nine boundary plots in (b) to six internal plots and eight boundary plots in (a). Second, internal bonuses enable compensation among fewer plots, likely leading to more conservation overall. For example, landowner  $D$  conserves four plots individually in (a), whereas they need to cooperate with  $A$  and  $C$  in (b) to jointly decide to conserve them (with four additional plots from  $A$  and  $C$ ).<sup>17</sup> Cooperation induced by external bonuses thus requires more complex compensation solutions than those achieved by individual landowners seeking internal bonuses only.

Figure 4 also illustrates how internal and external bonuses interact. The schemes' cost-effectiveness ranking –  $(d) > (a) > (c) > (b)$  with corresponding biodiversity of 0.15, 0.14, 0.08 and 0.07 respectively – indeed highlights potential complementarity between the two bonuses, as the most cost-effective scheme is  $AB(75, 25)$  with high internal and low external bonuses. Conversely, Figure 4 also shows potential substitutability between the two bonuses, as the second best scheme is that with internal bonuses alone in (a), far ahead of schemes in (c) with a high proportion of external bonuses and in (b) with external bonuses only.

To understand bonus complementarity, consider schemes in (a) and (d) in Figure 4. Moving from (a) to (d) does not change the budget nor landowners  $A$ ,  $C$  and  $D$ 's conservation decisions, but encourages landowner  $F$  to conserve two plots in cooperating with  $C$  and  $D$ .<sup>18</sup> Landowner  $F$  does

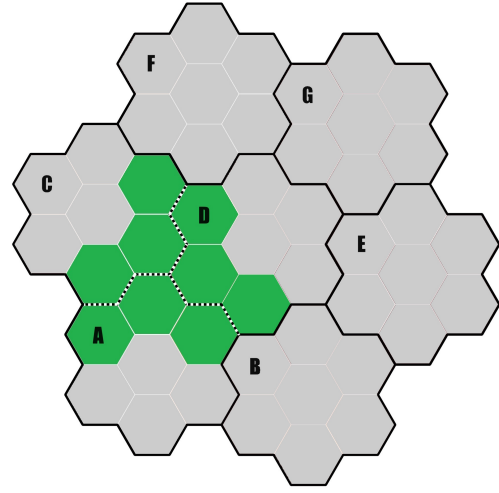
<sup>17</sup>Landowner  $D$  receives a total of €400 of internal bonuses in (a), for a total opportunity cost of €395. He receives €600 of external bonuses in (b), for a total opportunity cost of €367. That is,  $D$ 's windfall benefits are greater in (b) than in (a). A similar pattern appears with landowners  $A$  and  $C$ , who respectively receive windfall benefits of €246 and €310 in (b), but only €161 and €158 in (a).

<sup>18</sup>The stable coalition structure with  $A$  alone and  $\{C, D, F\}$  together is only one of the two possible stable coalition structures emerging from the AB in (d). Another stable structure involves  $A$ ,  $C$  and  $D$  cooperating and  $F$  being alone. While this structure would lead to greater biodiversity in (d) than in (a), it also generates additional payments, making it unsuitable for our example.



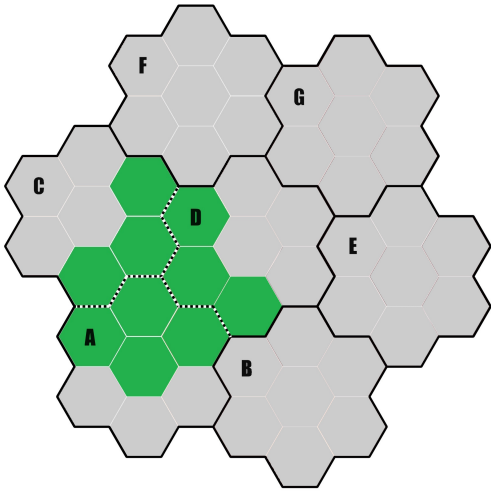
(a)  $AB(100, 0)$   
 $q^I = \text{€}50$  &  $q^E = \text{€}0$

Biodiversity= 0.14, Total payments=€1,800



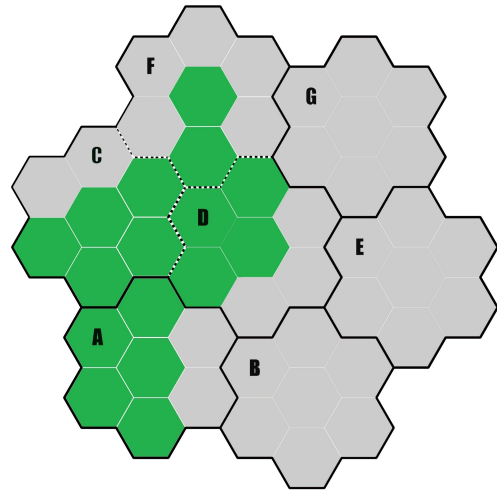
(b)  $AB(0, 100)$   
 $q^I = \text{€}0$  &  $q^E = \text{€}100$

Biodiversity= 0.07, Total payments=€1,800



(c)  $AB(25, 75)$   
 $q^I = \text{€}25$  &  $q^E = \text{€}75$

Biodiversity= 0.08, Total payments=€1,800



(d)  $AB(75, 25)$   
 $q^I = \text{€}45$  &  $q^E = \text{€}15$

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 A7 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).

not conserve these plots in (a) because their opportunity costs exceed the internal bonuses available there. By cooperating with  $C$  and  $D$  in (d),  $F$  conserves them because they receive the two bonus types (with associated payments of  $2 \times q^I + 3 \times q^E = \text{€}135$ ), which together exceed their aggregated opportunity cost of  $\text{€}133$ . Thus, for the same budget, combining external and internal bonuses here leads to increased conservation by landowner  $F$  without reducing that of others. Consequently, it increases AB cost-effectiveness.

To understand bonus substitutability, consider schemes (a) and (c) in Figure 4. Switching from (a) to (c) does not change the budget, but affects conservation decisions. In (a), all but one plot on the boundaries between the landholdings of  $A$ ,  $C$  and  $D$  are conserved, as well as six of their other plots. In (c), all nine plots on their boundaries are conserved cooperatively (thanks to large external bonuses), but only one other plot is conserved due to low internal bonuses. Hence, there is not much difference between the two bonuses in their propensity to incentivize plot conservation on landholding boundaries, but the internal bonuses enable the conservation of many more plots not on landholding boundaries. The regulator can thus largely substitute internal for external bonuses. Yet, AB cost-effectiveness is maximized in (d), when only a proportion of external bonuses are substituted (illustrating the marginal complementarity of internal and external bonuses there).

### 3.4 Sensitivity analyses

Below we test the sensitivity of our results to some key parameter changes. Appendix A11 in Supplementary Material shows that changing  $D$  does not alter our main conclusions (the decisions remain by definition identical since this does not affect the landowners' utility), although reducing differentiated and undifferentiated AB cost-effectiveness compared to HPs when  $D$  increases (as already documented for the undifferentiated AB in the literature; see, e.g., Wätzold and Drechsler, 2014). Appendix A12 shows that coordination costs affect our results only slightly; increasing  $C$  from 0.05 to 50 decreases cooperation – and AB cost-effectiveness to a lesser extent – in schemes with positive external bonuses but obviously leaves  $AB(100, 0)$  unchanged. At  $C = 50$ ,  $AB(100, 0)$  thus outperforms  $AB(50, 50)$  when budgets exceed  $\text{€}2,000$  (instead of  $\text{€}5,500$  in Figure 2). Appendix A13 finds that reducing spatial autocorrelation of opportunity costs (reducing Moran's index from 0.8 to 0.4) mainly lowers HP cost-effectiveness (consistently with other studies; see, e.g., Wätzold and Drechsler, 2014), but confirms previous patterns regarding AB differentiation. Finally, Appendix A14 shows few effects of complementing bonuses with HPs ( $p = \text{€}20/\text{ha}$  instead of  $p = 0$ );  $AB(100, 0)$  remains more cost-effective than  $AB(50, 50)$  when budgets exceed  $\text{€}5,000$ . Increasing  $p$  however

slightly increases AB cost-effectiveness compared to pure HPs, suggesting some complementarity between the two policies (as already documented by the literature; see, e.g., Bareille et al., 2023).

## 4 Discussion and concluding remarks

Scientists and policymakers are increasingly focusing on group-level schemes for biodiversity conservation (Westerink et al., 2017; Kotchen and Segerson, 2019, 2020; Nguyen et al., 2022). Equally rewarding conservation of adjacent plots whatever the landowners' identity, the AB is probably the best known of these group-level schemes. However, there is no evidence that ABs effectively encourage habitat agglomeration in practice. This paper has explored whether this lack of additionality can be due to the cooperation frictions that landowners need to overcome when jointly enrolling in ABs in real landscapes. Though rarely explicitly addressed in the literature, these cooperation frictions are indeed regularly suspected of reducing AB additionality (Goldman et al., 2007; Albers et al., 2008; Banerjee et al., 2017, 2021; Nguyen et al., 2022; Bareille et al., 2023). Using an ecological-economic model where conservation and cooperation decisions are endogenous, we have confirmed this intuition by showing that landowners respond to undifferentiated ABs by forming small coalitions limited to one to three landowners. Yet, we have demonstrated that regulators can overcome these frictions by differentiating bonuses *within* and *between* landholdings, favoring the former over the latter – because the latter can only be received via cooperation, while the former avoid such multi-landowner agreements. As regulators favor internal over external bonuses, they encourage individual over group-level enrollment.

Regarding policy, our results show that AB differentiation can improve the effectiveness of public spending, whether compared to standard HPs or undifferentiated ABs. Specifically, they suggest that, as budgets increase, greater differentiation in favor of internal bonuses is needed. While keeping small external bonuses is useful when budgets are tight, our results recommend the formulation of fully differentiated ABs for large budgets – in our case €8,500, corresponding to a habitat conservation objective of at least 80% of the landscape (see Table 2). Such conservation levels are however rare in practice, as ABs and other group-level approaches generally aim for 25% to 50% conserved areas (Bucholtz et al., 2010; Kuhfuss et al., 2016; Westerink et al., 2017; Nguyen et al., 2022). At these levels, our results suggest favoring partial differentiation. More precisely, for our calibration inspired from the Alsace group-level scheme (where about 35% of landholdings are conserved; see Limbach and Rozan, 2023), Table 2 specifically shows that the most cost-effective scheme at this level rewards internal twice as much as external bonuses.

Our results extend beyond the Alsace case, as they are robust to changes in several key model parameters. While the proper effects of these parameters align with previous studies' results on the comparison between undifferentiated ABs and HPs (in particular regarding the effects of species dispersal rate, spatial autocorrelation of the opportunity costs, coordination costs and extra HP on undifferentiated AB cost-effectiveness), we extend their validity to other ABs where bonuses are differentiated. These analyses notably show that the lack of additionality for group-level ABs is not due to coordination costs (see also Bareille et al., 2023), but to the instability of multi-landowner agreements.

However, our results obviously only hold under the validity of our stylized model and calibration. As discussed several times above, our analyses could be extended in several directions. We could consider further complex AB designs, explicitly accounting for heterogeneous or dynamic bonuses across space and time (see Appendix A1 for a discussion), or considering inter-group bonuses or intra-group side-payments (see footnotes n°6 and 8 respectively). We could also account for even more realistic landscape structures (see Appendices A1 and A2 for discussions), or fragmented land ownership.<sup>19</sup> While intuition suggests that our main result – i.e., that there are budget thresholds beyond which differentiation increases AB cost-effectiveness – will remain qualitatively, we leave the formal analyses of the quantitative impacts of these extensions for future research.

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<sup>19</sup>The effects of land fragmentation can be studied in keeping the same number of landowners and plots, but permuting certain plots between landowners. Two polar cases would emerge: (i) a spatially cohesive landscape (as we considered) and (ii) a highly fragmented one, where no landowner owns adjacent plots. In this latter case, the internal bonus is irrelevant and only the external bonus is effective. Thus, intuitions suggest that, outside this latter polar case, increasing fragmentation will not alter our main conclusions, while giving a relative advantage to external bonuses. See Drechsler (2023) for an analysis of the role of landscape fragmentation within a standard undifferentiated AB.

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## Supplementary Material

NOTE. The material contained herein is supplementary to the article entitled “Individual versus group-level agglomeration bonuses to conserve biodiversity”.

### A1 Ecological module

**Ecological function.** The ecological module of our ecological-economic game is built around equation (1) of the main text, with  $D > 0$ . Such a function has also been used in earlier contributions to the agglomeration bonus (AB) literature – in particular by those using simulations to solve spatially-explicit ecological-economic problems similar to ours (e.g., Wätzold and Drechsler, 2014; Bareille et al., 2023). It is a generalization of a common species survival function initially introduced by ecologists (e.g., Hanski, 1999). Denoting  $p_{i_k j_l}$  the probability of reaching a conserved plot  $j_l$  at a distance  $d_{i_k j_l}$  from another one  $i_k$ , this initial function is commonly specified as:  $p_{i_k j_l} = \exp(-d_{i_k j_l}/D)$ . Regardless of species’ dispersal rate  $D$ , the function is assumed to decline with increasing  $d_{i_k j_l}$  – i.e., the further an individual moves, the more likely it is to be killed. Yet, all species are not equal when faced with this difficulty, but characterized by different  $D$  indicating their own dispersion capacity over space. In this function, high  $D$  means that  $p_{i_k j_l}$  weakly declines with increasing  $d_{i_k j_l}$  so individuals are able to reach distant plots, while low  $D$  means they can only reach nearby plots.

With this definition in mind, equation (1) nicely captures two important features for biodiversity conservation: (i) the intrinsic suitability of the landscape structure (captured by the vector of conservation decisions over space  $\mathbf{x}$ ) and (ii) the specific species’ ability to disperse over space (captured by the species’ dispersal rate  $D$ ). Regarding the first feature, equation (1) states that the aggregated survival probability of the species, captured by the sum of the pairwise probabilities  $p_{i_k j_l}$ , increases both with habitat area and with decreasing distances between habitat patches.<sup>A1</sup> It depends on all the conservation decisions taken by landowners across the landscape ( $\mathbf{x}$ ). Typically, equation (1) states that habitat patches close to a group of patches contribute more to biodiversity conservation than isolated patches. Regarding the second feature, equation (1) states that the probability of survival reflects the ability of an individual of a given species to migrate from one conserved plot to another, this ability being measured by the dispersal rate  $D$ . This survival

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<sup>A1</sup>By generalizing the survival probability function from one pair of conserved plots to  $n$  pairs, note that the AB studies using equation (1) necessarily disregard whether the area between the pairs of conserved plots consists of suitable or unsuitable habitats.

probability does not depend on whether this dispersion occurs within or through agricultural or non-conserved portions of the landscape, but only on the distance.

**Numerical illustration.** To provide intuition on how our ecological module works, Table A1 displays the individual’s survival probability between 0 and 1 depending on (i) the distance between two conserved plots and (ii) the species’ dispersal rate. In order to match our empirical simulations, we compute such probabilities for various distances with  $D = \{1, 2, 4\}$ , normalizing to one the distance between the centroids of two adjacent plots in a landscape comprising hexagonal one-hectare plots (i.e., equal to 107.5 m; see Figure 1 in the main text), as the one used in the numerical application of the paper (see Section 2.2).<sup>A2</sup> The figures in Table A1 clearly illustrate the features of the survival probability function. First, the greater the distance  $d_{i_k j_l}$  between two conserved plots, the lower the survival probability of the individuals. For example, increasing the distance between the two plots from 100 to 300 meters decreases the survival probability from 39% to 6% for a species characterized by  $D = 1$ . Second, the higher the species’ dispersal rate  $D$ , the greater the survival probability of the individuals for any distance. For example, for a distance of 500 m, a species with  $D = 4$  has a 31% probability of surviving when moving from the first to the second conserved plots, while it has only a probability of 10% and 1% of doing so if  $D = 2$  and  $D = 1$  respectively.

Table A1: Probability of a species surviving between two plots depending on its dispersal rate and the distance between the conserved plots

	0 m	100 m	200 m	300 m	400 m	500 m	... 1,000 m
$D = 4$	–	0.79	0.63	0.50	0.39	0.31	0.10
$D = 2$	–	0.63	0.39	0.25	0.15	0.10	0.01
$D = 1$	–	0.39	0.15	0.06	0.02	0.01	0.00

NOTE. The table shows the probability of an individual surviving between two conserved plots separated by different distances as a function of the species’ dispersal rate ( $D$ ). The figures provided in the table come from the survival function  $p_{i_k j_l} = \exp(-d_{i_k j_l}/D)$ , with a normalization of the distance unit to 107.5 meters (corresponding to the distance between the centroids of two adjacent plots in landscapes made up of hexagonal one-hectare plots). The table indicates, for example, that a species with  $D = 4$  has a 50% survival rate when moving between two conserved plots 300 m apart, while a species with  $D = 1$  has only a 6% survival rate for this distance.

The survival probabilities, as depicted in Table A1, actually match the behavior of several species (some targeted by the Swiss AB scheme in practice; see; e.g., Wermeille et al., 2014). For example,  $D = 4$  closely approximates to the survival rate of the common butterfly “*Gonepteryx rhamni*”, a species targeted by the Swiss conservation policy that can move up to 1,000 m/year

<sup>A2</sup>Note that the values given to  $D$  in Table A1 only make sense under our normalized scale.

according to Gutiérrez and Thomas (2000). These authors notably indicate that, during their mark–release–recapture study, the remaining adult butterflies moved a distance of 512 m on average  $\pm$  467 m, which is consistent with the survival probabilities of the individual characterized by  $D = 4$  in Table A1. In our landscape depicted in Figure 1, this means that the *Gonepteryx rhamni* butterfly can virtually move across the whole landscape with a survival probability of over 10%.

Similarly,  $D = 2$  is a close approximation to the male European common hamster’s survival rate, a species protected by a group-level conservation program in Alsace (north of the Franco-Swiss border; see Limbach and Rozan, 2023). Indeed, Marquet (2014) indicates that male hamsters can move up to 300 m/year on average, which means they can spread over a quarter of the landscape shown in Figure 1 with a survival probability above 25%. This means that their survival probability after three years is less than  $2\% = 0.25^3$ , which is consistent with their life expectancy (30 months).

Finally,  $D = 1$  is a close approximation to the dispersal behavior of the female hamsters. Indeed, Marquet (2014) indicates that female hamsters move two to four times less than males. In our landscape depicted in Figure 1, this means that the female hamsters can only move over a tenth of the landscape with a survival probability above 15%.

As further explained in Section 2.2, we use these three animals as representative species for our simulations, using the male hamsters for our preferred analyses.

**Potential extensions.** While our ecological function  $B(\mathbf{x})$  is grounded in previous AB literature, it could be extended in several directions, with potential implications for AB design.

First, not all borders necessarily contribute equally to biodiversity (so biodiversity could be represented by a weighted index  $B^w = \sum_{i_k} \sum_{j_l \neq i_k} w_{i_k j_l} x_{i_k} x_{j_l} e^{-d_{i_k j_l}/D}$  with  $w_{i_k j_l} \geq 0$  the “ecological weight” of border  $(i_k j_l)$ ), such that regulators might want to further differentiate payments to prioritize the most valuable borders. It is however unclear what would be the impacts of these heterogeneous plot-specific suitability weights given the regulators’ already limited information about the opportunity costs. To treat this feature realistically, a model incorporating asymmetric information would be required.

Second, given that each conserved plot’s contribution to biodiversity depends on (i) its location relative to the other conserved plots (measured by  $\sum_{j_l \neq i_k} x_{j_l} e^{-d_{i_k j_l}/D}$  for plot  $i_k$ , see equation (1)), and (ii) all the other plots’ conservation status, implementation of more complex payments might be considered. For instance, specific bonuses might be provided for conserving a given number of plots  $n$  within a distance  $\bar{d}$ , with payments depending on  $n$  and  $\bar{d}$ . While our setting matches the

case with  $n = 2$  and  $\bar{d} = 1$ , future work could relax the standard AB structure with strict adjacency to investigate these more general cases.

## A2 Characteristics of our landscape

As depicted in Section 2.2 of the main text, our generated landscapes consist of seven landowners each owning seven one-hectare hexagonal plots. This landscape structure presents several advantages over those with square plots usually considered in the literature – for example, Bareille et al. (2023) considered a square-plot landscape consisting of nine landowners  $\times$  nine plots, while Wätzold and Drechsler (2014) considered a square-plot landscape made up of 100 landowners  $\times$  1 plots.

First, our landscape reduces the numerical resolution time required to run all of our simulations compared to, e.g., Bareille et al. (2023). 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 manuscript takes approximately five 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 with the squared landscape made of nine landowners would take about twenty-five days with the same computer. The detrimental issue linked to the exponential number of coalition structures to consider increases as the number of landowners increases. For example, in the case of Wätzold and Drechsler (2014) with 100 landowners, there are millions of billions of coalition structures to consider. Even in the case of only eight landowners considered in Banerjee et al. (2017), Banerjee (2018) and Banerjee et al. (2021), we would still need to consider  $Bell(8) = 4,140$  alternative coalition structures.

Second, all the peripheral landowners (i.e., all landowners except landowner  $D$ , see Figure 1) present the same relative spatial position compared to the central landowner (i.e., landowner  $D$ ), thus all presenting the same numbers of internal and external boundaries. This is a marked difference with squared landscapes with more than four landowners (i.e., as those considered in virtually all AB studies), where peripheral landowners have a different number of external boundaries (e.g., the squared landscape generated by Wätzold and Drechsler, 2014, considers peripheral landowners with either two or three external boundaries). That is, compared to a normal square-plot setup, our hexagonal landscapes provide greater symmetry between landowners.

Third, the proportion of external boundaries is slightly higher in our hexagonal landscape than in previous square-plot versions. In total, our landscape respectively presents 84 and 36 internal and external boundaries, compared to 108 and 36 internal and external boundaries in a square-plot landscape with 9 landowners  $\times$  9 plots, or 160 internal borders for 20 external borders only for square-plot landscapes made up of 4 landowners  $\times$  25 plots such as in Parkhurst and Shogren (2007)

and Panchalingam et al. (2019).<sup>A3</sup> That is, our hexagonal landscapes give a more even proportion of internal and external boundaries within the landscape, thus typically better matching the reality of agricultural landscapes (Häusler and Zabel, 2024). The greater proportion of external boundaries in our setup comes from the fact that hexagonal plots with external boundaries always have at least two external boundaries (three for the plots located at the furthest ends of the landscape), while square plots have at most two external boundaries (for the plots that are located on the landholding corners).

**Implications for differentiated ABs.** The landscape structure can be interestingly captured by the number of connections that require internal bonuses to be conserved. For example, note that 67% of the connections in our 7 landowners  $\times$  7 hexagonal plots landscape require internal bonuses to be conserved.<sup>A4</sup> Comparatively, conservation in landscapes with single-plot landowners (as in most of the literature; e.g., Wätzold and Drechsler, 2014; Banerjee et al., 2017, 2021) depends at 0% on internal bonuses, while this figure is 42% in 9 landowners  $\times$  9 plots squared landscapes of Bareille et al. (2023), and 71% in a 4 landowners  $\times$  25 plots case from Parkhurst and Shogren (2007). This plot proportion (that can only be conserved with internal bonuses) varies with the plot distribution between landholdings (i.e., the ownership structure), decreasing when the total number of landowners (resp. plots) increases (resp. decreases). Based on our results in Section 3, intuition suggests that the more plots depending only on internal bonuses, the greater the cost-effectiveness of internal compared to external bonuses.

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<sup>A3</sup>Obviously, landscapes considering only one plot per landholding impose external borders by construction (e.g., Wätzold and Drechsler, 2014; Banerjee et al., 2017, 2021), with no internal border at all.

<sup>A4</sup>This number is computed with the “*connectance*” metric (Rayfield et al., 2011; Häusler and Zabel, 2024), defined as the number of realized connections out of all possible connections. With unlimited budgets, 100% of connections will be realized with pure internal bonuses, whereas only 33% of them will be realized with pure external bonuses. The difference (67%) is the proportion of connections that can only be conserved with internal bonuses.

### A3 Landscape cost randomization

Figure 1 displays the average opportunity cost distribution across all plots, but the average values hide significant variation between our fifty generated landscapes. Figure A1 shows the distribution of the plots' conservation opportunity costs in €/ha for four out of fifty generated landscapes that we use for our simulations. All the landscapes are different, but have a similar type of distribution to represent coherent landscapes, comparable in terms of both geography and topography. It shows that, while the structure of each generated landscape closely resembles the averages, the structure of each landscape is unique. This is because we have fixed the plots with the lowest and highest opportunity costs as those located respectively at the south-western edge of landowner *A*'s landholding and at the northern edge of landowner *G*'s landholding for all fifty generated landscapes, which allows us to keep a similar spatial gradient of opportunity costs across all generated landscapes. Yet, given the randomization procedure described in Section 2.2, fixing these two anchors and a Moran's index value still enables a diversity of landscapes to emerge. For example, Figure A1.c represents a rather mountain-like landscape, with a clear gradient of opportunity costs closely mapping potential increase in altitude or slope. By comparison, Figure A1.d rather mimics a valley landscape, where the plots surrounding a virtual river crossing landowners *A*'s, *C*'s and *F*'s landholdings present significantly lower opportunity costs than the others. Finally, Figures A1.a and A1.b rather display more traditional patchy agricultural landscapes.



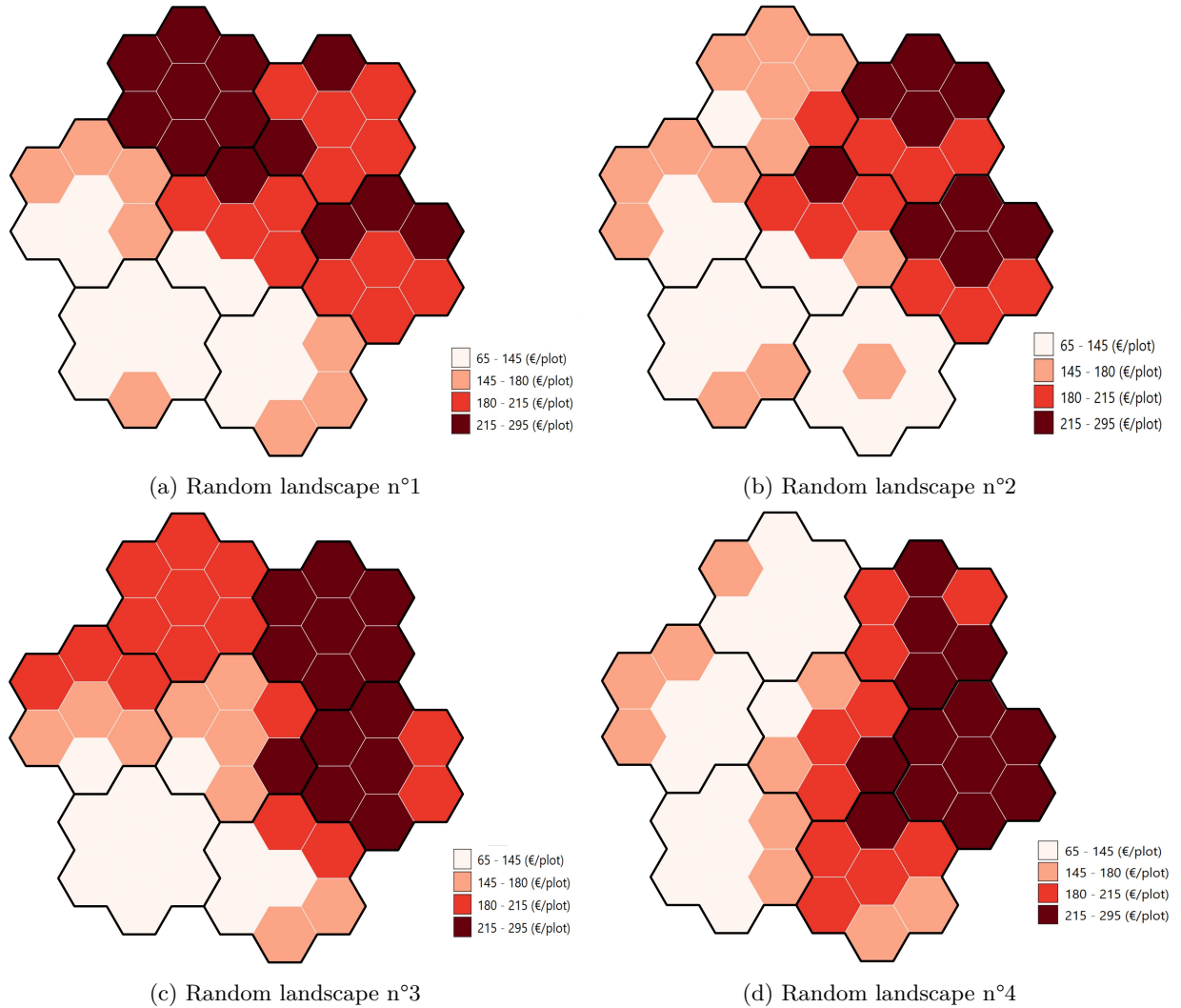


Figure A1: Examples of cost randomization for four landscapes.

NOTE. The figures display the average profitability of the productive activity (i.e., the opportunity costs of conservation) of the one-hectare plots across the landscape for four fictitious landscapes – out of 50 – generated for the purpose of our simulation exercise. Such landscapes have been generated by (i) drawing the plot-level opportunity cost from a uniform distribution with values ranging from €110/plot to €250/plot (and thus €180/plot on average) while (ii) setting the same plots with the lowest and highest opportunity costs across all of the 50 generated landscapes (respectively €110/ha and €250/ha for the south-western plot of landowner *A*'s landholding and the northern plot of landowner *G*'s landholding), as well as (iii) imposing a spatial cost auto-correlation at a Moran's index of 0.8 and (iv) adding random landowner-level shifters of  $\pm\text{€}45/\text{plot}$ .

## A4 Cost-effectiveness: benchmark calibration

Figure A2 shows the cost-effectiveness of the AB scheme  $AB(50,50)$  within the grand coalition and stable structures compared to homogeneous payments (HP). The x-axis shows total 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.

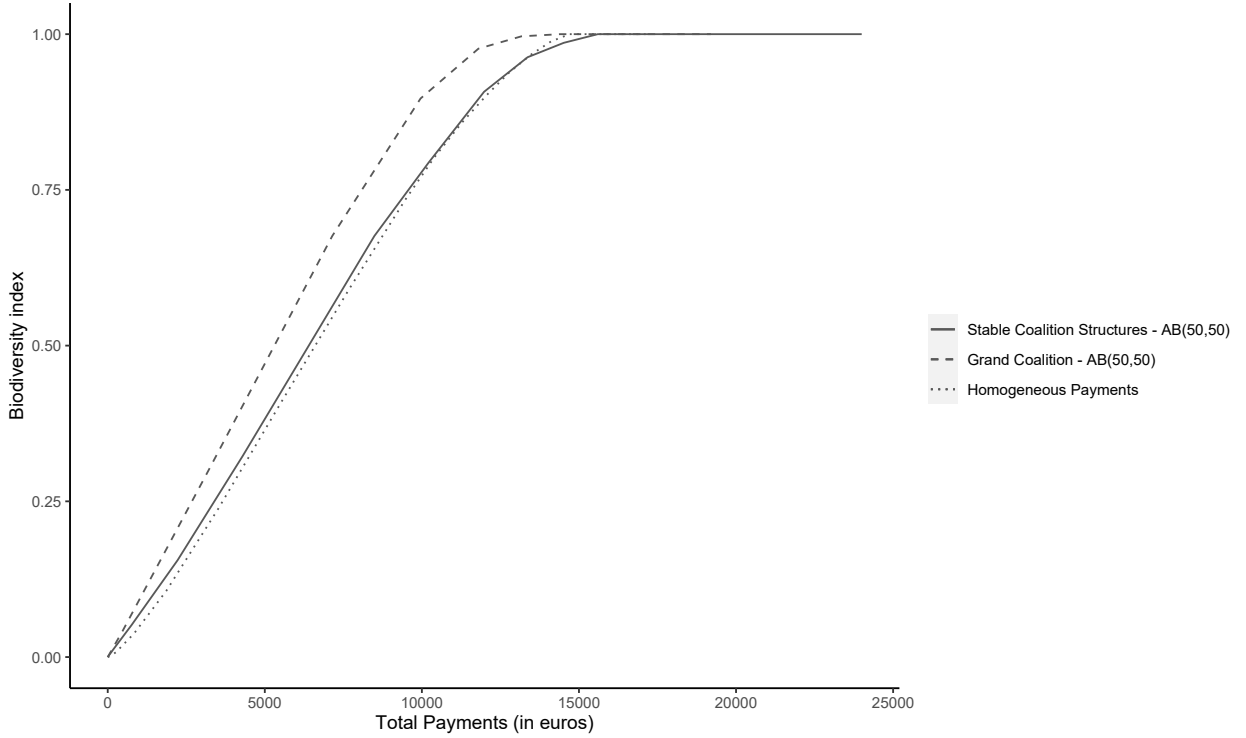


Figure A2: Cost-effectiveness of the  $AB(50,50)$  scheme, respectively assuming the grand coalition and stable coalition structures, compared to homogeneous payments.

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP schemes (dashed line) and for the  $AB(50,50)$  scheme within the grand coalition (exogenously assumed but not stable) and the stable coalition structures (endogenously 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 (with a Moran's index of 0.8).

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 bonuses 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 AB cost-effectiveness. Compared to the landscapes formed by the

grand coalition, the stable coalition structures that are endogenously formed in response to the AB produce landscapes that are about 5% to 10% less cost-effective for biodiversity conservation. This is valid for the whole range of budgets. In line with Bareille et al. (2023), we also find that HPs 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 large budgets*. Though the difference in cost-effectiveness between the two schemes is smaller in our case, we find that our setup 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.

## A5 Cost-effectiveness: zoom of Figure 2

Figure A3 zooms on Figure 2 of the main text for low budgets, highlighting the range of total payments where AB(50,50) is more cost-effective than AB(100,0).

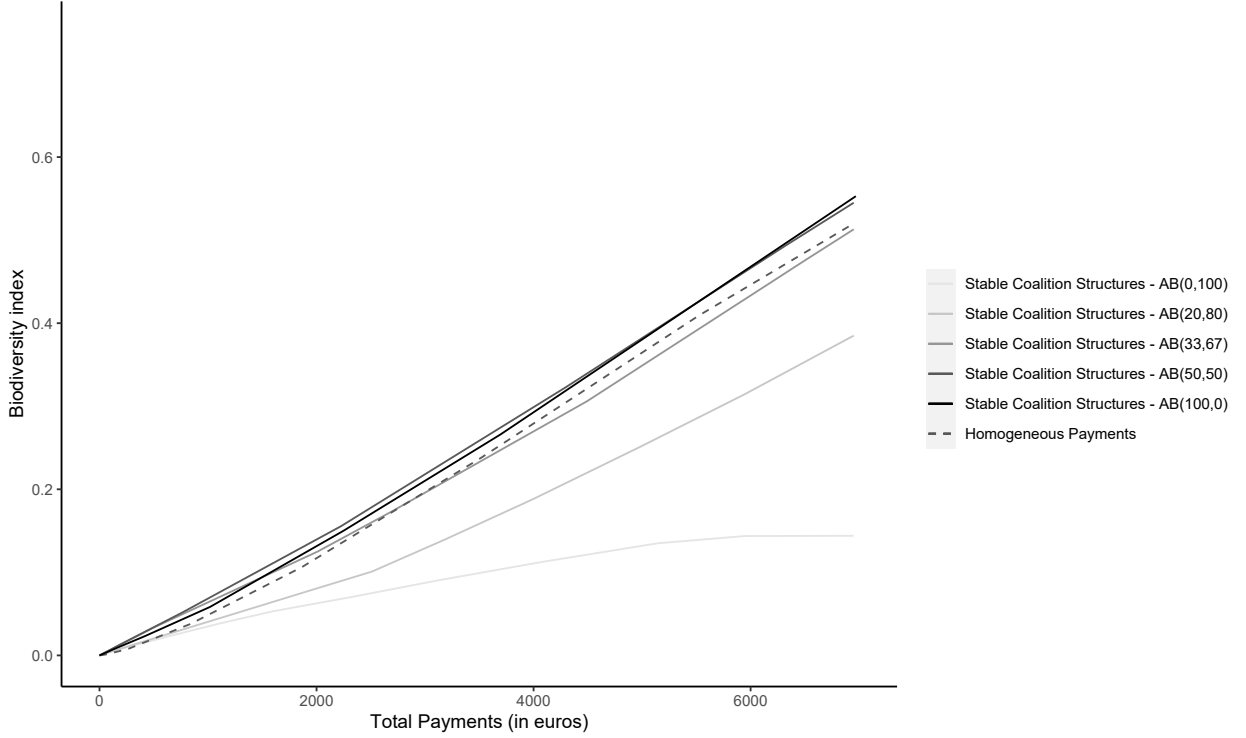


Figure A3: Cost-effectiveness of alternative AB schemes within stable coalition structures compared to HPs.

NOTE. The figure zooms on the normalized biodiversity level as a function of total payments (up to €7,000) for HPs (dashed lines) and for the scheme  $AB(z, 100 - z)$  within stable coalition structures. The 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 (with a Moran's index of 0.8).

## A6 Cost-effectiveness: additional results for alternative AB schemes

Figure A4 shows the cost-effectiveness of ABs additional to those presented in Figure 2 in the main text. It shows that, for large budgets,  $AB(100, 0)$  is the most cost-effective scheme, while, for smaller budgets, ABs that additionally (slightly) reward external bonuses can improve AB cost-effectiveness. The figure clearly shows that, the greater the regulator’s budget, the more the most-effective AB is differentiated towards internal bonuses. Formally, while  $AB(50, 50)$  remains the most cost-effective AB for low budgets (until about €3,000),  $AB(67, 33)$  becomes the most cost-effective scheme between about €3,000 and €5,000, and  $AB(80, 20)$  becomes the most cost-effective between about €5,000 and €8,500. Only above this budget threshold is  $AB(100, 0)$  identified as the most cost-effective scheme. Put differently, while (i) the usual undifferentiated AB is the most cost-effective solution for low budgets, (ii) partial differentiation increases AB cost-effectiveness for medium budgets and (iii) full differentiation is the most cost-effective solution for large budgets.

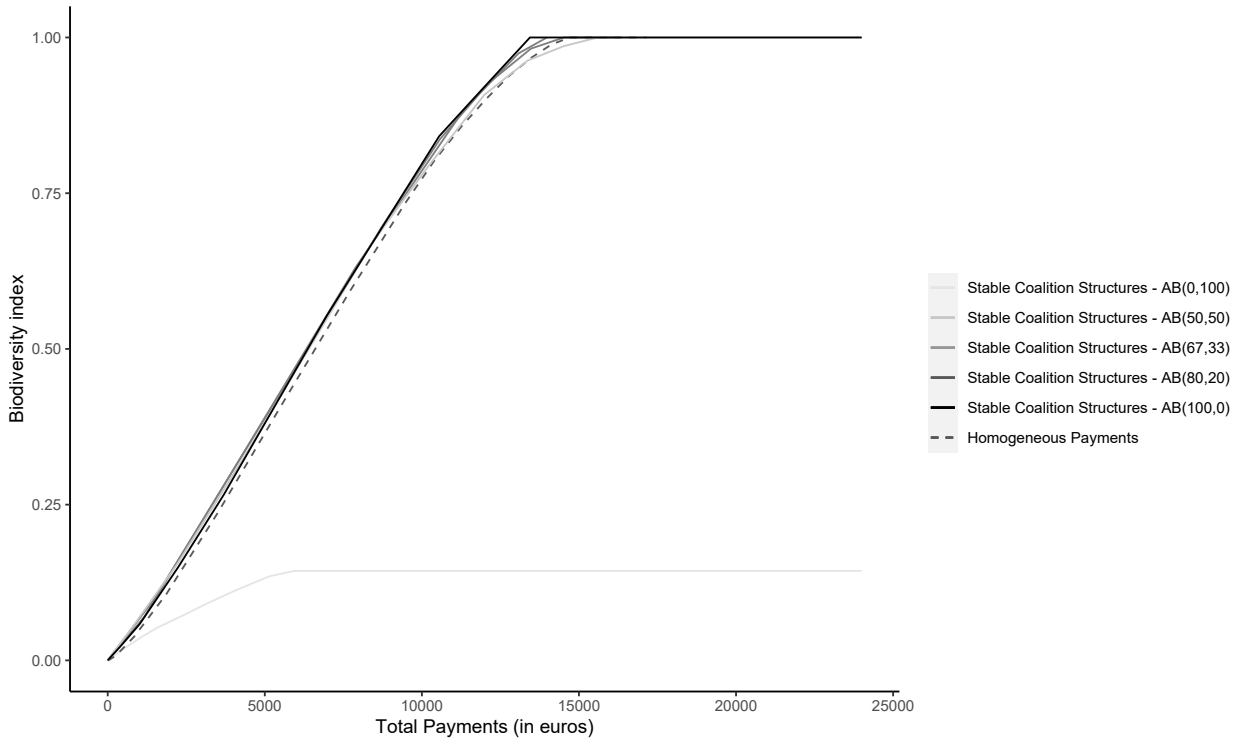


Figure A4: Cost-effectiveness of alternative AB schemes within stable coalition structures compared to homogeneous payments.

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP schemes (dashed lines) and for the scheme  $AB(z, 100 - z)$  within stable coalition structures. The 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 (with a Moran’s index of 0.8).

## A7 Cost-effectiveness: habitat size

Biodiversity levels combine two things: (i) total habitat size and (ii) habitat agglomeration in the landscape – see equation (1) of the main text. To distinguish the effects of the AB schemes on these two outcomes, Figure A5 shows the habitat size (measured as the number of conserved plots) reached with the same AB schemes as in Figure 2. It shows that  $AB(100,0)$  is the AB scheme leading to the largest habitat size regardless of the regulator’s budget. This means that the curve for  $AB(50,50)$  is above the curve for  $AB(100,0)$  in Figure 2 for budgets below €5.500 because *agglomeration effects are greater in  $AB(50,50)$  than in  $AB(100,0)$  for small budgets*. As Figure A5 shows that  $AB(100,0)$  leads to the greatest habitat area whatever the budget size, this indeed means that  $AB(50,50)$  provides greater habitat agglomeration for small budgets. In other words, cooperation induced by external bonuses allows landowners to increase the connectivity of the conserved habitats, even though the total conserved area is smaller (on average) than those reached with internal bonuses alone.

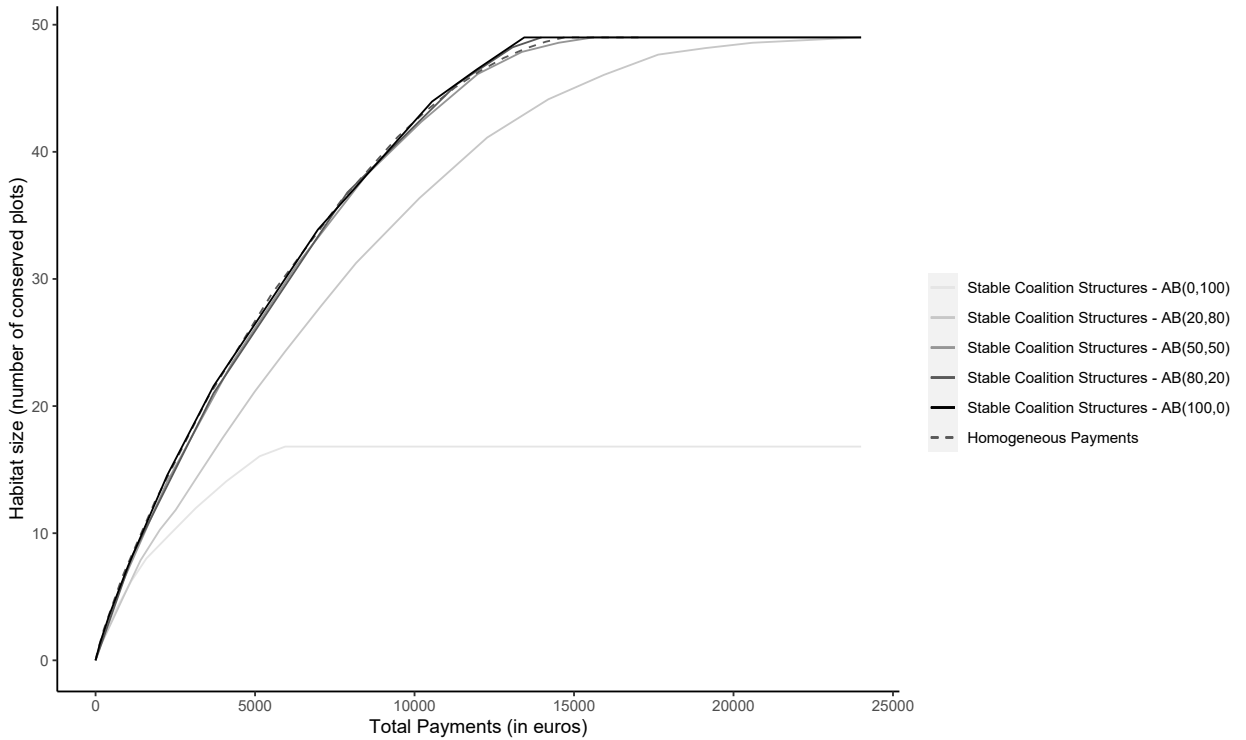


Figure A5: Habitat size reached under alternative AB schemes within stable coalition structures compared to HPs.

NOTE. The figure shows the habitat size (i.e., the number of conserved plots) as a function of total payments for HP schemes (dashed line) and for the scheme  $AB(z, 100 - z)$  within stable coalition structures. The 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 (with a Moran’s index of 0.8).

## A8 Cost-effectiveness: detailed outcomes by pairs of internal and external bonuses

Table A2 shows how AB cost-effectiveness (Panel C.) – computed here as the ratio of biodiversity to total payments – as well as its numerator (biodiversity, Panel A.) and denominator (total payments, Panel B.), change depending on the proportion of 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 A2: Biodiversity, payments and cost-effectiveness depending on internal and external bonuses

		Internal bonus						
		0	20	40	60	80	100	120
		A. BIODIVERSITY						
<b>External bonus</b>	<b>0</b>	0.00	0.00	0.06	0.55	1.00	1.00	1.00
	<b>20</b>	0.00			0.67			1.00
	<b>40</b>	0.00			0.75			1.00
	<b>60</b>	0.00	0.02	0.24	0.79	1.00	1.00	1.00
	<b>80</b>	0.02			0.84			1.00
	<b>100</b>	0.05			0.87			1.00
	<b>120</b>	0.07	0.09	0.40	0.88	1.00	1.00	1.00
			B. TOTAL PAYMENTS					
<b>External bonus</b>	<b>0</b>	0	0	1,018	6,970	13,440	16,800	20,160
	<b>20</b>	0			8,286			20,700
	<b>40</b>	0			9,356			21,240
	<b>60</b>	44	350	3,470	10,213	18,020	19,900	21,780
	<b>80</b>	648			11,159			22,320
	<b>100</b>	1,593			11,821			22,860
	<b>120</b>	2,314	2,919	6,320	12,491	19,640	21,520	23,400
			C. COST-EFFECTIVENESS					
<b>External bonus</b>	<b>0</b>	-	-	57.29	79.99	74.40	59.52	49.60
	<b>20</b>	-			80.86			48.31
	<b>40</b>	-			79.96			47.08
	<b>60</b>	40.54	52.01	70.17	77.72	55.49	50.25	45.91
	<b>80</b>	36.13			76.07			44.80
	<b>100</b>	33.26			73.25			43.74
	<b>120</b>	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 one million to facilitate reading), used as a measure of cost-effectiveness.

Panel A. of Table A2 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 A2).

Panel C. of Table A2 specifically 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 an  $AB(75, 25)$  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).



## A9 Cooperation: additional results for alternative AB schemes

Figure A6 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.

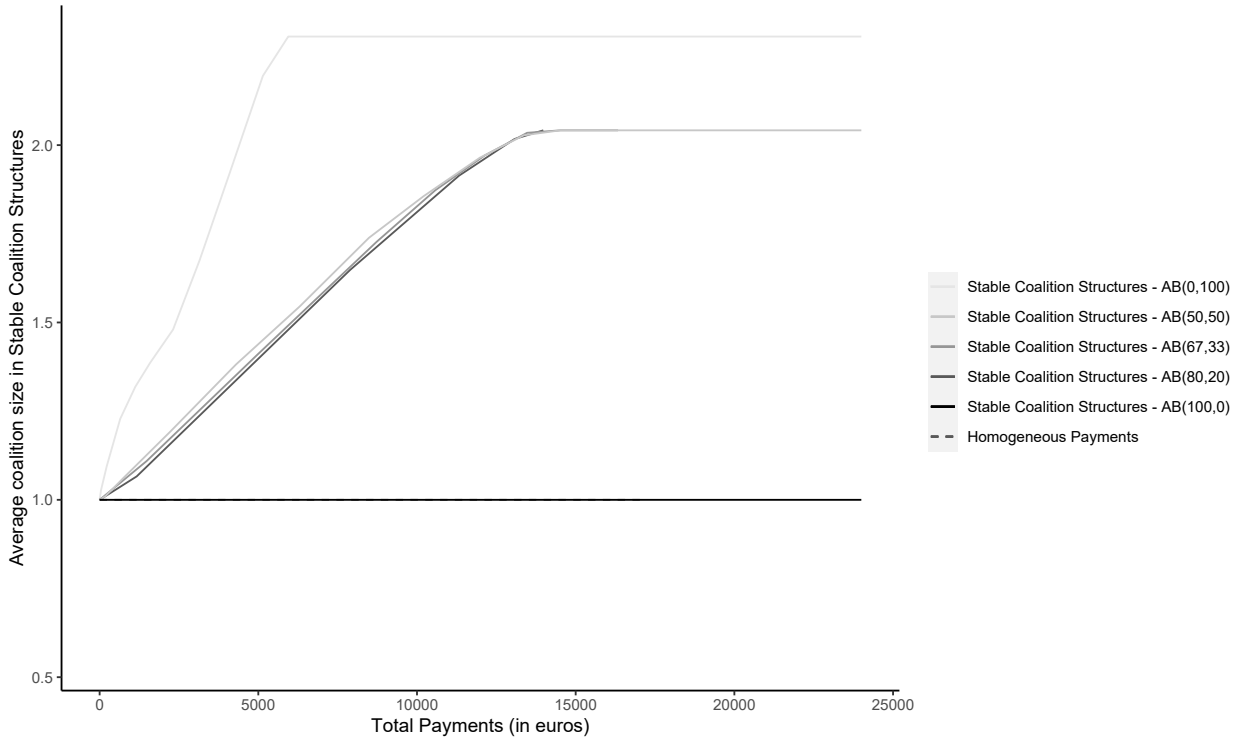


Figure A6: Average coalition size within the stable coalition structures responding to alternative AB schemes.

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  $AB(z, 100 - z)$ . The 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 (with a Moran's index of 0.8). Hidden by the  $AB(100,0)$  curve, HPs lead to one-landowner coalitions by definition.

## A10 Distribution of opportunity costs for Section 3.3

Figure A7 shows the distribution of the opportunity costs across the landscape for the example given in Figure 4 of the main text. These opportunity costs explain the enrollment of the different plots within the alternative ABs (differentiated by the proportion of internal and external bonuses).

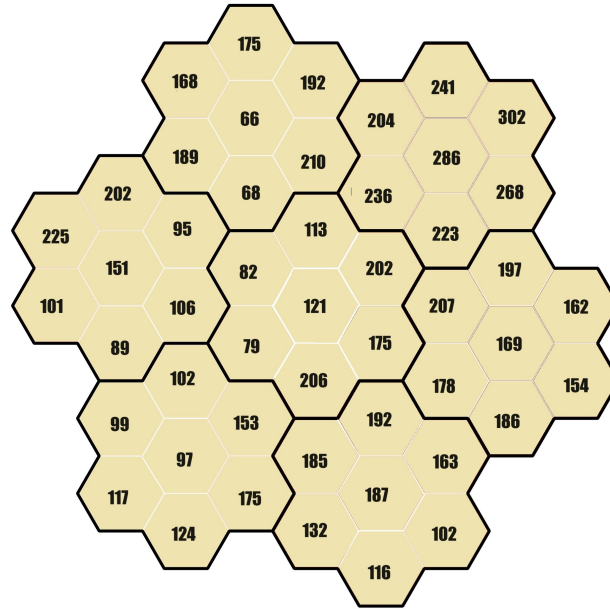


Figure A7: Distribution of opportunity costs in a random landscape.

NOTE. The figure shows the opportunity cost per plot across a landscape corresponding to the conservation decisions taken in Figure 4 of the main text in response to alternative ABs. Black lines are landholding boundaries.

## A11 Sensitivity: dispersal rate of biodiversity

Figures A8 and A9 show the biodiversity levels reached on average over all the stable coalition structures of the fifty landscapes as a function of total payments for five AB schemes with varying proportions of internal and external bonuses, when  $D = 4$  and  $D = 1$  respectively. That is, Figure A8 (resp. Figure A9) shows how AB cost-effectiveness changes when looking at species that can disperse more (resp. less) easily than in our benchmark analyses – note that the conservation and cooperation decisions remain identical to those in our preferred analyses as the incentives do not change (only the species dispersal rate changes). Figure A8 shows that AB cost-effectiveness decreases compared to that of HPs when species are more mobile, as usually found in the literature (e.g., Wätzold and Drechsler, 2014; Bareille et al., 2023). It also shows that  $AB(100,0)$  becomes more cost-effective than  $AB(50,50)$  when budgets are greater than €4,000, i.e., for a smaller threshold than those determined in our preferred analyses.<sup>A5</sup> This means that, in relation to our discussion in Section A1, where species can move more easily, agglomeration becomes less necessary to conserve biodiversity. This is also reflected in the wider gaps between the alternative AB curves. In particular, the maximum (relative) amount of biodiversity reached in  $AB(0,100)$  decreases from about 0.15 in Figure 2 in the main text to 0.13 in Figure A8. Since the conservation decisions remain identical to those of our preferred analyses, this reduction can only be attributed to the increase in species' dispersal rate.

Finally, as already observed in the literature, considering species with lower dispersal rates reinforces the interest of AB over standard HPs. For example, we identify in Figure A9 that the threshold above which HPs are more cost-effective than  $AB(50,50)$  is about €13,000 (when  $D = 1$ ; compared to €12,500 in Figure 2). When the species are much more mobile ( $D = 4$ ), Figure A8 shows that HPs are always more cost-effective than undifferentiated ABs (but not always than differentiated ABs).

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<sup>A5</sup>Symmetrically, when  $D$  decreases from 2 to 1, Figure A9 shows that  $AB(100,0)$  becomes more cost-effective than  $AB(50,50)$  for a higher threshold of total payments (when budgets are greater than €7,000).

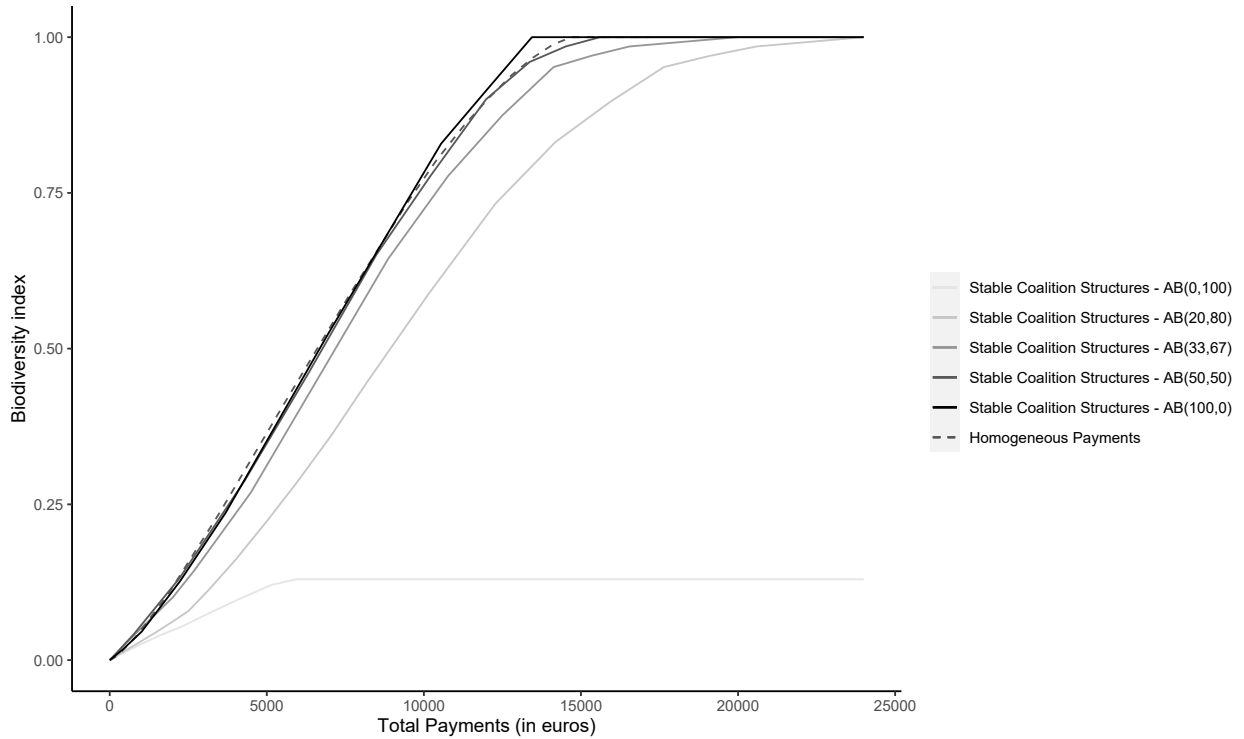


Figure A8: Cost-effectiveness of alternative AB schemes within stable coalition structures with more mobile species ( $D = 4$  instead of 2).

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP 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 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  $p = 0$ ,  $D = 4$  and  $C = 0.5$ . The outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8).

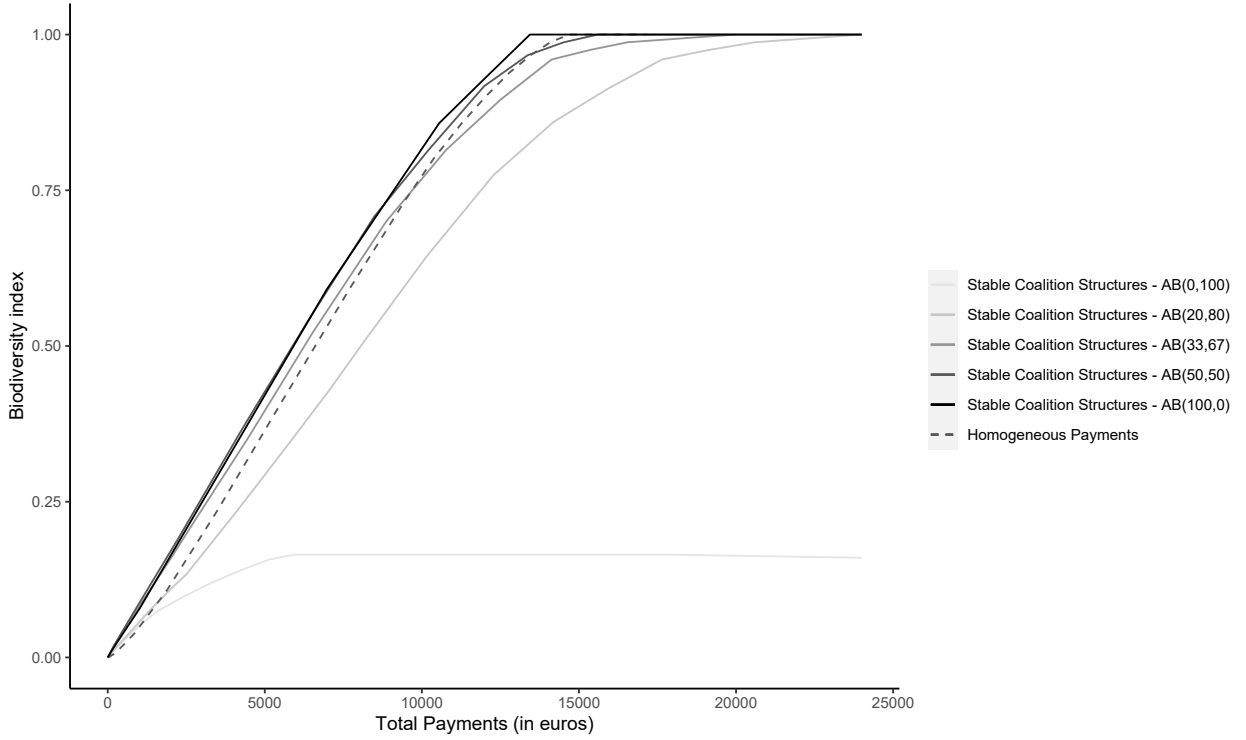


Figure A9: Cost-effectiveness of alternative AB schemes within stable coalition structures with less mobile species ( $D = 1$  instead of 2).

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP 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 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  $p = 0$ ,  $D = 1$  and  $C = 0.5$ . The outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8). Hidden by the  $AB(100, 0)$  curve, HPs lead to one-landowner coalitions by definition.

## A12 Sensitivity: coordination costs

Figures A10, A11 and A12 show changes in biodiversity as a function of total payments when coordination costs are set at  $C = 0.05$ ,  $C = 5$  and  $C = 50$  respectively (instead of  $C = 0.5$  in our preferred analyses), while Figures A13, A14 and A15 show similar changes for cooperation levels (i.e., coalition size).

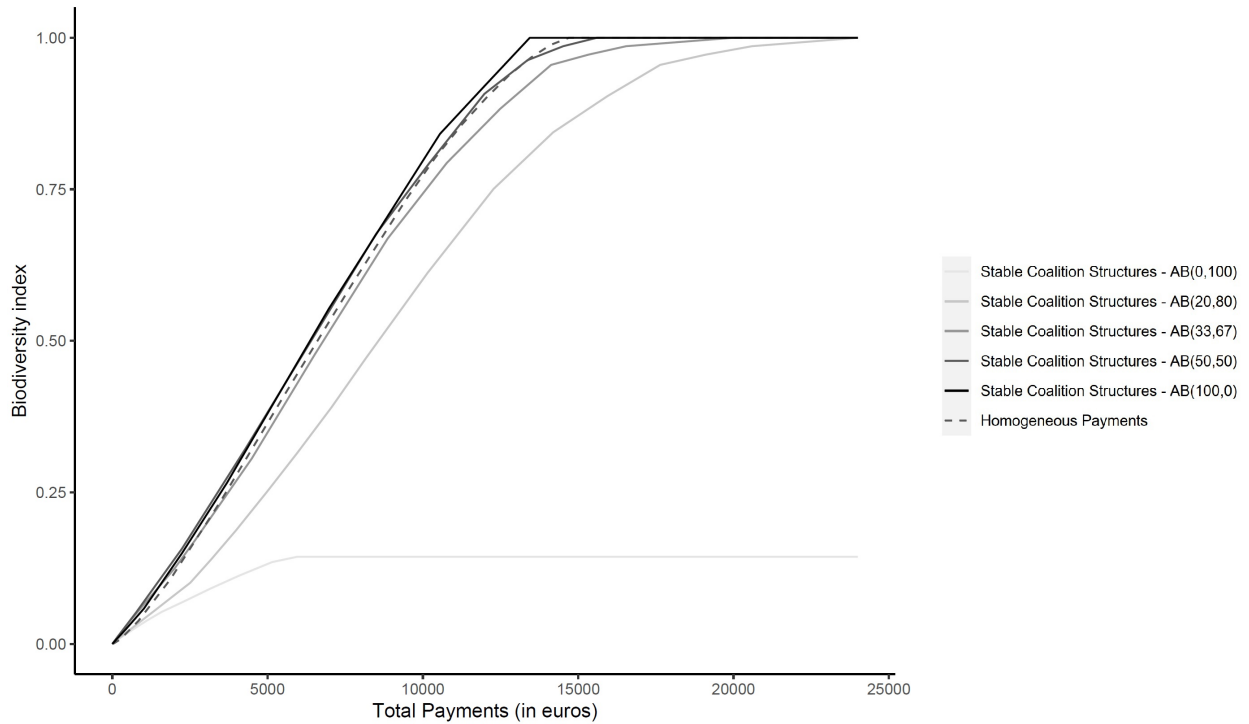


Figure A10: Cost-effectiveness of alternative AB schemes within stable coalition structures with higher coordination costs ( $C = 0.05$  instead of 0.5).

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP 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 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  $C = 5$ . The outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8).

The results remain close to those in our preferred analyses (Figures 2 and 3 in the main text). We barely see any difference when  $C$  is divided or multiplied by 10 (see respectively Figures A10, A11). Only by multiplying  $C$  by 100 can we observe some slight changes. Compared to HPs (which remain unaffected by the increase in coordination costs), Figure A12 shows that AB cost-effectiveness slightly decreases for all ABs including some external bonuses. Only the cost-effectiveness of  $AB(100, 0)$  remains totally unaffected here – which makes perfect sense given that landowners have no incentives to form coalitions under this scheme. As a result,  $AB(100, 0)$  becomes more

cost-effective than  $AB(50, 50)$  when the total payments exceed €2,000 (instead of €5,500 in our preferred analyses).

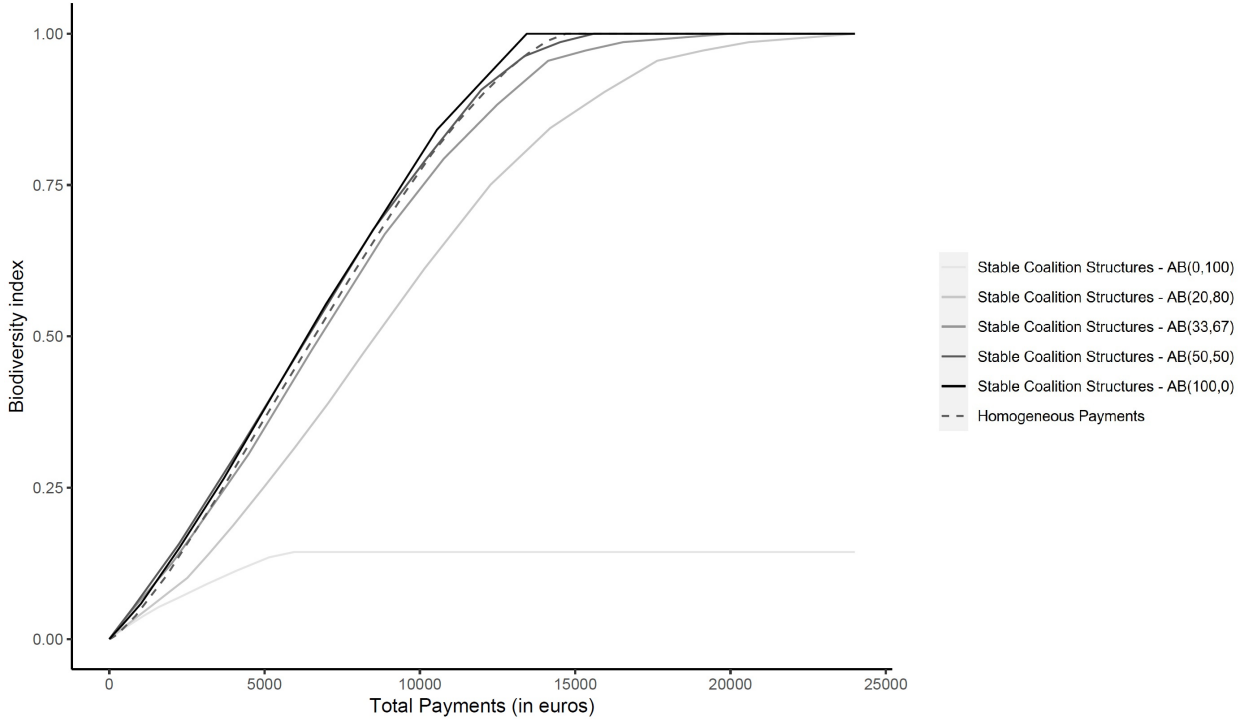


Figure A11: Cost-effectiveness of alternative AB schemes within stable coalition structures with higher coordination costs ( $C = 5$  instead of 0.5).

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP 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 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  $C = 5$ . The outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8).

We observe similar (though slightly more pronounced) patterns on cooperation. Coordination costs do not affect stable coalition structures for large budgets, but move the coalition size curves to the right – indicating that larger budgets are necessary to reach the same extent of cooperation when coordination costs increase. Specifically, although dividing or multiplying the coordination costs by ten has minor effects on coalition size (Figures A13 and A14), Figure A15 shows that the extent of cooperation decreases when multiplying the coordination costs by 100 ( $C = 50$ ) for all ABs including an external bonus. For example, the average coalition size in the stable coalition structures in  $AB(20, 80)$  is 1.8 when total payments equal €5,000 with  $C = 0.5$  (Figure 3), but only 1.6 with  $C = 50$  (Figure A15).

The negligible role of coordination costs on AB cost-effectiveness has also been highlighted by Bareille et al. (2023) in the particular case of  $AB(50, 50)$ . There, the authors explained that,

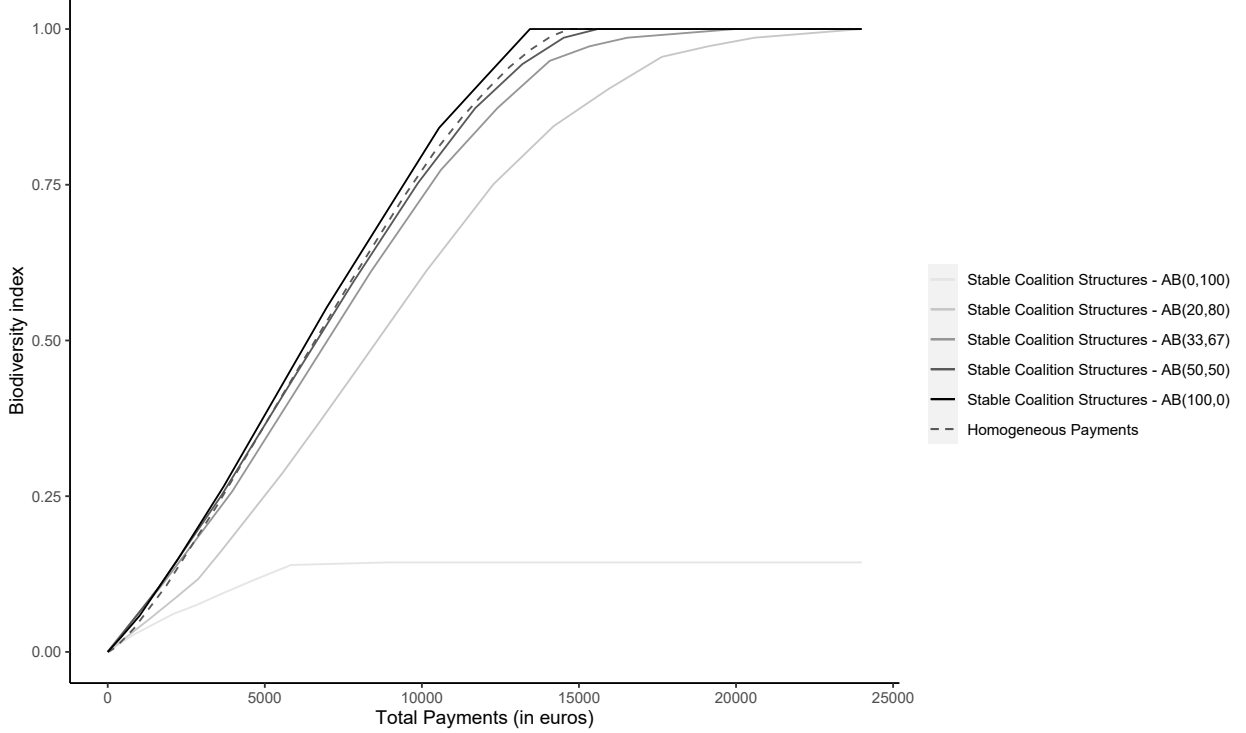


Figure A12: Cost-effectiveness of alternative AB schemes within stable coalition structures with higher coordination costs ( $C = 50$  instead of 0.5).

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP 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 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  $C = 50$ . The outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8).

although coordination costs are regularly suspected to be a crucial driver of cooperation failure in AB schemes (e.g., Albers et al., 2008; Banerjee et al., 2017), their results, accounting for endogenous coalition formation, show that coordination costs actually have limited impact on AB cost-effectiveness because they only affect the coalition formation stage of the game, not the second stage (conservation decisions).

The intuition for the limited impacts of coordination costs on AB cost-effectiveness is twofold. First, because increasing coordination costs makes cooperation less interesting, fewer plots will be conserved with the external bonus. Second, increasing coordination costs while keeping the budget constant implies a budget reallocation from external to internal bonuses related expenses. As such, more plots will be conserved via the higher internal bonuses. These two opposing effects of internal vs. external bonuses when coordination costs increase explain the small effect of coordination costs on AB cost-effectiveness. Another way to see this “budget reallocation effect” in our principal-agent



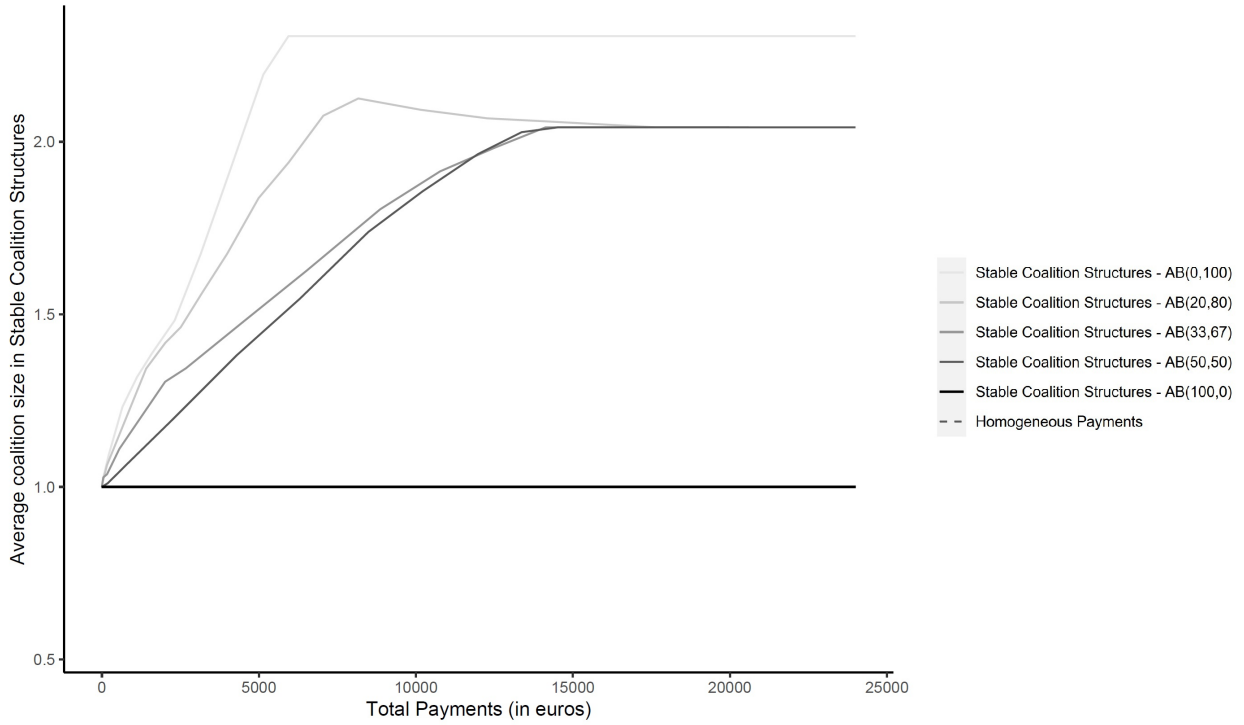


Figure A13: Average coalition size within the stable coalition structures responding to alternative AB schemes with lower coordination costs ( $C = 0.05$  instead of 0.5).

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 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  $C = 50$ . Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8). Hidden by the  $AB(100, 0)$  curve, HPs lead to one-landowner coalitions by definition.

framework is to note that the regulator anticipates that larger coordination costs imply smaller conservation decisions, such that the regulator optimally increases the bonus levels to achieve almost the same biodiversity levels with the same budget. As noted by Bareille et al. (2023), it results that “the main effect of the coordination costs rather relates to the design of AB schemes: higher coordination costs require higher bonuses to reach a given biodiversity target” (that is, for given  $p$ ,  $q^I$  and  $q^E$ , not for given  $TP$ ).

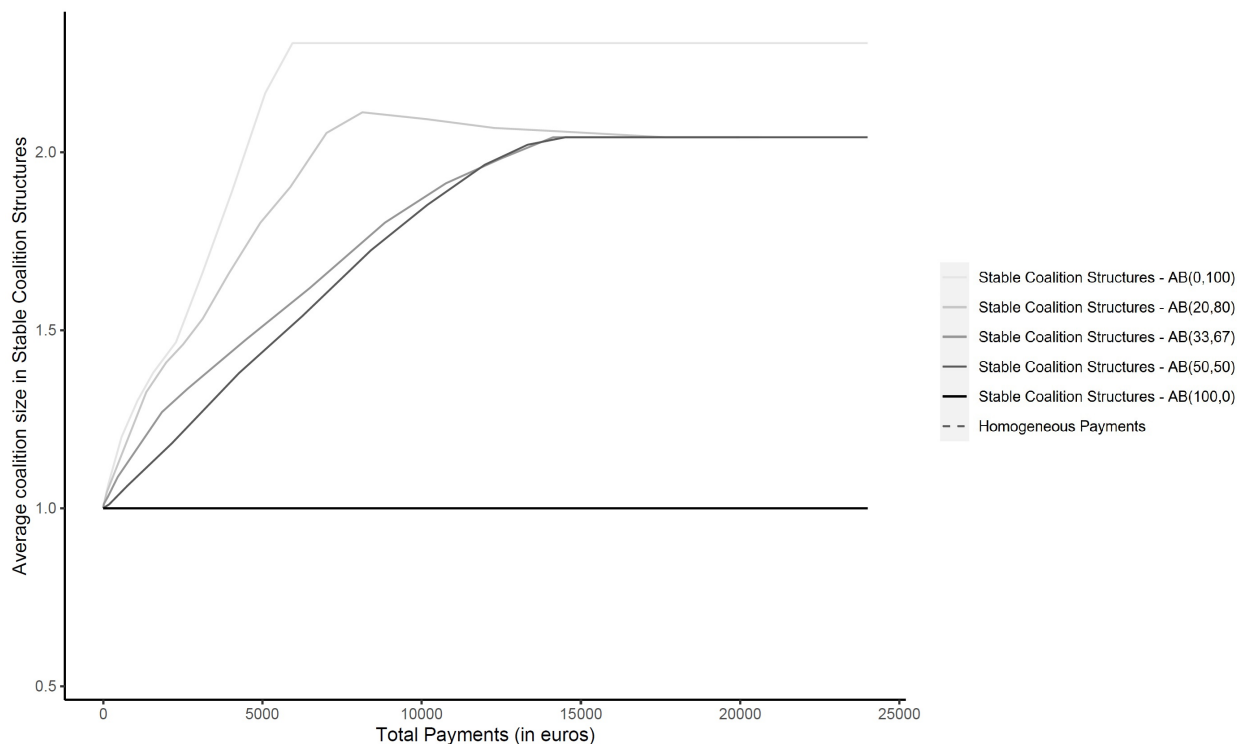


Figure A14: Average coalition size within the stable coalition structures responding to alternative AB schemes with higher coordination costs ( $C = 5$  instead of 0.5).

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 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  $C = 50$ . Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8). Hidden by the  $AB(100, 0)$  curve, HPs lead to one-landowner coalitions by definition.

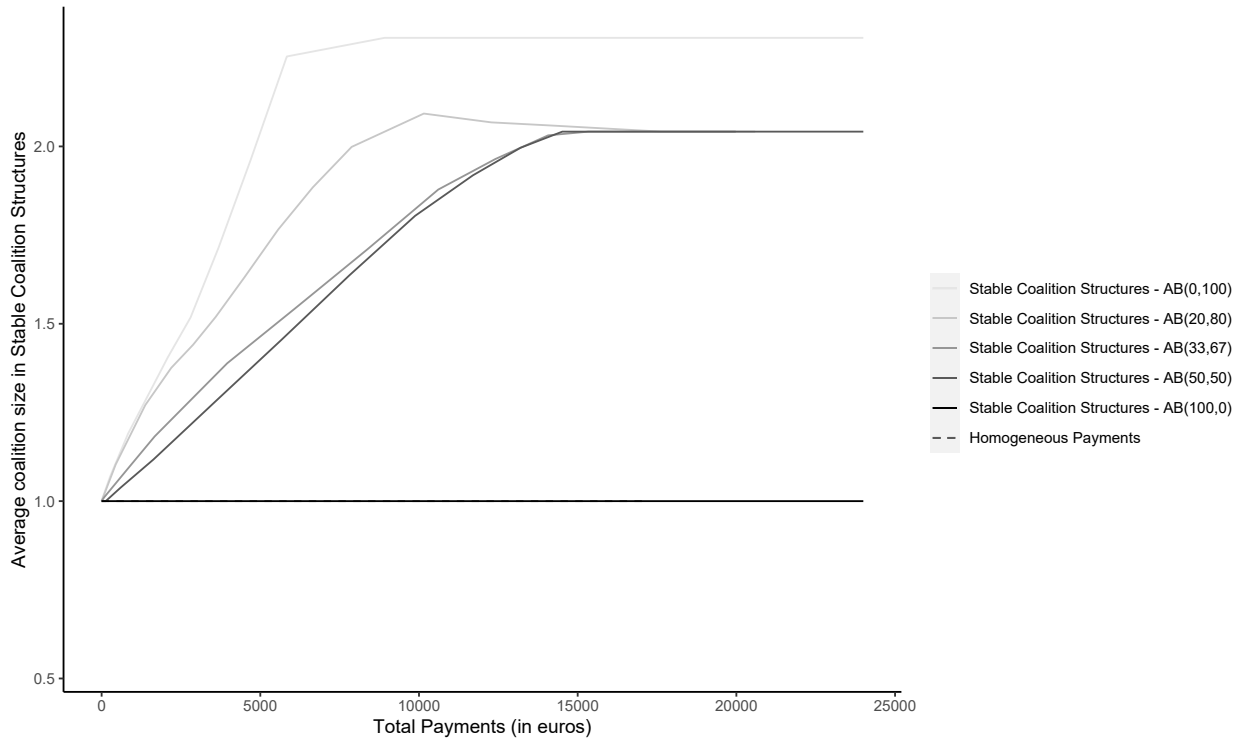


Figure A15: Average coalition size within the stable coalition structures responding to alternative AB schemes with higher coordination costs ( $C = 50$  instead of 0.5).

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 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  $C = 50$ . Outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8). Hidden by the  $AB(100, 0)$  curve, HPs lead to one-landowner coalitions by definition.

### A13 Sensitivity: spatial autocorrelation of opportunity costs

Figures A16 and A17 respectively show changes in biodiversity and cooperation levels as a function of total payments when the Moran’s index is fixed at 0.4 instead of 0.8. The results remain close to those in the main text (Figures 2 and 3). Compared to HPs (whose cost-effectiveness decreases given the reduction in the spatial autocorrelation of opportunity costs; see, e.g., Wätzold and Drechsler, 2014, for similar results in the literature), AB cost-effectiveness increases for all ABs except  $AB(0, 100)$  (see Figure A16). The ranking of the AB schemes is only slightly affected by the large reduction in spatial cost correlation, scheme  $AB(100, 0)$  becoming more cost-effective than  $AB(50, 50)$  when budgets exceed €6,000 (instead of €5,500 in our preferred analyses). Figure A17 shows that the extent of cooperation is also largely unaffected by the reduction of the Moran’s index (only the extent of cooperation in  $AB(0, 100)$  significantly decreases).

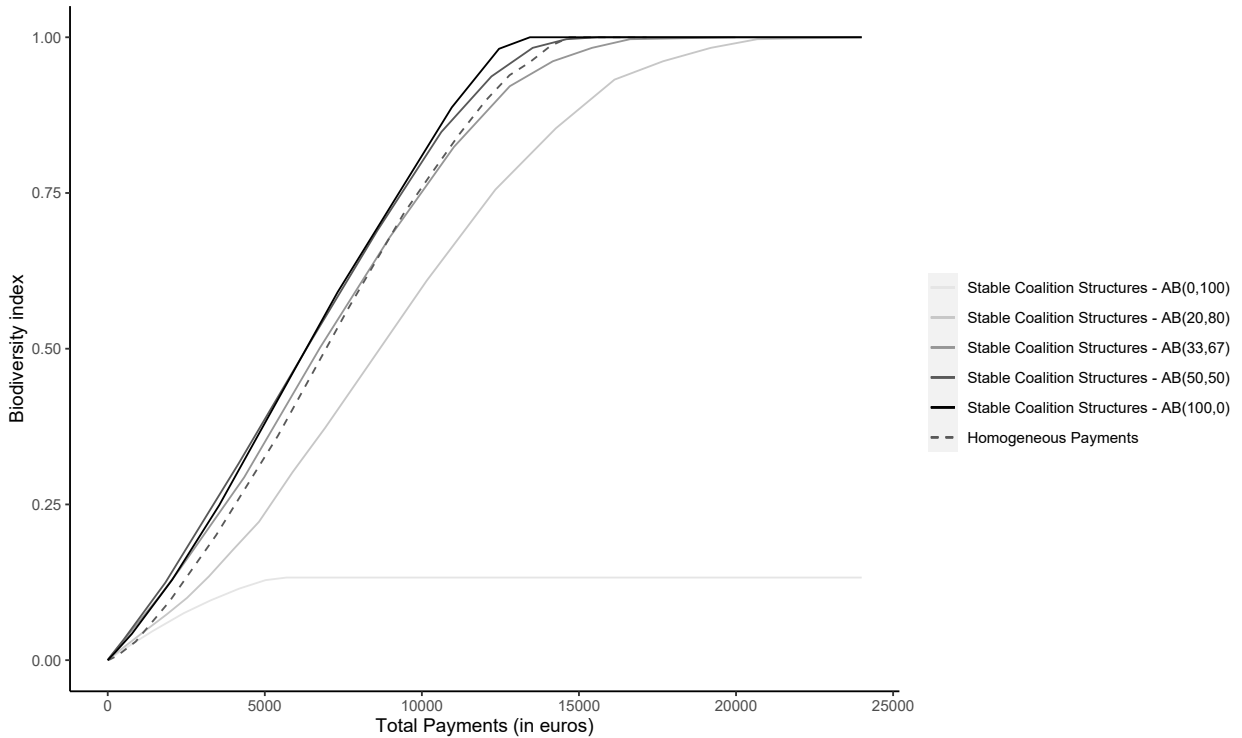


Figure A16: Cost-effectiveness of alternative AB schemes within stable coalition structures with lower spatial autocorrelation of opportunity costs (Moran’s index equal to 0.4 instead of 0.8).

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP 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 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 (with a Moran’s index of 0.4).

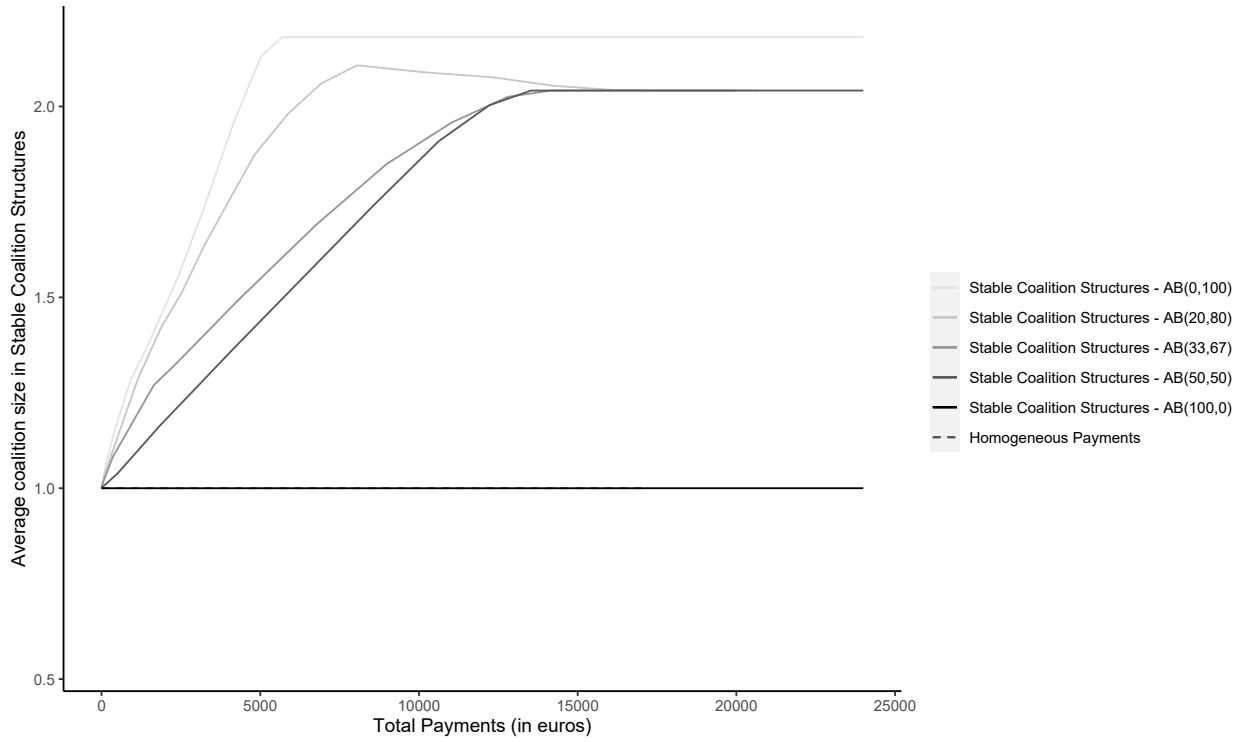


Figure A17: Average coalition size within the stable coalition structures responding to alternative AB schemes with lower spatial autocorrelation of opportunity costs (Moran's index equal to 0.4 instead of 0.8).

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 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 (with Moran's index equal to 0.4). Hidden by the  $AB(100, 0)$  curve, HPs lead to one-landowner coalitions by definition.

## A14 Sensitivity: complementary homogeneous payments

Figures A18 and A19 respectively show changes in biodiversity and cooperation levels as a function of total payments when complementing the two types of bonus with an HP of €20/ha (instead of  $p = 0$  in our preferred analyses). The results remain close to those in the main text (Figures 2 and 3 in the main text). Cost-effectiveness of ABs compared to HPs slightly increases for all AB schemes, suggesting some complementarity between the two policies (as already documented by the literature; see, e.g., Bareille et al., 2023). The ranking of the AB schemes is only slightly affected by the addition of the HPs, scheme  $AB(100,0)$  becoming more cost-effective than  $AB(50,50)$  when the budgets exceed €5,000 (instead of €5,500 in our preferred analyses). Figure A19 shows that the extent of cooperation is also largely unaffected by the addition of the HPs.

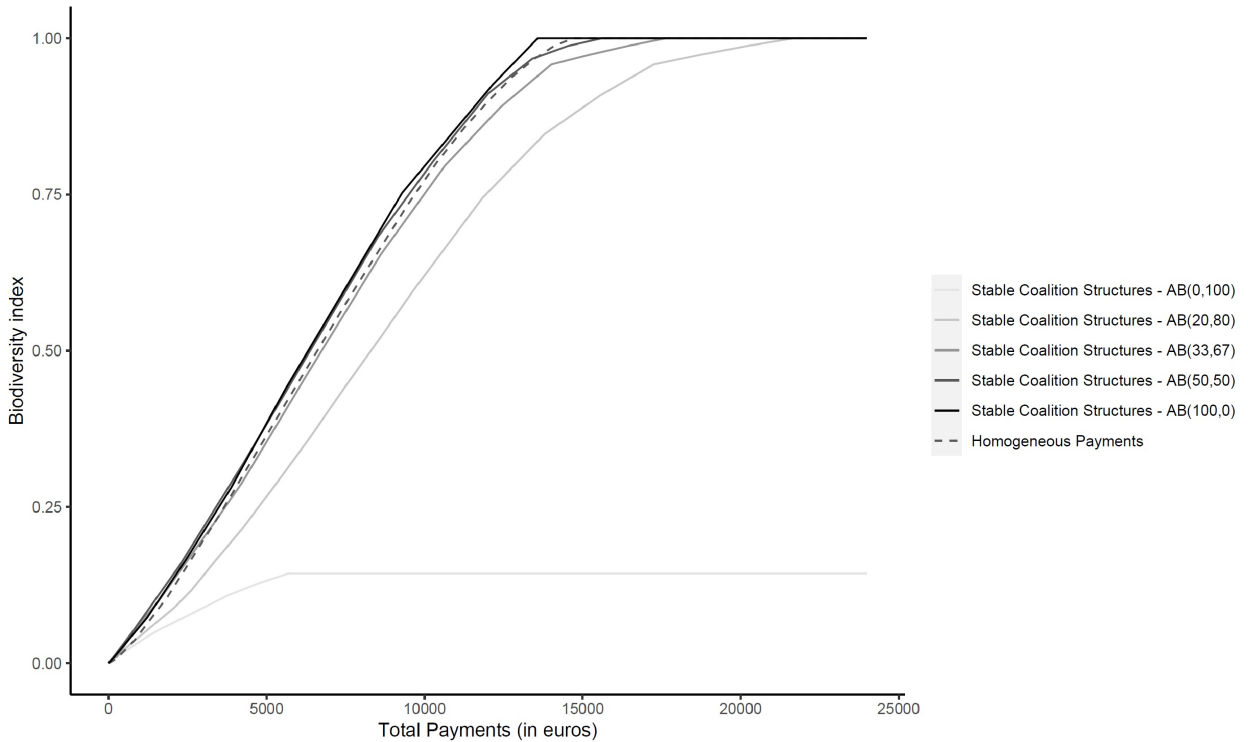


Figure A18: Cost-effectiveness of alternative AB schemes within stable coalition structures with coupled HPs ( $p = €20/\text{plot}$  instead of  $€0/\text{plot}$ ).

NOTE. The figure shows the normalized biodiversity level as a function of total payments for HP 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 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  $p = 20$ ,  $D = 2$  and  $C = 0.5$ . The outcomes are computed as averages covering all the stable coalition structures of the 50 simulated landscapes (with a Moran's index of 0.8).

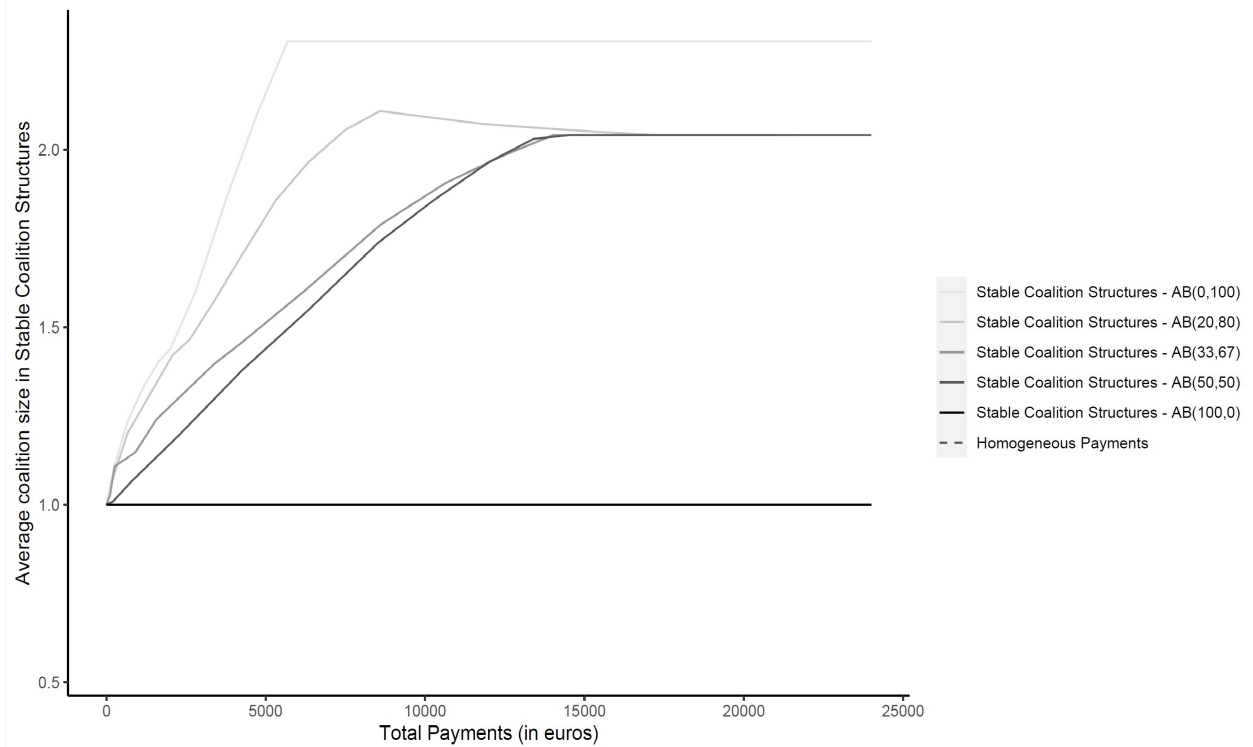


Figure A19: Average coalition size within the stable coalition structures responding to an alternative AB scheme with coupled HPs ( $p = \text{€}20/\text{plot}$  instead of  $\text{€}0/\text{plot}$ ).

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 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 (with Moran's index equal to 0.8). Hidden by the  $AB(100, 0)$  curve, HPs lead to one-landowner coalitions by definition.