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A spatial model for biodiversity offsetting

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ABSTRACT

In recent years, biodiversity offsetting has been adopted as a conservation strategy in many different countries. Biodiversity offsets are mechanisms used to compensate for ecological impacts resulting from development projects, especially those on non-built land uses. They usually rely on an equivalence principle based on achieving strict equality between the area that is developed and that which is offset. This approach still remains very controversial.

This article explores an alternative offset design method, where we look at biodiversity from a functional perspective and conceive public policies that aim to conserve biodiversity by maintaining important structural features of the landscape, not limited to the proportion occupied by each land-use. We develop a spatially explicit land use change model to implement our geometric-based compensation method and we define three different versions of the public compensation policy. We apply the model to real case studies in two French municipalities and we compare the cost and feasibility of compensation under the different public policies. We find that offsetting is easier and cheaper when public policies aim to conserve no more than the targeted semi-natural land area, but this approach has major ecological limits. When considering more complex geometric properties of the landscape (and therefore higher ecological expectations), compensation becomes, on average, more difficult and more expensive. Our work shows how new approaches to ecological compensation could be defined and how models could help select the best options in the field.

1. Introduction

To mitigate the ecological crisis, one public policy strategy consists of requiring ecological compensation when implementing development projects (Weissgerbera et al., 2019). This kind of policy has been applied in different countries such as the USA (McKenney and Kiesecker, 2010), Germany (Rundcrantz and Skärbäck, 2013) and France (Quetier et al., 2013; Wende et al., 2018). This principle is affirmed in most of the European Union's environmental legislation. In France, the mitigation hierarchy was incorporated into environmental law in 1976 but the offsets policy was strengthened only forty years later, with law n°2016-1087 of 8 August 2016. In France, this public policy is built on three successive steps (also called mitigation hierarchy) (Levrel et al., 2018; Bigard et al., 2020): first, project managers must avoid ecological impacts as far as possible, second they must reduce residual impacts, third the remaining residual impacts must be compensated for. The compensation relies on an equivalence principle (Quétier et al., 2012): the loss of biodiversity in one place has to be compensated for in a different place. The overall aim of this three-step procedure is to achieve *No Net Loss (NNL) of biodiversity* (Weissgerbera et al., 2019).

However, the efficiency of biodiversity offsetting (also called ecological compensation) remains controversial. The first limit of this method is the difficulty of unambiguously quantifying biodiversity (Moreno-Mateos et al., 2015; Marshall et al., 2020; Grimm, 2021), since the choice of metrics is critical in determining the success of offsetting but evaluating biodiversity is not easy and many different indicators could be used (Zu Ermgassen et al., 2019; Simpson et al., 2022; Marshall et al., 2021). Indeed biodiversity is a complex concept involving dynamics and spatial patterns (Moilanena and Kotiahoc, 2018) as well as different levels of characterisation (gene, species, population, ecosystem ...). In such a context, evaluating biodiversity loss becomes a difficult process. The second limit relates to endemic or emblematic ecosystems or species which might be difficult to compensate for (Jones and Bull, 2020). The third limit concerns the time horizon of the compensation: while it has been shown that urban development has long-term effects and delayed consequences, the impact of restoration usually only has a mid- or even short-term perspective (Weissgerbera et al., 2019). Finally, if the loss of biodiversity is too great, the No Net Loss objective might be unrealistic, making ecological offsetting inappropriate (Bezombes et al., 2019; Weissgerbera et al., 2019). Other

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Table 1
Land uses in our model.

Land use identifier in our model	CESBIO classes	Property
LU_1 — broad-leaved woodland	broad-leaved woodland (31)	Biodiversity habitat
LU_2 — coniferous woodland	coniferous woodland and moorland (36)	Biodiversity habitat
LU_3 — grasslands	grasslands (211) and lawns (34)	Biodiversity habitat
LU_4 — orchards	orchards (221) and vineyards (222)	Food producer
LU_5 — seasonal crops	summer crops (11) and winter crops (12)	Food producer
LU_6 — urban	continuous and discontinuous urban areas; industrial and commercial land (43); roads (44)	Cannot be converted to any other land use

criticisms relate to the practical conditions under which offsetting is implemented. Indeed there is a lack of control protocols covering the efficiency of compensation measures (Calvet et al., 2015; Quetier et al., 2013; Bezombes et al., 2019; Theis et al., 2019). In this context, the design of offsetting measures remains a sensitive issue in public policy debate.

Current offsetting strategies are often based on restricted targets (one species or habitat area…) and a common measure of offsetting benefits is simply the ratio between the damaged and compensatory areas, which is based on an equivalence principle of extremely limited ecological value (Quétier et al., 2012; Ban et al., 2022). In this article, we investigate an alternative method for defining equivalence based on a more functional approach. The objective is to maintain overall ecosystem function rather than similar land use composition. It is now well known that landscape structure plays a major role in ecosystem functioning (R.K. and Moore, 2004; Grafius et al., 2018; Gustafson, 2019) and landscape properties appear as a sound, although insufficiently-studied, alternative to land use proportions in ecological compensation processes. In this article, we therefore explore offsetting design through the maintenance of landscape structure, providing a simple but very adaptable tool for researchers and landscape managers.

Technically, this structure can be assessed using geometric properties and indicators. These indicators can be related to different biodiversity features, such as species diversity (Largest Patch Index, Patch Density, …) (Bailey et al., 2007; Tasser et al., 2008) or landscape fragmentation (Mesh Size, Division index…) (Jaeger, 2000). Landscape metrics regarding fragmentation or connectivity have been widely used to analyse ecosystem services (Walz, 2011; Frank et al., 2012). The interest of these geometric properties is to capture some of the structural characteristics of the landscape that might guarantee sustainable, long-term biodiversity dynamics.

The objective of the paper is methodological. We develop a spatially explicit land use change model to implement our geometric-based offsetting method in response to development. We use a genetic algorithm (Hamblin, 2013; Witing et al., 2022; Ban et al., 2022) to look for compensation landscapes that maintain the chosen geometric properties by shifting the land uses of some of the parcels. Based on this model, we explore different public policies regulating ecological compensation following the NNL objective built on different geometric properties of the landscape to be maintained (or improved). The model is applied to real case studies with six land uses corresponding to urban areas, different cropping areas and different woodland and grassland areas. We explore the maps of two French municipalities displaying different geometric architecture in order to illustrate the type of results generated by the model.

One of the main advantages of our modelling framework is its relative simplicity which, as a consequence, offers strong potential for generalisation. From this viewpoint, our modelling framework can be applied in different contexts, including different geographical areas and land use change issues.

2. The landscapes studied

2.1. Municipalities

We choose to work at the scale of the municipality, the smallest French administrative division making public decisions that is still meaningful for landscape development plans and is also consistent with the organisational level of the ecosystem. This scale is still large enough to observe the effects of the development-compensation process but still computationally tractable at this early development stage of our modelling framework. In fact, when the geographical area to be analysed is increased, the computing time required by the genetic algorithm to look for compensation increases exponentially. Note, however, that changing the scale of the study does not imply any methodological difficulty.

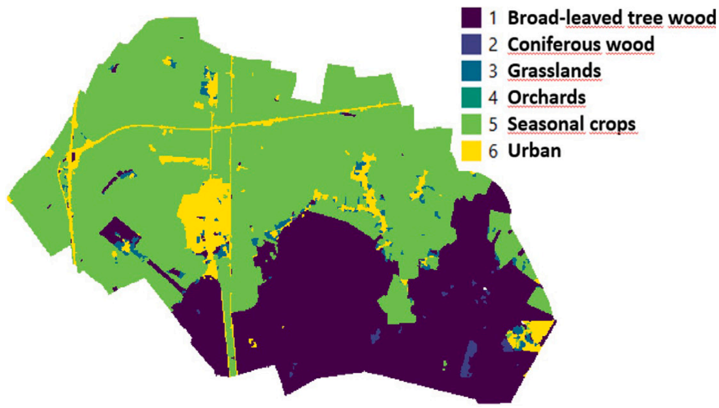
We studied two French municipalities in the Loiret department (in the Centre-Val de Loire region). We selected these two municipalities due to their different sizes and very different landscape configurations, as detailed in the next Section. The first, Chevilly (45093), covers 41.76 km^2 with balanced proportions of cropland and woodland; the second, Ligny-le-Ribault (45182), covers 59.21 km^2 mainly occupied by broad-leaved woodland. Henceforth we refer to them respectively as M_1 (Chevilly) and M_2 (Ligny-le-Ribault).

2.2. Land uses

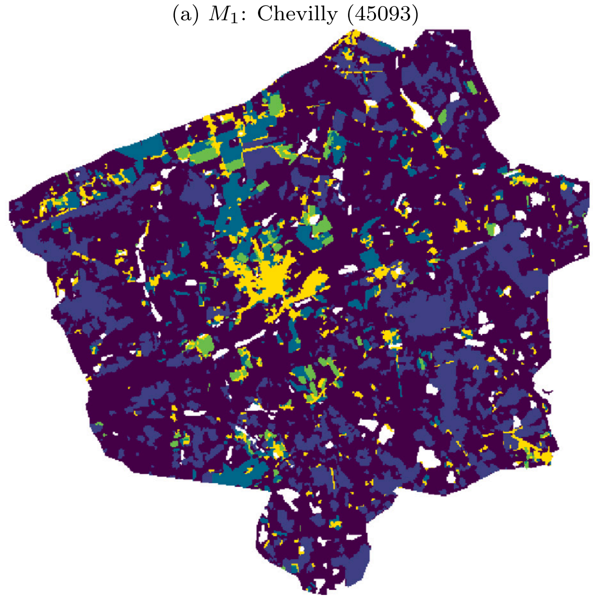
We obtained land use maps of these two municipalities to serve as the basis of our model. We defined a small number of general land uses which are considered as proxies for habitats and thus as indicators of the biodiversity level. We used the land cover data provided by the CESBIO (Center for the Study of the Biosphere from Space); we worked with the 2017 map of France in raster layer format, with a spatial resolution of 20 metres and 17 classes (or land uses). Data are available in shape file format in open source at government cadastral website. We merged the 17 classes of the CESBIO database into six land uses (Table 1).

The remaining CESBIO classes (natural mineral surfaces, beaches, water and glaciers) were not considered, since they are minor land uses in the landscapes involved and they are little impacted by either development or the compensation process. The two municipalities we studied have different land use compositions (Table 2). In M_1 (Fig. 1(a)) the main land use is seasonal crops (LU_5), representing 57% of the total area, followed by broad-leaved woodland (LU_1), 35% of the total area. M_2 (Fig. 1(b)) is mainly covered in broad-leaved woodland (LU_1), 68% of the total area, followed by coniferous woodland (LU_2), 18% of the total area, and a very small area (1.5%) of seasonal crops (LU_5).

We also observe that the two municipalities have different spatial distribution of their land uses (Fig. 1): in M_1, the two main land uses are organised into two distinct zones, while in M_2, LU_5 areas are very small and scattered among LU_1 areas. The units to be developed and



(a) M_1: Chevilly (45093)



(b) M_2: Ligny-le-Ribault (45182)

Fig. 1. The land cover maps of the two municipalities studied.

Table 2
We compare here the land use composition of the two studied municipalities.

Land use	PLAND M_1	PLAND M_2	LPI M_1	LPI M_2
LU_1	35%	68%	30.84%	63.28%
LU_2	0.005%	18%	0.22%	1.66%
LU_3	0.95%	6%	0.12%	0.78%
LU_4	0%	0%	0%	0%
LU_5	57%	1.5%	37%	0.17%
LU_6	7%	6%	2.48%	1.41%

PLAND is the percentage of the total area occupied by a class; and **LPI** is the percentage of land occupied by the largest patch of a given class. See Section 3.2 for more details.

compensated for are parcels. M_1 contains a total of 3024 parcels, while M_2 contains 4040. By choosing these two different municipalities (M_1 and M_2), we want to evaluate the impact of the original landscape's geometric properties on the performance in terms of compensation.

3. Public policies and landscape metrics

3.1. General purpose of public policies

When a parcel of land in a landscape is developed, the proportion of land uses and other landscape structure properties are modified. Public policy should regulate ecological compensation in order to recreate a new landscape achieving the NNL objective. In our model this corresponds to the maintenance of certain specific landscape properties, which we quantify through a number of meaningful landscape metrics.

3.2. Landscape metrics

Landscape metrics are an important tool in quantifying those elements of a landscape's spatial structure that have an impact on the ecological processes operating within it (Haines-Young and Chopping, 1996). Many different numerical indices have been defined with this scope, ranging from area to diversity metrics, which allow the monitoring of different aspects of biodiversity. Since we are adopting an ecosystem approach, rather than focusing on particular species, we consider here three general, simple, intuitive metrics. These can be easily measured using the FRAGSTATS program and interpreted in relation to landscape properties (Walz, 2011). By capturing these structural and functional properties of the landscape we can evaluate and compare the compensation options.

By considering landscape metrics as indicators of biodiversity, our goal is not to unambiguously quantify biodiversity and address emblematic species and ecosystem problems, but to capture some properties of the landscape that can be important in the maintenance of biodiversity. We choose a few intuitive metrics to test our model, but in our method the landscape metrics under consideration can very easily be changed in order to address specific issues. This is important when designing biodiversity offset programs (Gelcich et al., 2017).

- Percentage of Landscape ($PLAND$): the percentage of the total area occupied by a class; for a given $LU = i$ it is defined as:

$$PLAND^i = \frac{\sum_{j=1}^{n} a_{ij}}{A} 100,$$

where a_{ij} is the area (in m^2) of patch j in class i and A is the total area (in m^2) of the landscape.

- Largest Patch Index (LPI): the percentage of land occupied by the largest patch of a given class. It is often considered as a predictor of species diversity (Walz, 2011). For $LU = i$, it is defined as:

$$LPI^i = \frac{\max_{j=1}^{n}(a_{ij})}{A} 100,$$

where a_{ij} is the area of patch j of $LU = i$ and A is the total area of the landscape.

- Division Index (DIV): an indicator of landscape fragmentation (Walz, 2011). It is defined as the probability that two randomly chosen places in the landscape are not situated in the same undivided patch. For $LU = i$, it is defined as:

$$DIV^i = 1 - \sum_{j=1}^{n} \left(\frac{a_{ij}}{A}\right)^2,$$

Given that $0 < DIV < 1$, DIV equals zero if the entire landscape consists of one single patch and it increases the more the landscape is broken into separate patches.

Notice that although this article focuses on a few specific metrics, a strong point of our approach is that it remains robust to a change of metrics in the case where one metric or another would be more appropriate to a given case.

3.3. Public policy objectives

We specify a public policy's objective by a set of constraints of these landscape metrics, measured in the original landscape and in the compensated one. Let x^i be a landscape metric index measured for land use i and let $x^i(C)$ and $x^i(O)$ be respectively the index value measured in the Compensated landscape and in the Original one. We first define:

$$\Delta_x^i := x(C)^i - x(O)^i \tag{1}$$

where Δ_x^i measures the variation of the landscape metric index from the original landscape to the compensated one. Public policy objectives then consist of a set of constraints in the form $\pm\Delta_x^i \geq 0$, where the sign depends on the ecological quality behaviour with respect to the targeted index. If the ecological value of the measured property is increasing with respect to index x, then Δ_x is considered, otherwise, if the ecological quality decreases with the index, then in the policy objectives explained below we consider $-\Delta_x$. We define three different public policy objectives, two of which correspond to maintaining only biodiversity and the third to maintaining both biodiversity and agricultural production. Notice that it is impossible to maintain the area of each type of land, since we assume that developed parcels cannot be changed back into undeveloped ones. This trivial result illustrates a major structural failure in the classical area-equivalence compensation policies since it is not possible to strictly maintain the area of all habitats once development occurs.

Biodiversity objective — BO

The objective of these two policies is to maintain (or to increase) biodiversity alone, by conserving (or improving) certain geometric properties of selected land uses hosting biodiversity (**BO**). In the first case ($\mathbf{BO_A}$) the geometric property of the selected land uses to be conserved is the area; the aim of the public policy is translated in terms of constraints on the landscape metrics as follows:

$$\mathbf{BO_A}: \quad \Delta_{PLAND}^i \geq 0 \qquad i = 1,2,3 \tag{2}$$

In the second scenario ($\mathbf{BO_G}$) the objective consists of preserving more complex geometric properties of the same land uses, namely Largest Patch Index (LPI) and Division Index (DIV). It is defined as follows:

$$\mathbf{BO_G}: \quad \begin{cases} \Delta_{LPI}^i \geq 0 & i = 1,2,3 \\ -\Delta_{DIV}^i \geq 0 \Leftrightarrow \Delta_{DIV}^i \leq 0 & i = 1,2,3 \end{cases} \tag{3}$$

Biodiversity and agricultural production objective — BAO

We define one more policy whose objective is to maintain, in addition to biodiversity conservation, agricultural food production, achieved by conserving agricultural land area. In this case, thus, **BAO** targets the area ($PLAND$) of agricultural land uses and other geometric properties of woodlands and grasslands, namely LPI and DIV. This corresponds to the following set of constraints:

$$\mathbf{BAO}: \quad \begin{cases} \Delta_{LPI}^i \geq 0 & i = 1,2,3 \\ -\Delta_{DIV}^i \geq 0 \Leftrightarrow \Delta_{DIV}^i \leq 0 & i = 1,2,3 \\ \Delta_{PLAND}^i \geq 0 & i = 4,5 \end{cases} \tag{4}$$

4. Simulation plan

4.1. Introduction to the model

In Fig. 2 we show the conceptual scheme of our compensation process: for a given development of a parcel of land in one of the two municipalities, we use a genetic algorithm (Hamblin, 2013; Witing et al., 2022; Ban et al., 2022) to look for compensation landscapes that maintain the chosen geometric properties, by shifting the land-uses of some of the other parcels. The set of properties to be maintained is defined by the public policy applied. We then evaluate the cost and feasibility of successful compensation measures, in order to compare the effects of the different public policies as well as the impact of the landscape's original structure and the given development.

4.2. Developments

In each municipality, we studied three urban developments, where a parcel of land occupied by broad-leaved woodland is built upon. Development corresponds to a shift of land use, from LU_1 to LU_6. The three development cases studied differ in size and in their position with respect to the largest patch:

- U_1: Urban development of a parcel respectively of 122 pixels[1] in M_1 and 74 in M_2 that is not in the largest patch;
- U_2: Urban development of a parcel of 56 pixels in both municipalities in the largest patch. With $U2$ we wanted to test the behaviour of compensation in the case of a development that affects the largest patch. We expect it to have an impact under BO_G and under BAO;
- U_3: Urban development of a very large parcel, respectively of 511 pixels and 492 pixels, in the largest patch. With U_3 we wanted to test the behaviour of compensation in the case of a very large development, especially as far as feasibility is concerned.

4.3. Tested scenarios

In Table 3, we summarise all the tested scenarios: in each of the two municipalities (M_1 and M_2), we simulate three different developments (U_1, U_2, U_3) and each of these developments is compensated under three different policy objectives (BO_A, BO_G, BAO). We thus test a total of 18 different compensation scenarios, named by concatenating the acronyms of the public policy, the development and the municipality.

[1] 1 pixel $= 2.64 \times 10^{-4}$ m

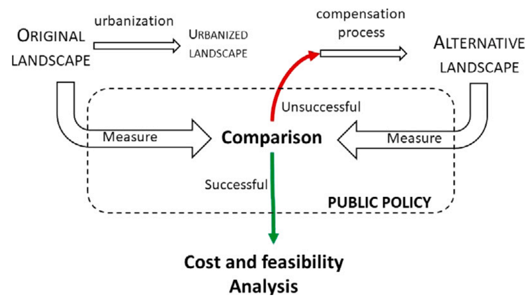


Fig. 2. Conceptual diagram of our model.

Table 3
Summary: the 18 scenarios tested, with three developments and three policy objectives in each of the two municipalities.

Policy objective	municipality M_1		
Biodiversity — Area	$BO_AU_1M_1$	$BO_AU_2M_1$	$BO_AU_3M_1$
Biodiversity — Geometric Properties	$BO_GU_1M_1$	$BO_GU_2M_1$	$BO_GU_3M_1$
Biodiversity and Agricultural Production	$BAOU_1M_1$	$BAOU_2M_1$	$BAOU_3M_1$
Policy objective	municipality M_2		
Biodiversity — Area	$BO_AU_1M_2$	$BO_AU_2M_2$	$BO_AU_3M_2$
Biodiversity — Geometric Properties	$BO_GU_1M_2$	$BO_GU_2M_2$	$BO_GU_3M_2$
Biodiversity and Agricultural Production	$BAOU_1M_2$	$BAOU_2M_2$	$BAOU_3M_2$

4.4. The compensation process

Once the given parcel is developed, we simulate the compensation process by using a genetic algorithm, a search and optimisation technique based on natural selection, largely used in ecology (Hamblin, 2013; Ban et al., 2022; Witing et al., 2022), as well as in a variety of other fields. The genetic algorithm we have defined is such that one parcel of land (bigger than 3 pixels) in the same municipality is randomly selected and every land use (except urban) is tested and evaluated. The fitness function is defined accordingly to the policy's objective and it depends on the deltas of the landscape metric indexes measured for the different land uses involved. It is linearly increasing in the ecological value of the compensated landscape. Full details on the genetic algorithm and the associated fitness function can be found in the Python source code, available on GitHub.[2]

If the fitness function improves but is not optimal, the compensation continues with a second parcel and so on, until the compensation is successful, i.e. all the constraints are satisfied. The compensation fails if, after 400 attempts (i.e. internal loops), the fitness function does not improve and thus no compensation is found. The number of internal loops has been chosen in order to have both a good rate of success and a good computable tractability. We define a binary variable $succes/failure$ to keep track of the internal cycle performance. When the compensation is successful, we also keep track of the total number of compensated pixels, which is considered as an estimation of the compensation cost.

4.5. Meta-simulation

For each of the 18 scenarios defined, we simulated 2000 compensation processes. To evaluate the economic impact of public ecological compensation, we assess the scenarios described above using a set of three indicators, two related to the cost of compensation and one to its feasibility. For each scenario, we consider the **median compensation cost** ($medC$) and the **minimum compensation cost** ($minC$) among the 2000 simulated compensation processes. The former provides information about the average cost in the case of a "blind" landscape manager, the latter provides information about the cost when the landscape manager is willing/able to minimise it. Note that we consider the median in order to eliminate outlier effects observed for the average. We then complete this cost information by an assessment of the feasibility of the compensation process. This feasibility is defined by the percentage of successful compensation trials among the 2000 that were simulated.

[2] https://github.com/IlariaBrun/SpatialModelForBiodiversityOffsetting

5. Results

5.1. Median cost

In this section, we analyse the behaviour of the median cost ($medC$) of compensation under the different tested scenarios, where $medC$ is the median of the costs of all successful simulated compensation processes and the cost is defined as the normalised number of compensated pixels (normalised for the size of the development).

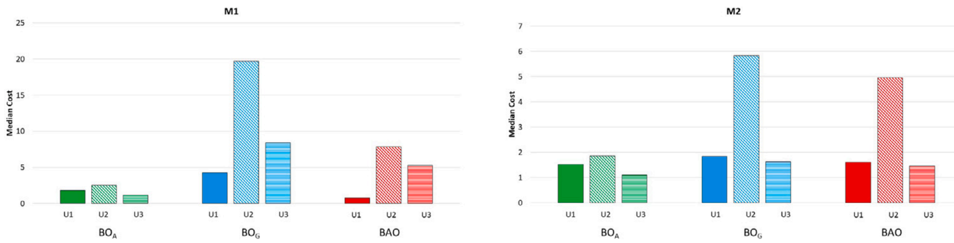
An interesting result obtained for the median cost $medC$, concerns the comparison among different policy objectives, where a hierarchy clearly emerges in both municipalities. We find that:

$$medC(BO_G) > medC(BAO) > medC(BO_A),$$

with only one exception, for development U_1 in municipality M_1, where $medC(BO_G) < medC(BO_A)$ (see Fig. 3). Under BO_G (in blue), $medC$ is always higher in both municipalities, no matter the type of development. In municipality M_1 the gap between the costs for different policy objectives is more obvious.

This quasi-systematic ranking means that policy objective BO_G, which conserves some structural properties (namely LPI and DIV) of land uses LU_1, LU_2 and LU_3 is more costly than BO_A, which conserves only the surface area of these LUs, and this is true for both the municipalities tested and all types of development. Furthermore, under BO_A, the compensated area is never more than twice that which is developed, while to achieve BO_G, the compensated area is always bigger, even reaching 20 times the original area in the case of scenario $BO_AU_2M_1$. It is interesting to note that under BAO where, besides the maintenance of some structural properties of woods and grassland (LU_1, LU_2 and LU_3), a further constraint is added in terms of the surface area of agricultural land-use (LU_4, LU_5), $medC$ is lower than under BO_G. This result can be explained by the fact that the constraint imposed on the maintenance of the agricultural land-uses obliges less "invasive" compensation to be considered, since agricultural land must be conserved.

In our case study, the shape of the municipality does not affect the ranking of compensation scenarios but it still has an impact on the marginal differences. Within municipality M_2, mainly covered by woodland (LU_1), the differences between the costs for BO_A and BAO are smaller than in M_1, where the main land use is seasonal crops (LU_5), concentrated in the northern part of the municipality, followed by woodland (LU_1), concentrated in the south (Fig. 3). Thus, since in M_2 the percentage of agricultural land use is really low (1, 5%, see Table 2) compared to that in M_1 (57%), it is naturally less costly to maintain those areas.



(a) municipality M_1 (b) municipality M_2

Fig. 3. This figure summarises the results of the simulations for the **median cost** $medC$ of ecological compensation under the 18 tested scenarios. The results obtained for policy objective BO_A (conserving the total area of woodland and grassland (LU_1, LU_2, LU_3)) are plotted in green, those for BO_G (conserving other structural indicators for woodland and grassland (LPI and DIV)) are in blue while BAO (conserving the total area of agricultural land ($LU4$, $LU5$) and other structural indicators for woodland and grassland (LU_1, LU_2, LU_3)) are in red. The results for municipality M_1 are on the left and those for M_2 on the right. Finally, different types of development are explored: the left-hand (solid) bars are related to U_1 (development of a parcel outside the largest patch), the central (hatched) bars to U_2 (development within the largest patch), and the right-hand (horizontal line) bars to U_3 (very big development in the largest patch). Note that the cost is normalised per unit area of development.

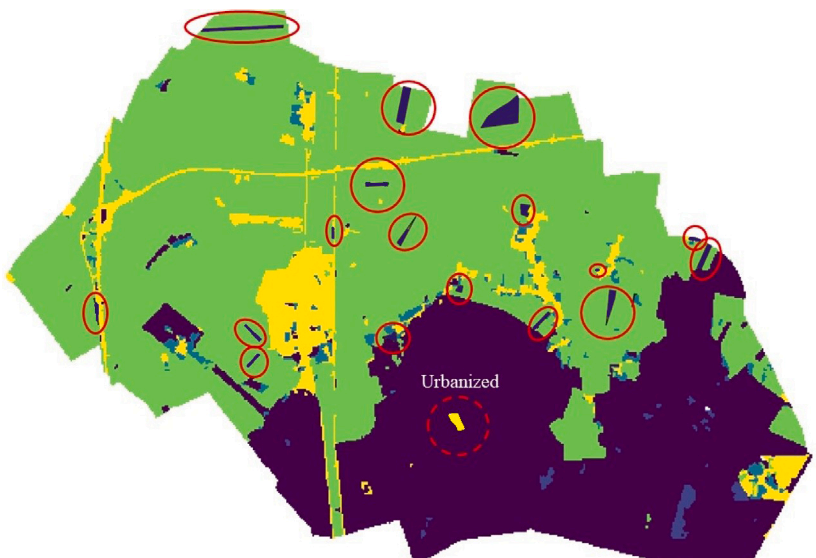


Fig. 4. In this figure we show an example of a successful compensation in municipality $M1$, to compensate the urban development $U2$ (plot on the largest patch), under policy BO_G, which has the highest median cost. In this case, the compensated surface is almost 13 times bigger than the urban development (712 compensated pixels for 56 urbanised ones); in all of the 17 plots of land used for compensation, $LU5$ has been changed into $LU1$.

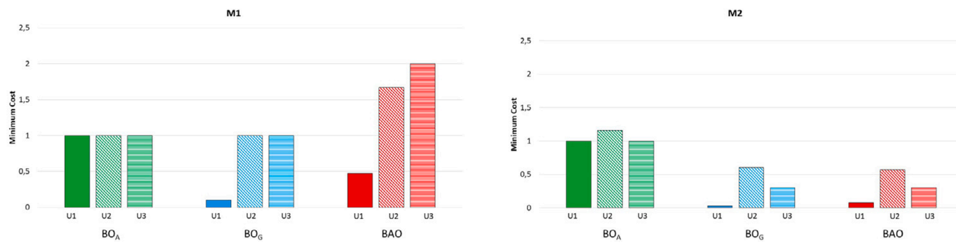
As expected, when the developed parcel is in the largest patch, as for U_2 and U_3, the compensation for BO_G and BAO is more costly than for U_1: this observation can be explained by the fact that both scenarios impose the maintenance of the largest patch area (LPI). As a consequence, an impact of the development in the largest patch calls for a greater number of compensated pixels (see Fig. 4).

5.2. Minimum cost

Although minimal cost is very sensitive to sampling, exploring the minimum cost of compensation under the different tested scenarios still reveals interesting patterns. The minimum cost (minimum of the normalised number of compensated pixels, normalised per unit area of development) is defined as the minima of all the different successful configurations of compensation simulated. The behaviour of the minimum cost is very different to that of the median cost, and no clear hierarchy emerges among the different policy objectives (Fig. 5).

As expected, in both municipalities, the $minC$ under BO_A is 1 for all the 18 scenarios, since the only policy objective is to conserve the area of green landscapes. Under BO_G, the compensated area is always smaller or equal to the developed area. This would mean that by carefully choosing where and how to compensate in order to maintain the targeted structural properties of woods and grasslands (LU_1, LU_2, LU_3), then a much smaller area can be used in compensation.

Furthermore, we see that, unlike the situation for the median cost $medC$, for the three tested developments in both municipalities, under policy objective BO_G (preserving structural properties of green landscapes) the minimum compensation cost $minC$ is lower than (or equal) to that under the other two policy objectives, while $medC$ was the highest in the equivalent case. In general, for $minC$, the differences between the different scenarios is rather small and the hierarchy among the different policy objectives depends on the municipality as well as on the location of the development. In municipality M_2, for all the developments, under policy objective BO_A, the compensation processes have the highest $minC$, while $medC$ is the lowest in these cases, see Fig. 3. This behaviour of $minC$ suggests that by carefully choosing the compensation, one could compensate using smaller areas under BO_G and BAO, that is by targeting more complex structural properties than the area of LU_1, LU_2 and LU_3. We also observe that, in municipality M_2, we find that $minC(BO_G) \sim minC(BAO)$: since the percentage of agricultural land is very low in this municipality, the constraint of maintaining this area (imposed under BAO) has a weak impact on the



(a) municipality M_1 (b) municipality M_2

Fig. 5. This Figure shows the results of the simulations performed for the **Minimum cost** $minC$ of the ecological compensation processes under the 18 tested scenarios. The results obtained for policy objective BO_A (conserving the total area of woodland and grassland) are plotted in green, those for BO_G, (conserving other structural indicators for woodland and grassland (LPI and DIV)) are in blue while those for BAO (conserving the total area of agricultural land and other structural indicators for woodland and grassland) are in red. The results for municipality M_1 are on the left and those for M_2 on the right. Finally, different types of development are explored: the left-hand (solid) bars are related to U_1, the central (hatched) bars to U_2, and the right-hand (horizontal lines) bars to U_3.

cost of compensation. Finally, we observe that in M_2, the minimum costs of compensation under BO_G and BAO are lower than in M_1. This is due to the particular configuration of land uses in M_2, which makes it easier to maintain the habitats' properties.

5.3. Feasibility

This section analyses the feasibility of the compensation processes, which measures the ratio of successful compensation processes to the total number simulated. We study the feasibility under the three policy objectives for the 18 tested scenarios. We observe that under BO_A and BO_G policies, compensation is generally very easy, especially in M_1 (Fig. 6). Compensation proves to be more difficult under BAO (in red, on the right-hand side for each municipality) when the rate of success is lower. This result means that it is generally harder to maintain both the area of agricultural land (LU_4, LU_5) and the targeted structural properties of woodland and grassland (LU_1, LU_2, LU_3) than to just consider either the area (BO_A, in green) or the structural properties of the latter land-uses (BO_G, in blue). The gap is particularly evident in the case of U_3 (very big development in the largest patch) in M_1, where the feasibility of compensation in scenario $BAOU_3M_1$ is around 20%, while it is 100% for the other two policy objectives: as a matter of fact, with such a big development to compensate for, it is very difficult to find a successful compensation under BAO, which requires maintenance of the areas of agricultural parcels and of the more complex structural properties of woodland and grassland. For the same kind of development, the situation changes in municipality M_2, where for the three scenarios, the feasibility is lower. In particular, the lowest feasibility is observed under BO_A (maintenance of the area of woodland and grassland): since this municipality is mainly covered by grassland and woods and the developed area is very big, it is very hard to find agricultural parcels (LU_4, LU_5) for compensation in order to maintain the targeted land-use (LU_1, LU_2, LU_3) composition, given that the existing urban areas cannot be modified. In this case, it is easier to maintain the structural properties of woodland and grassland land-uses, but the additional constraint on maintaining the agricultural area imposed under BAO, further reduces the feasibility of compensation.

5.4. Relationship between cost and feasibility

We analyse the feasibility of the 18 tested scenarios as a linear function of the median cost $medC$, since the behaviour of the latter is more significant than that of $minC$ (Fig. 7). We observe that policy objective BO_A (green dots), i.e. the case whose goal is to conserve woodland and grassland composition, is the cheapest, most feasible and therefore the easiest for a landscape manager to achieve.

As shown in the above sections, alternative policy objectives that aim to achieve better ecological performance by going beyond the simple maintenance of surface area are generally more costly and less feasible than their simpler counterparts. Beyond this general finding, we look here more precisely at the comparison between these two alternative policy objectives. Results show that shifting from policy objective BO_G to policy objective BAO decreases costs (Fig. 3) but it also decreases feasibility (Fig. 6), whatever the municipality and the development considered. We better show this particular behaviour in Fig. 8, where we can see that, in both municipalities, but especially in $M2$, by shifting from BO_G to BAO, $medC$ reduces but the feasibility also becomes lower. This means that adding a constraint involving the maintenance of agricultural habitats requires smaller compensation areas (i.e. lower cost) but makes it harder to find a solution.

6. Discussion

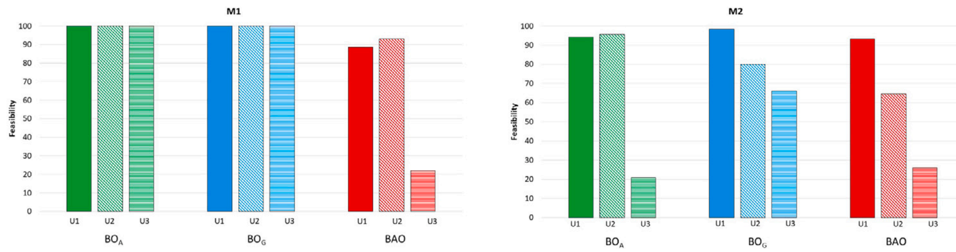
6.1. The weaknesses of the current NNL policy

Although biodiversity offsetting looks appealing in theory, the actual implementation of the law still remains open to interpretation (Weissgerbera et al., 2019; Moreno-Mateos et al., 2015) and achieving NNL in practice raises a variety of problems. Biodiversity is a very complex concept, and the legislation does not specify at which level it should be examined: ordinary or extra-ordinary species, entire populations or functionalities and ecosystem services (Quétier et al., 2012; Bezombes et al., 2019)? Neither does it specify which indicators and metrics should be adopted to correctly assess biodiversity and its loss (Marshall et al., 2020) although the answer to none of these questions is obvious.

Our results show that it is impossible to simply maintain the area of all the habitats: despite its apparent triviality, this result is crucial to proving the weakness of a strict vision of the NNL policy when biodiversity is approximated for by habitat areas. As a consequence, compensation generally only focuses on some habitats or features to be protected and/or restored but even then it is still very difficult to maintain the ecological equivalence (Polasky et al., 2020). Beside this structural impossibility, only focusing on area-based compensation misses the impacts that development has on habitat configuration. Modifications to landscape structure are however known to have a major impact on biodiversity (R.K. and Moore, 2004). Although rarely considered as an option, enhancing the landscape context may be as important as maintaining land-use proportions in restoration projects (De Souza Leite et al., 2013).

6.2. Geometric based NNL principle: an operational solution?

In order to overcome these problems, this study explores different operational interpretations of the NNL principle, based on certain landscape geometric properties. Since the relationship between ecological function and landscape structure is nowadays well known (Gustafson, 2019; R.K. and Moore, 2004), this article tests compensation policies



(a) municipality M_1 (b) municipality M_2

Fig. 6. Feasibility of compensation under the three policy objectives: BO_A in green, on the left; BO_G in blue, in the centre and BAO in red, on the right. In 6(a) the results for municipality M_1, in 6(b) M_2; each bar represents a different development, from left to right U_1 (solid bar), U_2 (hatched bar), U_3 (bar with horizontal lines).

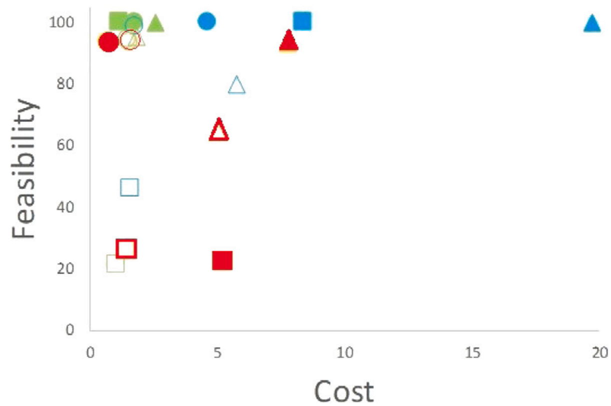


Fig. 7. The simple correlation of median cost $medC$ and feasibility of compensation processes under the three different policy objectives. Colours correspond to the different public policy objectives (BO_A in green, BO_G in blue, BAO in red), symbols correspond to the different development options (U_1 = circle, $U2$ = triangle, U_3 = square) the two municipalities (M_1 = solid symbols, M_2 = empty symbols).

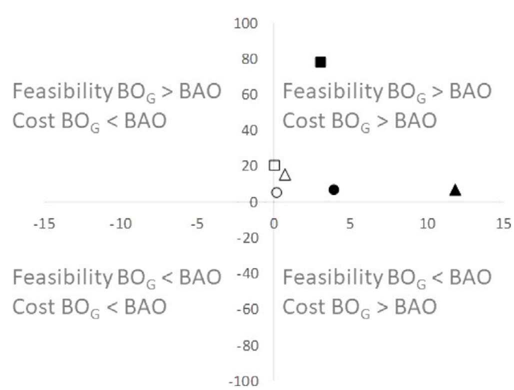


Fig. 8. Additional costs (on the horizontal axis) and feasibility gains (on the vertical axis) linked to a shift from public policy option BO_G to BAO for the different municipalities (M_1 = solid symbols, M_2 = empty symbols) and developments (shapes).

based on the relationship between biodiversity and landscape geometric properties. Landscape properties are quantified through a number of landscape metrics which have been chosen for their ability to capture important habitat features and for their ease of computation.

Our study shows that a specification of the NNL principle based on geometric properties is able to meet compensation objectives. To further examine the NNL specification, we challenged these new operational interpretations of the NNL principle with different public policy objectives (involving both biodiversity alone and coupled biodiversity–agricultural objectives) in order to assess their robustness. More precisely, we defined and compared three alternative policy objectives based on these metrics: first, a policy objective that consists of simply maintaining the area of semi-natural habitats, second, one that aims to maintain other geometric properties of these habitats instead of area, third, one which adds to the second policy objective a further constraint on maintaining agricultural area in order to guarantee food production. Our results show that all three policy objectives make it possible to find compensation solutions.

The comparison of these three different public policy objectives highlights how they differ regarding both feasibility and compensation cost. The policy based on the area of semi-natural habitats only is the easiest and the least expensive in terms of median cost even though biodiversity outputs are expected to be limited. Indeed, this policy only considers biodiversity as an area to be maintained and neglects many properties such as landscape fragmentation, whose avoidance is essential for ecosystem conservation (Gustafson, 2019; Walz, 2011; Polasky et al., 2020). Furthermore, compensation under such a policy implies the destruction of agricultural area, which is then used for compensation, and this has important negative consequences on food production in a context where the acquisition of agricultural land is becoming increasingly difficult (Le Coent and Calvet, 2015). Neglecting agricultural habitat in the compensation process moreover means failing to take into account a wide range of biodiversity, already particularly threatened by global changes (Sánchez-Bayo and Wyckhuys, 2019).

The other two policies, which target better effects on biodiversity, are both more costly and less feasible and differ in their positions in the trade-off between feasibility and compensation costs. More precisely, with the public policy only preserving geometric properties of the landscape (in our case, the area of the largest patch and the division index, a measure of fragmentation) instead of the area of semi-natural habitats, compensation generally becomes more difficult and more expensive. By adding a further constraint to the policy objective by insisting on the maintenance of the agricultural land area, compensation becomes even more difficult (lower feasibility). The median cost associated with this compensation policy however decreases, reflecting the fact that the set of possible solutions is reduced in a non-uniform manner. A likely explanation is that the additional constraints on agricultural areas reduces the set of possible solutions, but tends towards the less costly ones. In other words, the costly compensation options involving inefficient shifts of land-use in many agricultural parcels are no longer possible but the less costly options, efficient in terms of land utilisation, are still feasible. This counter-intuitive result is worthy of note since in such a complex decision-making process involving non-deterministic systems like ecosystems, stakeholders are likely to choose sub-optimal solutions (Kahneman and Tversky, 1979). Therefore, reducing the set of possible options towards those that are less costly is likely to have positive effects in such a context where stakeholders do not fully optimise their decisions.

The minimum cost metric is very sensitive to sampling and therefore our results analysis does not greatly emphasise it. However, it is interesting to note that the minimum cost of compensation when preserving other geometric properties is always lower or equal to that of maintaining the area, which means that a landscape manager who carefully chooses where and how to compensate could achieve their objective using smaller areas when conserving certain targeted structural properties rather than focusing on surface area.

6.3. Limits and perspectives

In this modelling framework, we advocate a landscape perspective to capture functional dimensions of ecosystems at the landscape scale. This choice presents the advantage of avoiding specific quantification of biodiversity which is always extremely ambiguous. Our model therefore captures overall ecosystem function rather than a specific component of biodiversity. However, it would be possible to include, in addition to these landscape-based proxies for the overall ecosystem, indicators related to specific emblematic or endemic species if this proved to be relevant to another case study.

Our model is a simple tool to study a possible alternative to ecological compensation, and it can be very easily adapted to a variety of different scenarios, according to the objective of the study and the situation considered. A key metric, central to landscape ecology, that would be worth focusing on would be landscape heterogeneity. However, since definition of heterogeneity should be based on a functional categorisation of land-uses that depends on the species considered (Fahrig et al., 2011). The same issue applies to other metrics and the choice of the ecological equivalence criterion should therefore be carefully tuned to the ecosystem considered.

Our modelling framework allows such a tuning of the ecological parameters considered, which makes it applicable to different contexts. Not only can the scale of the landscape be modified and the land uses merged differently, but also all the other parameters we defined can easily be modified to study a particular issue. The choice of landscape metrics to be considered in the definition of public policies can be adapted according to conservation goals and can be easily implemented in our model. In the same way, other policy objectives can be defined, with different constraints regulating biodiversity offsetting.

A more systematic analysis of the patterns found in the properties of the compensation patches would be a central perspective of this work. It would therefore require extensive simulations and further methodological developments. More complex performance indicators can also be defined to better evaluate the cost and feasibility of compensation processes. The cost considered here depends on the compensated areas alone, which is a significant simplification. By defining more complex cost functions, considering the kind of land-uses changes, the price of land or the externalities due to land use changes, we could obtain a more precise picture of compensation costs.

The focus of this study is on the spatial dimension of the problem and in its current version, our model is static. Adding a temporal dimension would be an interesting yet challenging perspective for future development. But that is a strength of such an approach: it is flexible and relatively easy to adapt to new questions. In this article we have proposed an alternative to methods used to determine ecological compensation in practice. Beside all the benefits that our approach may bring to ecological compensation we still believe that such compensation raises many difficulties in practice, being hard to both interpret and implement and having uncertain effects (Weissgerbera et al., 2019). We therefore insist on the fact that, wherever possible, the first two steps of the mitigation hierarchy should always be preferred to compensation. More effort should be made to avoid, rather than compensate for, damage to biodiversity while current legislation should be made clearer and controls strengthened on the basis of better knowledge of the consequences of development and restoration. In this context, more models should be developed to help decision-makers applying public policies to anticipate the effects of development and how it can be compensated for.

CRediT authorship contribution statement

Ilaria Brunetti: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Rodolphe Sabatier:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Lauriane Mouysset:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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