Spatial differentiation of compensation payments for biodiversity-enhancing land-use measures[1]

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Abstract

Compensation payments for biodiversity-enhancing land-use measures have gained increasing importance over the last decade, particularly in the context of agri-environmental policy. Given that both the costs and the benefits of biodiversity-enhancing land-use measures are subject to spatial variation, considerations of allocational efficiency call for spatially differentiated compensation payments for such measures. However, when deciding whether to implement uniform or spatially differentiated compensation payments, the regulator has to balance the allocational efficiency losses of uniform payments with the disadvantages of spatially differentiated payments. To help resolve this issue, this paper provides a conceptual framework that allows the extent of allocational efficiency losses associated with uniform payments for biodiversity-enhancing land-use measures to be assessed. A simple ecological-economic model is presented which calculates the efficiency losses associated with uniform payments for different types of benefit and cost functions.

JEL: Q20

Key words: Ecological-economic modelling, compensation payments, biodiversity, agri-environmental policy

1. Introduction

Whereas some endangered species require reserves to survive, others depend on particular types of human land use. For example, many species in Western Europe can only survive in agricultural landscapes if landowners carry out biodiversity-enhancing land-use measures (Hampicke and Roth 2000). However, such measures are usually costly. Since the political will often exists that landowners and in particular farmers should not be forced to carry them out, compensation has to be paid (Bromley and Hodge 1990, Hanley et al. 1998). Over the past decade compensation payment schemes for biodiversity enhancing land-use measures have gained increasing importance in Europe, particularly in the context of agri-environmental policy. Examples of such schemes are the Countryside Stewardship and the Moorland schemes in the UK and the nature protection contract schemes ("Vertragsnaturschutzprogramme") in various German states (Hanley and Oglethorpe 1999, Hampicke and Roth 2000).

Designing compensation payments for biodiversity-enhancing land-use measures has to take into account that both the costs and the benefits of such measures are subject to spatial variation. As well as regional differentiation, differentiation may also be prominent on a much smaller scale, for instance between plots of land owned by different farms. The possible reasons for cost differences include differences in soil qualities, opportunity costs for labour, opportunity costs for land and the availability of equipment to carry out biodiversity-enhancing land-use measures. Benefit differentiation may be caused by different habitat quality.

Given the spatial differences in costs and benefits, considerations of allocational efficiency call for spatially differentiated biodiversity-enhancing land-use measures, and, hence, spatially differentiated compensation payments. While allocational efficiency may require compensation payments to vary among regions or even on a farm-by-farm basis, the administrative costs of such differentiation may be significant, and objections based on equity or legal concerns may lead to political acceptance problems in implementing such differing payments. Thus, when deciding whether to implement uniform or spatially differentiated compensation payments, the regulator has to balance allocational efficiency losses on the one hand with administrative costs as well as equity and legal concerns on the other.

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Allocational efficiency losses may also be prevented by paying compensation for *results* rather than *measures*. Under this approach, for instance, compensation would not be paid to a farmer for creating a suitable habitat for an endangered plant but only for the actual presence of the plant on his fields. Although compensation payments for results do not yet play an important role in conservation policy, they are an option which recently has been increasingly discussed in various European countries and is being introduced on an experimental basis in for instance Germany. Such types of payment prevent losses due to spatially inefficient allocation because they encourage those farmers to produce the desired ecological effects who can do so at the least expense. Although avoiding problems of spatially inefficient allocation compensation, payments for results have other potential disadvantages such as high administrative costs for verifying whether the ecological results have actually been achieved (e.g. whether an endangered plant is actually growing) and inefficiencies through positive externalities (e.g. the seeds of an endangered plant being blown onto a neighbour’s meadows). Furthermore, farmers may find it difficult to accept such a scheme as payments hinge not only on their own efforts but also on exogenous influences such as weather conditions. In both types of decision – spatially homogeneous versus spatially differentiated payments and payments for measures rather than for results – the regulator has to weigh up the various advantages and disadvantages of both alternatives, including aspects of spatial allocational efficiency.

The aim of this paper is to increase understanding of spatial allocational efficiency issues with respect to biodiversity protection and particular regard to the policy instrument of compensation payments. For this purpose a conceptual framework is developed that allows the extent of spatial allocational efficiency losses of uniform payments to be evaluated under different circumstances, i.e. under different cost/benefit structures.

Kolstad (1987) analysed the extent of efficiency losses with spatially uniform regulation on a theoretical level. Among his findings were that efficiency losses increase when the marginal cost and benefit functions are steep. More policy-oriented research started back in the 1970s when the issue of spatial differentiation in environmental policy instruments was discussed against the background of regional differences in air pollution (see e.g. Tietenberg 1978). Spatial issues have re-emerged recently in the literature on nonpoint source pollution, especially in the context of water quality suffering from certain types of agricultural land use (for an overview see Shortle and Horan 2001). As in this paper, one issue in this debate is the extent of efficiency losses caused by uniform policy instruments (taxes and performance standards). Findings indicate that losses can vary significantly from negligible (Fleming and

Adams 1997) to significant (Carpentier et al. 2001) depending on the empirical context. However, due to the abstract nature of the benefit function in Kolstad (1987) and the particular focus on water quality in the nonpoint pollution literature, the applicability of this literature's results to biodiversity protection is limited.

To focus on biodiversity protection, the ecological benefit function has to be based on ecological theory. This requires incorporating ecological and economic knowledge into the evaluation of conservation instruments. So far, only a few studies have explicitly integrated both ecological and economic knowledge into such an evaluation. Recent work using this approach includes analyses of the extent to which efficiency improvements can be achieved by integrating economic costs (land prices) into the selection criteria of conservation sites compared to an approach that only considers ecological parameters, such as the number of endangered species (Ando et al. 1998, Polasky et al. 2001). Similarly, Johst et al. (2002) integrated economic cost data and the results of an ecological model into a numerical modelling procedure to determine spatio-temporally efficient compensation payments for species protection.

On a more general level, Wu and Bogess (1999) show that the specific shape of the ecological benefit function influences the spatial allocation of conservation funds. For instance, if a threshold in the ecological benefit function exists (i.e. cumulative effects are present), the optimum spatial allocation of limited conservation funds is such that funds should be concentrated in one region in order to exceed the threshold instead of being distributed evenly among regions. Drechsler and Wätzold (2001) systematically examine how the budget size, the shape of the cost function and the shape of the benefit function affect the efficient spatial allocation of conservation funds.

These ecological-economic studies have contributed to our understanding of how best to spatially allocate conservation funds under different ecological and economic circumstances. What they have not addressed is the question that for the reasons outlined above spatially efficient allocation may pose problems, and that in this context it is important to know the extent to which losses through inefficient allocation may arise. This is the starting point of this paper, which focuses on the particular problem of allocational efficiency losses through spatially homogeneous compensation payments. More specifically, the paper considers a situation where the regulator has decided to devote certain financial resources to conservation and is interested in maximising the ecological benefits. Consequently, we refer to a compensation payment scheme as being efficient when for given economic costs no other spatially differentiated compensation scheme is able to achieve higher ecological benefits. Thus, like Baumol and Oates (1988) we use the term ‘efficiency’ as being equivalent to what parts of the literature dub ‘cost-effectiveness’.

We use a numerical optimisation model with two regions to analyse efficiency losses through spatially uniform compensation payments. The model’s cost and benefit functions are briefly explained in Section Two. Section Three describes the model, Section Four how it is analysed and Section Five presents the results. The model assumptions are modified in Section Six to address the issue of spatially correlated benefits. Section Seven discusses the results and gives some recommendations for further research.

2. Benefit and cost functions

In this section, the benefit and cost functions are introduced which form the basis of the model. Both functions relate the costs and biodiversity benefits to the area that has been transformed through biodiversity-enhancing land-use measures into land suitable for conservation.

The benefit functions are taken from Drechsler and Wätzold (2001), where how they are derived from ecological theory is explained in detail. However, as many readers may not be familiar with ecological theory, a brief account of their ecological content would not be amiss.

The general derivation of an ecological benefit function poses some problems. Firstly, benefits from a habitat can be assessed by different criteria. This implies that a number of different benefit functions have to be taken into account in order to cover at least part of the possible range of judgements. Furthermore, each ecosystem is unique to some extent and there is no detailed common scale to compare their benefits. Nevertheless, ecosystems have to be – and are – compared for conservation management decisions, and if the focus is on general properties, common scales do exist which allow different ecosystems to be compared.

One such common property is species richness (i.e. the number of species) and the first benefit function assumes that the benefit B depends on species richness S on a habitat patch where S is a function of the size of the habitat area A:

$$B = S = \alpha \cdot A^{z} \qquad (1)$$

α represents some positive constant and the exponent, z, ranges from 0.15 to 0.35, depending on the habitat type and the taxonomic group of the species considered. For instance, z will differ between mammals and reptiles.

Another possible measure of ecosystem benefit is to focus on key stone or umbrella species. Key stone species may be considered more 'valuable' than others in terms of conservation because their activities govern the well-being of other species. Umbrella species demand high habitat quality, so if theses species are conserved, others that are less demanding will be conserved as well.

While the 'performance' of individual species in a habitat and their dependence on habitat area may hinge on many details, some general rules still exist. The expected lifetime T of a population is a universal measure of population viability (persistence and probability of survival) and is related to the carrying capacity of its habitat. The carrying capacity expresses the maximum number of individuals the habitat can sustain under optimum conditions and is closely related to the habitat area A. Wissel et al. (1994) found that

$$B = T = b \cdot A^{y} \quad \text{for } 0<v^2<2, \quad \text{and}$$

$$B = T = b' \cdot \ln(A) \quad \text{for } v^2 \geq 2. \tag{2}$$

with $y=2/v^2-1$. The quantity v is the coefficient of variation in population growth and b and b' are some proportionality factors. The variation in population growth depends on the variability of the environment and the extent to which it affects the population. Therefore, v is also denoted as environmental variability – a parameter which depends on the species and quality of the habitat. As a general rule, the lower the habitat quality, the higher the environmental variability v.

Equations (1) and (2) provide some plausible bound on a large range of possible benefit functions as they focus on species richness and individual species as well as habitat quality. In both equations benefits are related to area via a power law, with the exception of $v^2 \geq 2$. However, the logarithmic function ln(A) is very similar to Eq. (1) with z=0.15, and we found that the logarithmic function leads to similar results to those for z=0.15. For this reason, in the following we consider only Eq. (1) with various z (cf. Fig.1).

Below we assume that initially a region contains habitat of area A_0 corresponding to an initial benefit of

$$B_0 = \alpha \cdot A_0^z \tag{3}$$

If habitat area is increased by an amount of ΔA to a value of $A=A_0+\Delta A$ the benefit increases by

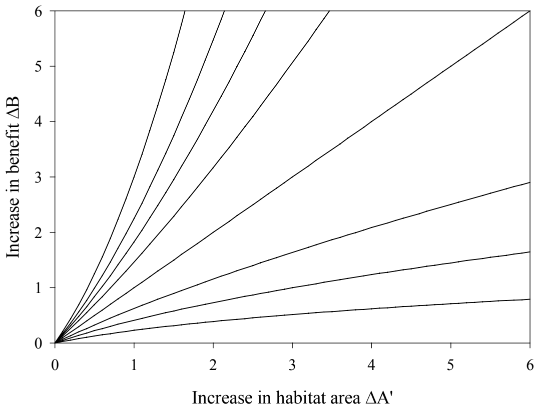
$$\Delta B = B - B_0 = \alpha \cdot (A_0 + \Delta A)^z - \alpha \cdot A_0{}^z = \alpha \cdot A_0{}^z \cdot \left[(1+\Delta A')^z - 1\right] \tag{4}$$

where $\Delta A' = \Delta A / A_0$ is the increase in area scaled in units of the initial habitat area. Without loss of generality, we set the constant $\alpha \cdot A_0^z = 1$ and write

$$\Delta B = (1 + \Delta A')^z - 1 \tag{5}$$

Fig.1 shows ΔB for a range of different z.

Figure 1: Increase in benefit ΔB as a function of habitat area increase $\Delta A'$ for various z (from bottom to top: 0.3, 0.5, 0.7, 1, 1.3, 1.5, 1.7, 2).



It illustrates that functions with a rather small z ($z<1$) imply that the larger the habitat, the lower the marginal benefits brought about by the measures, i.e. $d^2(\Delta B)/d(\Delta A)^2 < 0$. By contrast, a comparatively large z ($z>1$) leads to increasing marginal benefits, and so cumulative effects are observed.

With regard to the cost function we assume linearly increasing marginal costs c with an increase in area (ΔA) where biodiversity-enhancing land-use measures are being carried out

$$c = dC / dA = c_0 + e \cdot \Delta A\,. \tag{6}$$

The slope of the increase in marginal cost is given by e. Increasing marginal costs are a reasonable assumption because the cost of biodiversity-enhancing land-use measures differs from one plot of land to the next (cf. Introduction). Thus, they range from low to high implying rising marginal costs with increasing ΔA. The total costs C of carrying out biodiversity-enhancing land-use measures in an area ΔA are then given by the integral of Eq. (6):

$$C = c_0 \cdot \Delta A + e / 2 \cdot (\Delta A)^2\,. \tag{7}$$

Similar to the benefit function, we scale ΔA in units of A_0: $\Delta A' = \Delta A/A_0$. Equation (7) then writes

$$C = c_0 A_0 \left[\Delta A' + \frac{eA_0}{2c_0} \cdot (\Delta A')^2 \right] \tag{8}$$

A value of e=0 represents constant marginal costs; a value of $e=c_0/A_0$ means that an increase in habitat area by an amount of A_0 increases marginal costs by c_0, which is regarded as a plausible maximum for the value of e.

3. The model

The purpose of the model is to show the circumstances under which allocational efficiency losses of spatially homogeneous compensation payments for biodiversity-enhancing land-use measures are particularly high compared to spatially differentiated compensation payments and compensation payments for results. For this aim a model with two regions (1 and 2) is developed with different cost and benefit functions. Costs are assumed to differ with respect to the slope of the marginal cost function, e, and benefits with respect to the parameter indicating the type of species respectively habitat quality, z. These are the only differences between the two regions. The variables are respectively denoted as e_1, e_2, z_1 and z_2 for regions 1 and 2.

Total benefit increase ΔB_{tot} is given by

$$\Delta B_{\text{tot}} = \Delta B_1 + \Delta B_2 \tag{9}$$

with ΔB_1 and ΔB_2 measuring the increase in benefit in regions 1 and 2, respectively, as derived from the benefit function (Eq. 1). In Eq. (9) we assume that the benefits in the two regions are additive. Total costs, C_{tot},

$$C_{\text{tot}} = C_1 + C_2 \tag{10}$$

are the sum of costs in regions 1 and 2, C_1, and C_2, respectively. We assume that biodiversity-enhancing land-use measures are allocated via the instrument of compensation payments. Here for each region (i=1,2) a payment p_i (uniform within the region) is offered for carrying out such measures and increasing the habitat area by ΔA_i. We assume that landowners will carry out biodiversity-enhancing land-use measures as long as compensation payments are higher than or equal to the corresponding marginal costs $p_i \geq c_i$. Marginal cost differ between single plots of land within one region and if p_i is low only a few land-owners will participate in the conservation efforts. As payments rise, participation will increase and ΔA_i will grow. With Eq. (6) it follows that a compensation payment of p_i in region i will increase habitat area by

$$\Delta A_i = \frac{p_i - c_0}{e_i} \qquad (i=1,2) \tag{11}$$

To determine allocational efficiency losses of homogeneous compensation payments for given costs[2], in a first step we calculate the efficient payments p_1 and p_2 (which do not necessarily have to be equal) as functions of the total costs $C_{\text{tot.}}$ The payments are determined through the optimisation problem

$$B_{\text{tot}} \quad \rightarrow \quad \text{max} \quad \text{under the constraint}$$

$$C_{\text{tot}} = C_1 + C_2 \qquad \text{and} \qquad C_i \geq 0 \; (i=1,2). \tag{12}$$

Although the model can be formulated in a rather straightforward manner, an analytical solution is impossible for $z_1 \neq z_2$. The Lagrangian approach leads to an equation that contains the term $z_i(e_i A_0 + p_i - c_0)^{(z_i - 1)}$ where $i=1,2$ (cf. Drechsler and Wätzold 2001) which cannot be solved analytically unless $z_1 = z_2$. Furthermore the Lagrangian approach is known to fail to detect the optimum if the benefit functions are convex ($z_i > 1$). Therefore the model is solved numerically. For each level of total costs C_{tot} we vary a variable q from 0 to 1 in steps of 0.01 and calculate $C_1 = qC_{\text{tot}}$ and $C_2 = (1-q)C_{\text{tot}}$, which allows a systematic scan of the different options to allocate C_{tot}. For each value of q the total benefit ΔB_{tot} is determined and the maximum recorded. From Eqs. (8) and (11) the efficient ΔA_i and p_i follow directly. In this way, all quantities are determined as functions of $C_{\text{tot.}}$

In the second step we analyse the benefit obtained from homogeneous payments and compare it to that obtained by the efficient payments above. For a given homogeneous payment $p=p_1=p_2$, we calculate the corresponding increases in habitat area ΔA_i via Eq. (11), from this the corresponding costs C_i via Eq. (8), and the benefits via Eq. (5). Total benefit and total costs follow from Eqs. (9) and (10). The total benefit is compared to the *efficient* total benefit corresponding to the same total costs, as determined in the first step.

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[2] Alternatively, one may be interested in the allocational efficiency losses of homogeneous payments for given budgets for compensation payments ($B=p_1\Delta A_1+p_2\Delta A_2$). The relationship between the budget B and total cost C is that the budget has to cover not only costs but also a producer surplus (R) for those landowners whose costs of carrying out biodiversity enhancing land-use measures exceed the compensation payments ($p_i > c_i$), i.e. $B=C+R$. We chose cost as from the angle of economic theory this is the relevant parameter.

The ratio between the 'homogeneous' and the efficient total benefits is a measure of the allocational efficiency loss of the homogeneous compensation payments and is determined as a function of total costs.

4. Model analysis

The model is analysed in two steps. In the first step we explore the general behaviour of the model and consider different preliminary scenarios, each being defined by the benefit and cost structure in region 1. The corresponding parameters z_1 and e_1 assume different values between 0.2 and 3 (i.e. strongly decreasing and increasing marginal benefits) and between $0.05c_0/A_0$ and $0.95c_0/A_0$ (i.e., weakly and strongly increasing marginal costs), respectively. The parameters for region 2 (z_2 and e_2) are varied from the values of z_1 and e_1 in increments of 0.1 and $0.05c_0/A_0$, respectively.

Total costs C_{tot} range from $2c_0A_0$ to $125c_0A_0$. Values below $2c_0A_0$ lead only to small efficiency losses, regardless of the other model parameters. A value of $125c_0A_0$ represents the costs arising from multiplying the habitat area in region 1 by a factor of 125, and is regarded as an upper plausible bound. Although in principle each value of C_{tot} leads to a different model result, preliminary analyses of the model revealed that the efficiency changes only slowly with total costs. Therefore we distinguish among three cost ranges: small ($C_{tot}/c_0A_0 = 2$-8), medium (8–30), and large (30–125) costs. For each range the efficiency is calculated for all cost values included and an average is taken. This results in three values for efficiency for each combination of z_1, z_2, e_1 and e_2: one for small, one for medium and one for large costs.

Based on the results of this first step, in the second step we form five main scenarios which encompass most of the model's behaviour. A main scenario is defined by the combination of benefit structures in the two regions, i.e., by z_1 and z_2. The scenarios are:

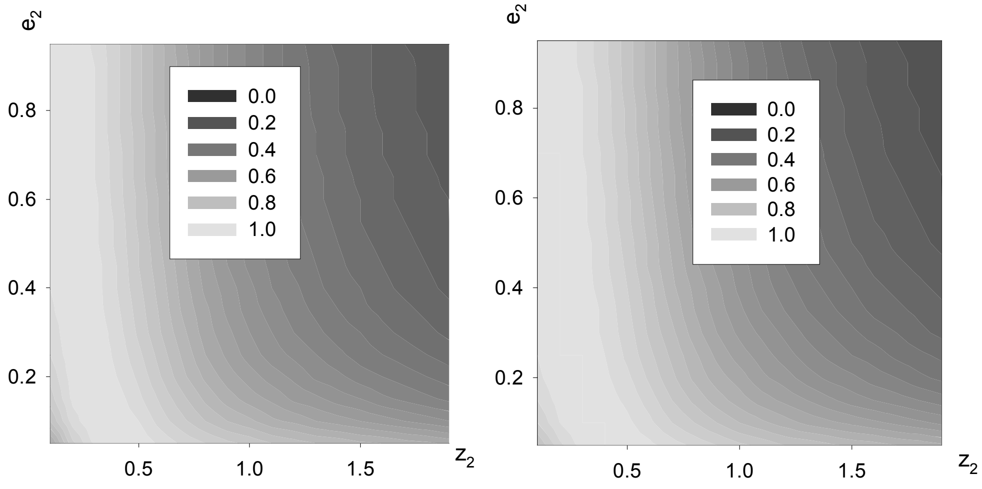
S_1: z_1=0.3, z_2=0.7
S_2: z_1=0.5, z_2=0.5
S_3: z_1=0.3, z_2=1.7
S_4: z_1=1.3, z_2=1.7.
S_5: z_1=1.5, z_2=1.5

In each scenario, e_1 and e_2, which determine the cost functions in the two regions, are varied systematically between $0.05c_0/A_0$ and $0.95c_0/A_0$ in increments of $0.05c_0/A_0$.

5. Results

Fig. 2 shows the efficiency of the instrument for one of the preliminary scenarios and two cost levels.

Figure 2: Efficiency of the homogeneous instrument (white=100%; black=0%) relative to the spatially differentiated instrument as a function of the benefit (z_2) and cost functions (e_2) in region 2. Marginal costs in region 2 (e_2) are scaled in units of c_0/A_0. The benefit and cost functions in region 1 are fixed at $z_1=0.3$ and $e_2=0.15c_0/A_0$. Total costs are low (left figure) and high (right figure).



The following observations are of interest:

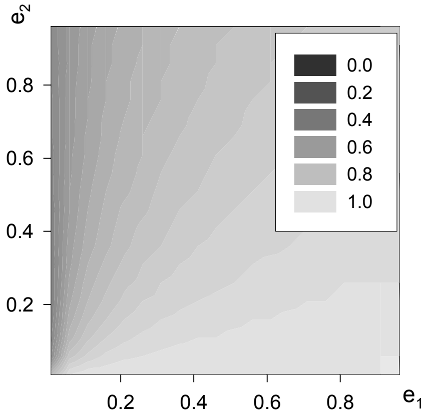
- The efficiency losses become higher when the differences between z_1=0.3 and z_2 increase.
- The efficiency losses can reach almost 100% (see also Fig. 5).
- The level of total costs seems to have little influence on the model results.

We also found in the first step that the qualitative behaviour of the model depends mainly on two conditions:

1. Whether the benefit functions in both regions are identical (z_1=z_2)
2. How many of the two benefit functions are concave

Combinations of all possible answers to the two questions are encompassed in the five scenarios S_1–S_5. Figure 3 shows the efficiency for the first scenario (z_1=0.3, z_2=0.7) as a function of the increase in marginal costs in the two regions (e_1 and e_2).

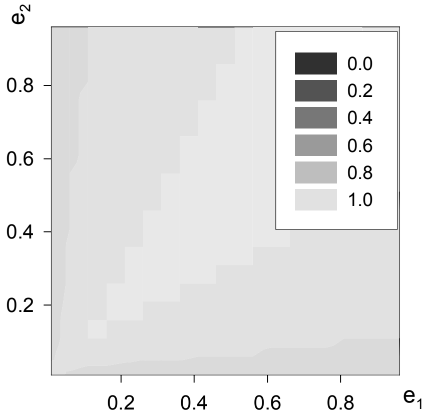
Figure 3: Efficiency of the homogeneous instrument (white=100%; black=0%) relative to the spatially differentiated instrument as a function of the cost functions e_1 and e_2. Marginal costs e_1 and e_2 are scaled in units of c_0/A_0. The benefit functions are fixed at $z_1=0.3$ and $z_2=0.7$. Total costs are high.



It can be seen that the efficiency losses are minimal when e_1>>e_2 and maximal when e_1<<e_2. This is plausible. In the former case the cost structure leads to more of the biodiversity-enhancing land-use measures being allocated in region 2. This region provides the higher benefit and thus allocation is efficient. In the latter case the biodiversity-enhancing land-use measures are concentrated in region 1 with low benefit, leading to an inefficient allocation.

The results for the second scenario (z_1=z_2=0.5) are shown in Fig. 4.

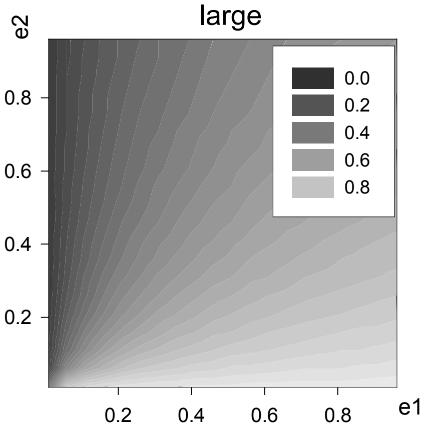
Figure 4: Same as Fig. 3, but with z_1=z_2=0.5.



Naturally, the instrument is efficient if the cost structures of the two regions are identical (e_1=e_2) because they lead to an even allocation of biodiversity-enhancing land-use measures. Due to the concavity of both benefit functions (with equally decreasing marginal costs) this even allocation leads to maximum total benefit. However, even if $e_1 \neq e_2$ the efficiency losses are only small. This can be seen by exploring how an inhomogeneous instrument could improve the efficiency. Assume, without loss of generality, e_1>e_2. If the payments in both regions are equal, the allocation of biodiversity-enhancing land-use measures and area is concentrated in region 2, leading to a misallocation from the point of view of the benefit functions. Now consider two alternatives: increasing the payment in region 1 relative to that in region 2, or doing the opposite. In the first case, $p_1>p_2$, the allocation of the total area would become more uniform, but due to the larger e_1 less area could be allocated in total. Altogether the net advantage of the inhomogeneous instrument would be only moderate. In the second case, $p_1<p_2$, more area could be allocated for the same total costs, but it would be allocated exclusively in region 1, which would be inefficient due to the concavity of the benefit functions. Altogether, the homogeneous instrument is relatively efficient if the benefit functions are equal and concave, regardless of the shape of the cost functions.

Figure 5 with z_1=0.3 and z_2=1.7 (scenario S_3) looks very similar to Figure 3, except that the efficiency losses are much larger and can reach almost 100%.

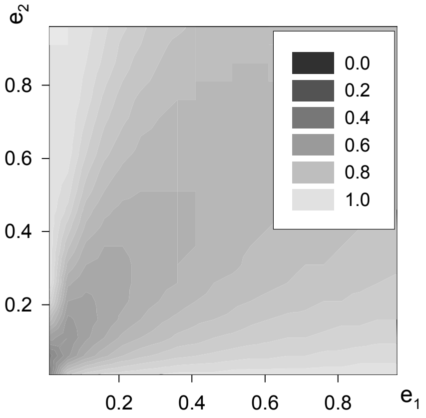
Figure 5: Same as Fig. 3, but with z_2*=1.7.*



Alongside the result that increasing difference in the benefit functions increases efficiency losses, this indicates that if one of the benefit functions is concave, it makes no qualitative difference whether the other one is concave or convex.

The efficient allocation changes considerably when both benefit functions are convex. First we consider scenario S_4, where both benefit functions are identical (z_1=1.3 and z_2=1.7: Fig. 6).

Figure 6: Same as Fig. 3, but with z_1*=1.3 and* z_2*=1.7.*



Similar to Figs. 3 and 5, low efficiency losses are observed when the marginal costs in region 2 with the higher marginal benefit are smaller than those in region 1 ($e_1>>e_2$). In contrast to Figs. 3 and 5, however, small efficiency losses are also observed in the opposite case, i.e. when the marginal costs in region 2 are much higher than in region 1 ($e_1<<e_2$).

To understand this unexpected result for $e_1<<e_2$, consider two alternatives to the homogeneous instrument and see if they lead to higher benefits: high payments in region 1 with low payments in region 2, and vice versa. In the first case, $p_1>p_2$, a much greater area would be obtained than with the homogeneous instrument due to the low costs of land in region 1. However, this area would be relatively useless from an ecological angle due to the comparatively low benefits ($z_1<z_2$). This problem could be fixed in the second case, $p_1<p_2$, where a larger proportion of total area is allocated in region 2. However, due to the high costs in region 2, the total area would be smaller than in the first case, so nothing would be achieved.

All in all we are confronted with a choice between two evils: either we allocate biodiversity-enhancing land-use measures in line with the cost structure ($e_1<<e_2$) but ‘against’ the benefit structure ($z_1<z_2$) (first case), or we allocate them in line with the benefit structure but ‘against’ the cost structure. This means that (i) the maximum benefits that can be obtained under efficient allocation are small, and (ii) the benefit is comparatively insensitive to the (relative) allocation of the biodiversity-enhancing land-use measures in regions 1 and 2.

One may well ask why such a result only appears when both benefit functions are convex. The answer is that here the marginal benefits increase in both benefit functions, which means that even if the allocation of area is concentrated in the region with the lower z, a sufficient increase in costs can achieve any desired benefit. While the efficiency loses are dramatic when biodiversity-enhancing land-use measures are allocated to a region with the *most strongly* *decreasing* marginal benefits (region 1 in scenarios S_1 and S_2; Figs. 3 and 5), the allocation of biodiversity-enhancing land-use measures to the region with the *less strongly increasing* marginal costs is less adverse.

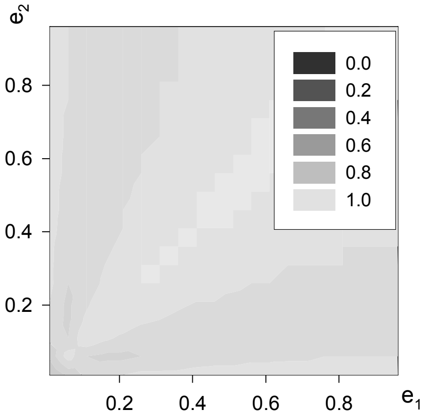
The highest efficiency losses in Scenario 4 are observed when both cost functions are equal, especially when marginal costs only increase slowly ($e_1 \approx e_2 << c_0/A_0$). Here the homogeneous instrument leads to the even allocation of biodiversity-enhancing land-use measures, while due to the strongly increasing marginal benefit in region 2 (z_2=1.7) this region should be preferred.

This effect is slightly less severe when marginal costs sharply increase ($e_1 = e_2 \approx c_0/A_0$) because the homogeneous allocation of costs becomes more advantageous (cf. Drechsler and Wätzold 2001) as a greater total area can be obtained for the given total costs. This fact partly overrules the call of the benefit functions for inhomogeneous allocation and consequently, efficiency losses are lower than in the case of $e_1 \approx e_2 << c_0/A_0$.

Altogether, in this scenario the efficiency losses obtained by the homogeneous instrument are small, as long as the cost functions differ strongly between the two regions.

Lastly we consider scenario S_5, where both benefit functions are convex and identical ($z_1 = z_2$=1.5) (Fig. 7). It is shaped by a 'battle' between cost structure and benefit structure. As the marginal benefits increase in both regions equally, an inhomogeneous allocation of the costs – favouring either region 1 or 2 – is efficient from a benefit point of view. Such inhomogeneous allocation of total costs is achieved by homogeneous payments when the cost functions strongly differ. Consequently, the homogeneous instrument ought to be inefficient if the cost functions are similar ($e_1 \approx e_2$). Indeed, there are small efficiency losses if $e_1 \approx e_2 << c_0/A_0$. But why is the homogeneous instrument efficient again when $e_1 \approx e_2$ approach c_0? Here the cost structure overrules the benefit structure and as already mentioned in the discussion of Fig. 6, increasing marginal costs call for the homogeneous allocation of biodiversity-enhancing land-use measures and thus boost the efficiency of the homogeneous instrument.

Figure 7: Same as Fig. 3, but with $z_1 = z_2 = 1.5$.



To provide an overview the results for the five scenarios are summarised in Table 1.

Table 1: Summary of scenario results.

Scenario	S_1 (z_1=0.3,z_2=0.7)	S_2 (z_1=0.5,z_2=0.5)	S_3 (z_1=0.3,z_2=1.7)	S_4 (z_1=1.3,z_2=1.7)	S_5 (z_1=1.5,z_2=1.5)
Number of convex benefit functions	0	0	1	2	2
Identical benefit functions	No	yes	no	no	yes
$e_1 >> e_2$	+	+/-	+/-	-	-
$e_1 << e_2$	--	+/-	---	-	-
$e_1 \approx e_2 << c_0/A_0$	-	+	--	---	+/-
$e_1 \approx e_2 \approx c_0/A_0$.	-	+	--	--	+
+ : efficient (95-100%), - : little efficiency losses (80-95%) -- : medium efficiency losses (40-80%), --- : high efficiency losses (0-40%); percentages indicate the degree of efficiency of homogeneous payments relative to efficient inhomogeneous payments.					

6. Correlation of benefits across regions

So far, we have assumed that the benefits in the two regions are independent. However, this may not necessarily be the case and benefits could be correlated, i.e. the marginal benefit in one region may depend to some extent on the benefit in another region. The simplest, most general way of modelling this effect is to assume that the total benefit is not the sum but the product of the individual benefits (cf. Eq. 9):

$$B_{\text{tot}} = B_1 * B_2 \tag{13}$$

A biological justification for this benefit function can be found in the metapopulation concept (e.g. Hanski 1999). A metapopulation consists of a number of subpopulations that are physically separated but interact with each other through the exchange of individuals. Individual subpopulations can become extinct, but empty habitats may be recolonised by neighbouring subpopulations. Furthermore, the immigration of individuals into an existing subpopulation may reduce its risk of extinction. In this manner the subpopulations stabilise each other and the increase in the habitat of one subpopulation has positive effects on the other subpopulations. Frank and Wissel (2002) developed a closed formula for the expected lifetime of a metapopulation. For a metapopulation consisting of two subpopulations, it can be shown that its life time is approximately related to the product of the expected lifetimes of the two subpopulations. In Eq. (2) we related the ecological benefit B_i in a region i (i=1,2) to population lifetime. If we assume that the subpopulations in the two regions interact and exhibit metapopulation dynamics, it is plausible to assume that the total benefit is related to the product of the individual benefits in the two regions, as is stated by Eq. (13).

With Eq. (5) and some algebra, the benefit increase obtained from area increases ΔA_1' and ΔA_2' becomes

$$\Delta B_{\text{tot}} = \Delta B_1 * \Delta B_2 + \Delta B_1 + \Delta B_2 \tag{14}$$

In the same manner as in the preceding sections, we determine the efficiency losses of homogenous payments for the benefit function Eq. (14). Fig. 8 shows the results for the scenarios S_1–S_5 investigated above. In all the scenarios the area of highest efficiency is located along a straight line through the origin. Comparison of the five scenarios reveals that the slope of the line depends on z_1 and z_2. Roughly speaking, efficiency losses through homogenous payments turn out to be minimal if $e_2/e_1=(e_2/e_1)_{\text{eff}}\approx z_1/z_2$ (or in other words if the line of minimal efficiency losses has an angle with the e_1-axis of $\varphi=\varphi_{\text{eff}}\approx\text{arctg}(z_1/z_2)$). This implies that if z_1 is larger than (equal to) z_2, homogeneous payments are efficient if e_2 is larger than (equal to) e_1.

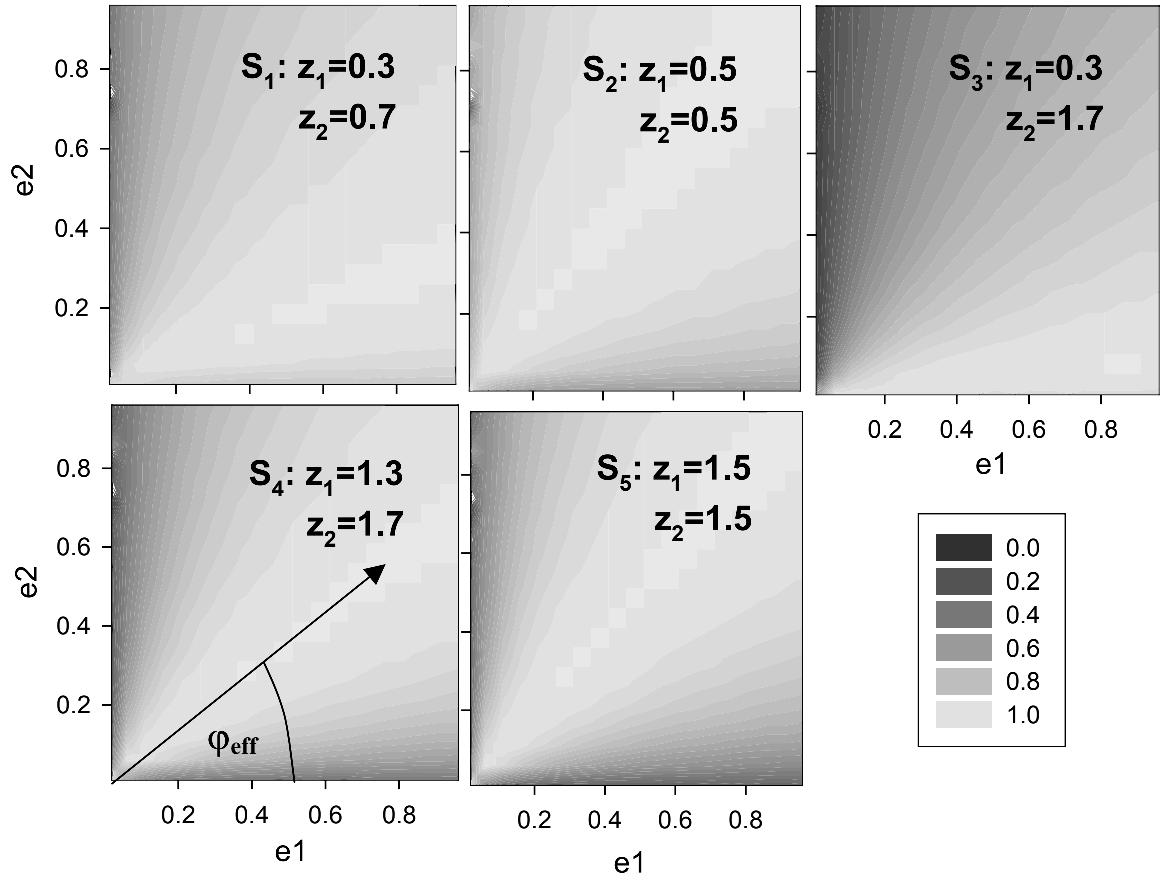
This result can be understood if we focus for the moment on pure benefit maximisation and neglect costs, i.e. we assume that C_i are proportional to ΔA_i. Under the constraint A_1+A_2=const., the total benefit increase, Eq. (14) can be shown to be maximal if

$$(A_0+A_1)/(A_0+A_2)=z_1/z_2. \qquad (15)$$

If z_1 is equal to z_2, as in scenarios S_2 and S_5, it is optimal to have the same habitat increase in both regions. If z_2 is larger than z_1 (scenarios S_1, S_3 and S_4) then habitat increase in region 2 should be larger than in region 1.

Now we turn back to the full model and take into account cost differences and the fact that the changes in habitat size have to be induced by compensation payments. If both regions are to receive the same amount of habitat through homogenous payments (as in scenarios S_2 and S_5), this is only possible if the cost functions in both regions are identical. If region 2 is to receive more habitat than region 1 (cf. Eq. 15) through homogenous payments (scenarios S_1, S_3 and S_4) then the costs in region 2 have to be lower than in region 1 by a corresponding factor.

Figure 8: Efficiency of the homogeneous instrument with correlated benefits (Eq. 9) for scenarios S_1–S_5. The angle between the line of highest efficiency and the e_1-axis is denoted as φ (see text). Remaining details as in Fig. 3.



After having understood why efficiency losses of uniform payments are lowest when Eq. (15) is fulfilled, we now turn to the question of how the efficiency is reduced as the ratio e_2/e_1 deviates from the optimal value z_1/z_2. In scenario S_5, efficiency is about 100% if $e_2/e_1=z_1/z_2=1$ (φ=45°) and approximately linearly decreases to zero as φ increases to 90° or decreases to 0. Hence very roughly, efficiency decreases by about 2% as the angle φ=arctg(e_2/e_1) deviates from the optimal angle φ_{eff}=arctg(z_1/z_2) by 1°. A similar decrease in efficiency with deviation from φ_{eff}=arctg(z_1/z_2) can be found in scenarios S_3 and S_4. A weaker decrease in efficiency can be observed in scenarios S_1 and S_2.

Why is the efficiency in scenarios S_3-S_5 more sensitive that in S_1 and S_2? In the former three scenarios the convex nature of at least one of the two benefit functions can lead to high synergy effects between the two regions (i.e. the higher the ecological benefit in one region the more beneficial a habitat increase in the other) if habitat area is allocated efficiently, and consequently if habitat is not allocated efficiently, the losses may be severe. In scenarios S_1 and S_2, synergy effects are limited due to the concavity of both benefit functions and therefore efficiency losses are less severe.

7. Discussion

We investigated the efficiency of homogeneous compensation payments when costs have to be allocated between two regions which differ in their cost and benefit functions. In the mathematical model we analysed, marginal costs may increase strongly or slowly and the benefit functions may be concave, convex or linear and independent or correlated. Irrespective of the shape of the cost and benefit functions and whether the benefit functions were independent, the amount of biodiversity-enhancing land-use measures to be allocated had little effect on the efficiency of the homogeneous payments.

To interpret the results of the preceding section in a practical way, we should briefly recall the ecological meaning of z. In the presentation of the model we outlined that concave benefit functions describe a situation of saturating benefits which applies when the benefit is proportional to species richness or when the objective is to increase the lifetime of an individual species which is subject to high environmental variation and/or lives in a habitat of poor quality. By contrast, convex benefit functions describe the situation observed in the vicinity of an ecological threshold and are likely to apply when a species is subject to low environmental variation and/or inhabits high quality habitat.

The results clearly indicate that inefficiencies through homogeneous payments may be substantial. Within the framework of the model, allocational efficiency losses were close to 100% under certain conditions in the case of both independent and correlated benefits. This suggests that the regulator ought to take potential allocational efficiency losses into account when deciding whether to implement spatially homogeneous or differentiated payments for biodiversity-enhancing land use measures, or whether to implement compensation payments for measures or for results.

In the case of independent benefits, we found that the qualitative behaviour of the model strongly depends on whether both benefit functions are convex (scenarios S_4–S_5) or not (scenarios S_1–S_3). In the latter case the results were as expected: Efficiency losses are negligible if either both benefit functions are identical/similar, regardless of the cost functions (scenario S_2), or if benefit and cost functions 'agree', i.e. if the marginal costs are higher in the region with the lower benefit ($e_1 >> e_2$). In the other cases the efficiency losses were higher, especially if benefit and cost functions strongly 'disagreed', i.e. if the marginal costs were higher in the region with the higher benefit ($e_2 >> e_1$ in scenarios S_1 and S_3).

Totally different results are obtained when both benefit functions are convex (S_4-S_5). Here the two key questions are whether the two cost functions are similar/identical, and whether the two benefit functions are similar/identical. If the cost functions in the two scenarios are strongly dissimilar, then efficiency losses are small, regardless of whether cost and benefit functions 'agree' or not (i.e. whether $e_1 >> e_2$ and $e_2 >> e_1$). If the two cost functions are identical/similar ($e_1 \approx e_2$), efficiency losses strongly depend on whether the benefit functions are identical/similar, as well. If the benefit functions are identical/similar (S_5), efficiency losses are negligible; if they are dissimilar, efficiency losses are substantial (S_4).

Correlated benefits may occur when a certain species is to be conserved, subpopulations of this species exist in the two regions, and their interaction exhibits metapopulation dynamics. The inclusion of correlated benefits into the model strongly modifies the results. In this case, homogeneous compensation payments are efficient when the ratio e_2/e_1 is about equal to the ratio z_1/z_2 of the exponents of the benefit functions (cf. Eq. 3). The more this condition is violated, the higher the efficiency losses. The extent of these efficiency losses is significantly higher when at least one benefit function is convex than when both functions are concave.

Future research may attempt to assess the empirical relevance of the problem tackled in this paper on a conceptual level. Kolstad (1986) empirically examined efficiency losses from spatially uniform economic instruments (price or quantity controls) for regulating air pollution, and found that efficiency losses may be significant. Similar results were obtained by Carpentier et al. (1998), who analysed cost savings through spatially differentiated performance standards for reducing nitrogen runoffs from dairies in the Lower Susquehanna Watershed in the U.S. In contrast, Fleming and Adams (1997) found in their empirical study on taxes to control groundwater nitrates arising from irrigated agriculture that specifically tailored taxes only lead to small efficiency gains. What would be the results of empirical studies addressing the issue of spatial differentiation versus homogeneity for compensation payments aimed at protecting biodiversity? It should be relatively easy to conduct such studies for compensation programmes for species protection. Given spatially differentiated data on economic costs and ecological benefits (which may be gained through species-specific ecological simulation models; see for example Burgman et al. 1993, Hanski 1999, Johst et al. 2001), efficiency losses may be calculated using methods of numerical optimisation. Through the incorporation of valuation methods, such studies may also provide a good opportunity to take into account different social (e.g. recreation or aesthetic) values arising from biodiversity-enhancing land-use measures.

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