UFZ-Discussion Papers

Department of
Ecological Economics and
Environmental Sociology (OEKUS)

1/1999

Towards an efficient spatial allocation of biodiversity-enhancing farming practises

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Februar 1999

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Abstract

The paper analyses the efficient spatial allocation of farming practices which have a positive impact on biodiversity. For this purpose a spatial allocation model for two different regions is developed which allows guidelines to be derived on how to achieve the highest possible ecological benefit within a given budget provided to support farming practices for conservational purposes. The difference from other economic models dealing with the efficient spatial allocation of environmental goods is that the benefit function of our model is based on ecological theory. In contrast to other conservation biological models, our model includes more realistic economic assumptions. Therefore our results differ from those obtained in monodisciplinary studies. To assess the implementation possibilities of our model's policy recommendations we investigate existing programmes which have been developed under EU Regulation 2078/92 in the German Federal States. The analysis shows that spatial differentiation already exists and that existing types can be used to implement the policies recommended by our results.

Keywords: biodiversity, interdisciplinary research, agriculture, EU-Regulation 2078/92

JEL-classification: D62, Q1, Q24

1. Introduction

The choice of farming practices is one of the main factors that influence biodiversity in central Europe (see e.g. Hampicke 1991; Nowicki 1997). In medieval times the expansion of agriculture was the decisive factor behind the increase in the number of animal and plant species in central Europe. The logging of forests and the increase of the area devoted to a wide range of farming practices led to a rise in the variety and number of habitats. In the twentieth century this trend has been reversed. The industrialisation of agriculture has brought about a number of developments leading to a decline in biodiversity. For example, measures destroying valuable habitats such as cutting down hedges and small copses have been carried out to facilitate the use of machinery. The evening-out of soil humidity resulted from the demand from crops for a certain amount of soil humidity but eradicated both extremely dry and extremely wet habitats. The increased use of fertiliser has reduced the frequency of oligotrophic soils, which are habitats for many endangered species. The use of pesticides has reduced the abundance of many plants and insects. The early cutting of grassland to gain valuable fodder has reduced the diversity of flowers, which in turn reduced the food supply for certain insects.

A change in farming practices can slow down or even reverse these adverse developments. For example, farmers can reforest hedges and copses. They can also use fertiliser and pesticides only in selected areas or with reduced intensity. Another possibility is to only cut grass after a certain date, which would allow most of the flowers to bloom. These measures, however, are costly for farmers. Accepting the existing allocation of property rights as given, farmers have to be compensated if society wants them to change their farming practices (Coase 1960; Bromley and Hodge 1990; Bromley 1997; Hackl and Pruckner 1997). From the point of view of economic theory, such compensation payments are justified if a change in farming methods leads to growth in consumer surplus greater than the decrease in producer surplus (Bonnieux et al. 1998). At a European level, the EU's Common Agricultural Policy has moved towards taking into account environmental benefits from farming, mainly with Regulation 2078/92.[1] Under this scheme farmers are compensated when they practise environmentally friendly farming methods. The EU intends to expand this policy within Agenda 2000.

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[1] For a survey of EU policy instruments designed to benefit the environment and related to agricultural land use practices, see Nowicki (1997, p.71).

One of the criticisms of the existing policies to compensate farmers for environmental measures is that subsidies have been allocated without taking into account regional ecological specifics. It has been argued that subsidies could achieve higher ecological benefits in terms of biodiversity if were geared more specifically to certain areas (Bundesamt für Naturschutz 1997). The aim of our paper is to develop guidelines on how to allocate the resources from a given budget among different regions such that the maximum possible ecological benefit is obtained. In particular, we are interested whether we should allocate more money to regions with an already high percentage of area devoted to conservational purposes or more money to regions with less area devoted to such aims. We develop a spatial allocation model with two regions which differ in the initial amounts of land devoted to conservational purposes. The basic structure of our model is similar to that of other models for the efficient spatial allocation of environmental goods (e.g., Siebert 1985; Siebert 1998). In contrast to these studies we use benefit functions which are based on ecological theory. This enables us to formulate policy recommendations more specifically.

The next section is devoted to the introduction of several environmental benefit functions that relate benefits in terms of biodiversity to the area available for conservational purposes. In section 3 we develop our model and derive the results in section 4, which are discussed in section 5. In section 6 existing programmes to subsidise farming practices for conservational purposes are analysed with respect to spatial differentiation. Policy recommendations and conclusions are presented in the last section.

2. The benefit functions

In this section we introduce several alternative functions that measure benefits from biodiversity as a function of the area available for conservational purpose. The general derivation of such a benefit function is problematic for two reasons. Firstly, benefits from an ecosystem can be assessed by different criteria. This means that a number of different benefit functions have to be considered in order to encompass at least part of the possible range of judgements. Secondly, because of the high variability of ecosystems, each ecosystem is unique to some extent and a common scale does not exist at a detailed level. However, if we focus on general properties, such as species richness, common scales which allow the comparison of different ecosystems, do exist.

One of the most fundamental relationships between biodiversity and area is provided by the theory of island biogeography by MacArthur and Wilson (1967). This theory relates the species richness (i.e., the number of species) on an island or habitat patch to the habitat area. Species richness is not the only possible measure of the value of an ecosystem – but it is certainly a plausible one and used in landscape planning. Therefore a plausible assumption is to measure the benefit B of an ecosystem by its species richness S which is related to area A via (e.g., Begon et al. 1990; Wissel and Maier 1992):

$$B = S = \alpha * A^z \tag{1}$$

where α is some positive constant, and the exponent, z, ranges from 0.15 to 0.35, depending on the habitat type and on the taxonomic group of the species considered (Begon et al., 1990; Wissel and Maier, 1992). For instance, z will differ between birds and mammals or between land birds and water birds, and so on.

The use of species richness as a measure of ecosystem benefits has been criticised because it does not reflect the functioning or 'stability' of the ecological community of plants and animals. Certain species known as 'key-stone species' may be more 'valuable' than others in terms of conservation, because their activities govern the well-being of others. However, it is usually very difficult to identify the key-stones of an ecological community. Another concept is the concept of umbrella species (Berger 1997). Here use is made of the fact that not all species of an ecosystem are equally vulnerable to changes and the destruction of their habitat. This is because their demand for habitat quality and size varies. If conservation measures focus on the most vulnerable and most demanding species (usually the physically largest), it is assumed that the others will benefit from these actions as well. The most demanding species thus serve as 'umbrellas' to the others. Again, this concept is controversial, too, because what is beneficial to one species may be a disadvantage to another. A critical overview of the various concepts is contained in Simberloff (1997). Nevertheless, a plausible alternative to the use of species number as the only measure of ecosystem benefit is to focus on individual species such as endangered, keystone or umbrella species (Settele et al. 1996).

What is needed now is a measure of the 'performance' of individual species in a habitat and its dependence on habitat area. This will depend on many details, but for simple cases some general rules exist. Lande (1993) and Wissel et al. (1994) related the expected lifetime T of a population to the carrying capacity K of its habitat. (The expected lifetime is a universal measure of population viability (persistence and probability of survival): Wissel et al., 1994). The carrying capacity gives the maximum number of individuals the habitat can sustain under optimal conditions and is closely related to habitat area. Wissel et al. (1994) introduced the exponent $a=2/v^2-1$ and found that

$$T = \beta * K^a \quad \text{for } 0<v^2<2 \qquad (2)$$
$$T = \beta * \ln(K) \quad \text{for } v^2 \geq 2.$$

The quantity v is the coefficient of variation of population growth and β is some positive constant. The variation in population growth depends on the variability of the environment and the extent to which the population is affected by it. Therefore v is also denoted as environmental variability. Equation (2) states that the viability of the population increases algebraically or logarithmically with habitat size, depending on environmental variability, v. Environmental variability depends on the species and on the quality of its habitat. As a simple rule, strong environmental variability ($v \geq 1$) is often observed in small, fast growing species, such as many insect populations; small $v \leq 1$ are often observed in larger organisms, such as mammals (see, e.g., Begon et al. 1990; Stearns 1992). Usually, the lower the habitat quality the higher environmental variability.

One simple way of measuring the benefits of an ecosystem is now to select a target species and measure the benefits of the ecosystem by the viability T of that species. If we assume that the carrying capacity K is proportional to the area A of the habitat we obtain:

$$B = T = b' * A^a \qquad \text{for } 0<v^2<2$$
$$B = T = b' * \ln(A) \qquad \text{for } v^2 \geq 2 \qquad (3)$$

where b' is some proportionality factor. As eq. (1) focuses on all species and eq. (3) on a single species, they might be said to provide some plausible bounds on a large range of possible benefit functions. In both equations benefits are related to area via a power law, with the exception of strong environmental variability, v>2. A range of benefit functions is shown in Fig. 1 (see Annex 1 for tables and figures). It is apparent that for a wide range of areas A, the logarithmic function ln(A) is very similar to the power function eq. (1) with $z=0.15$. Indeed, we found that the logarithmic function leads to results very similar to those for $z=0.15$. Therefore in the following we consider only power functions (eq. 1) with various z. Large z refer to individual species with little environmental variability and small z may refer to species richness (eq. 1) as well as to individual species with strong environmental variability (eq. 3).

As z and v (eqs. (1 and 3) depend on the type and quality of the habitat, so does the exponent in the benefit function. Therefore when different habitats are compared using the same benefit function for both of them, they must be of a similar type and quality. For instance, high quality forest should only be compared with high quality forest, but not with poor quality wetland. Similarly, if the focus is on individual species (eq. 3) different habitats may only be compared with respect to species with similar environmental variability.

3. The model

Our aim is to develop guidelines on how to allocate the resources from a given budget devoted to conservational purposes, C_{tot}, among different regions such that the total utility of society U is maximised. For this purpose we develop a spatial allocation model with two regions which differ in the initial amounts of land devoted to conservational aims. We assume the benefits B to be an adequate measure of utility (U~B) and we consider benefits only. Total benefits are given by:

$$B_{tot} = B_1 + B_2 \tag{4}$$

where B_1 and B_2 are the benefits for regions 1 and 2. The relationship between benefits and protected area for individual regions were derived in the section above (eqs. (1) and (3)). We assume that farmers choose biodiversity-enhancing farming practises and increase the amount of protected area, as soon as the subsidies offered to them equal their costs. Therefore in each region costs are identical to the amount of subsidies and we consider costs only. The relationship between area A_i and costs C_i ($i=1,2$) in each region is described by a simple cost function. This is assumed to be identical in both regions and assumes that marginal costs c_i increase linearly with area:

$$c_i = dC_i/dA_i = c_0 + e * \Delta A_i \qquad (i=1,2) \qquad (5)$$

where dC_i/dA_i are the marginal costs and ΔA_i is the increase in protected area in region i. The costs C_i of an area increase ΔA_i are then given by the integral of eq. (5):

$$C_i = c_0 * \Delta A_i + e/2 * (\Delta A_i)^2 \qquad (i=1,2). \qquad (6)$$

Similar to the cost function, we assume that the benefit function (eqs. (1) and (3)) is the same in both areas. Both areas are therefore comparable, but differ in their initial amount of protected area A_{i0} (i=1,2). Without restriction of generality we assume that the initial amount of protected area in region 1 is smaller than in region 2, $A_{20} \geq A_{10}$.

The aim is now to divide the resources C_{tot} into C_1 and C_2 and increase the protected areas in the two regions to $A_i=A_{i0}+\Delta A_i$ such that total benefits, $B_{tot}=B_1(A_1(C_1))+B_2(A_2(C_2))$, are maximised:

$$B_{tot} \rightarrow \max \qquad \text{under the constraints}$$
$$C_1+C_2 = C_{tot} \text{ and } C_i \geq 0 \; (i=1,2). \qquad (7)$$

Specifically, we are interested in the efficient proportion $q_1=\Delta A_1/(\Delta A_1+\Delta A_2)$ of total area increase $(\Delta A_1+\Delta A_2)$ that falls into region 1. In the trivial case of constant marginal costs (e=0) this problem can be solved analytically; in the non-trivial cases it has to be solved numerically[2]. Below we will derive the plausible ranges of the model parameters and the parameter combinations for which numerical maximisation is performed. For convenience we will also rescale some of the quantities introduced above. As the basic scale of protected area we choose the initial amount of protected area in region 1, A_{10}:

$$A_i'=A_i/A_{10} \qquad \text{and} \qquad \Delta A_i'=\Delta A_i/A_{10} \qquad (8)$$

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[2] For this we form the first derivative of the benefit-cost ratio, B_{tot}/C_{tot}, with respect to q_1 and set it to zero: $d(B_{tot}/C_{tot})/dq_1=0$. The solution of this equation under the constraints leads to the efficient q_1.

Then eq. (1) writes

$$B(A_i') = \alpha' * (A_i')^z \quad \text{with } \alpha' = \alpha * A_{10}^z \tag{9}$$

Considering eq. (8) in the cost function (5) leads to

$$c_i = c_0 + e' * \Delta A_i' \text{ with } e' = e * A_{10}. \tag{10}$$

We scale costs C_i in units of $c_0 * A_{10}$,

$$C_i' = C/c_0/A_{10}, \tag{11}$$

and rewrite eq. (6) as

$$C_i' = \Delta A_i' + 0.5 * e'/c_0 * (\Delta A_i')^2 \tag{12}$$

We see that, except for a scaling factor, the cost function is only characterised by the ratio $e'/c_0 = e * A_{10}/c_0$. This quantity has a very simple meaning and measures the relative increase of marginal costs, c_i, when the amount of protected area, A_i, is increased by the size of protected area in region 1 (A_{10}):

$$[c_i(A_i+A_{10}) - c_j(A_i)] / c_i(A_i) = [c_0 + e * A_{10} - c_0] / c_0 = e * A_{10} / c_0 \tag{13}$$

This equation immediately allows us to find a plausible upper bound on the ratio e'/c_0, which is 1. Choosing $e'/c_0 = e/c_0 * A_{10} = 1$ means, for instance, that if the amount of protected area in region 1 (A_{10}) is doubled, marginal costs, c_1, will double as well. A stronger increase in marginal costs seems to be very unrealistic. A lower bound for e'/c_0 is set at 0.01, which means that marginal costs increase by 1% when protected area is increased by an amount A_{10}. We consider the following values:

$$e'/c_0 \in \{0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1.0\}$$

The value of c_0, i.e. the scale of the costs, is set to 1, as we are not interested in the absolute values of costs but only in relative changes.

The second important model parameter is the exponent in the benefit function, z (eq. 1). As a plausible lower bound we choose z=0.15 (Fig. 1). The upper bound can be set at a value of 2, because the costs, C_{tot}, never increase faster with area A than in a quadratic manner. If z were greater than 2, then clearly the benefit-cost ratio would increase with area and the efficient allocation of costs would always put everything into region 2 because it has more protected area and the higher benefit-cost ratio. Non-trivial solutions can only be expected for z<2. We consider

$z \in \{0.15, 0.35, 0.65. 0.95, 1.05, 1.35, 1.65, 1.95\}$

It can be seen that in eq. (9) a change in A_{10} is equivalent to multiplying benefits by some positive factor. Such a change does not affect the efficient allocation of costs, C_1 and C_2, and without restriction of generality we can set $A_{10}=1$ in eq. (9). Similarly, the proportionality factor c' can be set to 1, as it, too, does not affect the solution of the allocation problem. To investigate the effect of different amounts of protected area in region 2, we consider two possible values for A_{20}' of 2 and 5, i.e. the amount of protected area in region 2 may be twice or five times as much as that in region 1.

4. Results

For convenience we introduce the quantities

$\Delta A = \Delta A_1 + \Delta A_2$, $\quad \Delta A' = \Delta A/A_{10} = \Delta A_1' + \Delta A_2'$ and

$$q_1 = \Delta A_1'/\Delta A' = \Delta A_1/\Delta A \qquad (14)$$

where ΔA is the total increase in protected area in both regions and q_1 gives the proportion that falls into region 1. For constant marginal costs (e=0), optimisation can be carried out analytically, because here the costs $C_{tot}=c_0 * \Delta A$ are independent of their allocation between the two regions. With some algebra one finds for $z<1$ (eq. 9), i.e. for benefits growing less than proportionally with protected area:

$$q_1 = 1 \qquad \text{for } \Delta A < A_{20} - A_{10}\text{, and}$$
$$q_1 = 0.5 * (1 + (A_{20} - A_{10}))/\Delta A \qquad \text{otherwise} \qquad (15)$$

This means that all the resources are spent in region 1 with the smaller initial amount of protected area ($q_1=1$), as long as the total area increase ΔA remains below $A_{20}-A_{10}$. In general terms, a critical area, Δ_{cr}, exists, such that if $\Delta A<\Delta_{cr}$ all resources ΔA are spent in one region. If ΔA exceeds Δ_{cr} then q_1 decreases hyperbolically until a value of 50% is reached. The interpretation of this result is trivial. Protected area is increased in region 1 until the amount is equal in both regions (then we have $A_1=A_{10}+\Delta A= A_{10}+A_{20}-A_{10}=A_{20}$). From then on any further increase in protected area is allocated equally between both regions.

For $z=1$ (eq. 9) where benefits are proportional to protected area, efficient allocation is achieved by dividing resources equally between the two regions ($q_1=0.5$). For $z>1$ where benefits grow more strongly than proportionally with protected area, all resources ought to be spent in region 2 with the larger initial amount of protected area ($q_1=0$).

This changes when marginal costs increase with protected area ($e>0$) (Figs. 2 and 3). For $z<1$ we still find $q_1=1$ if $\Delta A<\Delta_{cr}$ and $q_1<1$ if $\Delta A>\Delta_{cr}$ (cf. eq. 15), but now Δ_{cr} is smaller than the difference $A_{20}-A_{10}$ and further decreases if marginal costs increase more rapidly (i.e., if e'/c_0 grows). A similar development occurs if the exponent z in the benefit function approaches 1. Then Δ_{cr} decreases as well.

Equivalent but partly opposite results are obtained for $1<z<2$ (Fig. 4). As in the case of $z<1$ ($e>0$), a critical area Δ_{cr} exists and decreases, if marginal costs (e'/c_0) increase more rapidly. However, in contrast to the case of $z<1$, Δ_{cr} *decreases* as z increases. Altogether, the critical area Δ_{cr} decreases, i.e. the efficient allocation becomes more even as the exponent z of the benefit function approaches 1. This is plausible, because at $z=1$ we always obtain $q_1=0.5$, i.e. even allocation, regardless of the cost function.

Although the results for $z<1$ and $z>1$ appear very similar, an important difference can be observed upon closer examination of the q_1 curves. We consider an exponent $z=1.05$ and weakly increasing marginal costs ($e'/c_0=0.01$; solid line in Fig. 5) and find that if there are resources to increase protected area by $\Delta A'=10.5 * A_{10}$, all of them should be allocated to region 2. If there are enough resources to increase the total protected area by $\Delta A'=12 * A_{10}$, then 40% of $\Delta A'$ (i.e. $5 * A_{10}$) should be allocated to region 1 and $7 * A_{10}$ to region 2. Now assume we start from A_{10} and A_{20} and believe there are resources to increase protected area by $10.5 * A_{10}$ (which are all allocated to region 1), but then we realise that there are resources left to protect a further $1.5 * A_{10}$ (leading to a total increase of $12 * A_{10}$). From above we know that $5 * A_{10}$ out of these $12 * A_{10}$ should be in region 1, but we only have $1.5 * A_{10}$ to allocate. The best we can do is to fully allocate it to region 1, but this only gives us a q_1 of $1.5/12=12.5\%$, which is much lower than the 40% required above. Therefore by allocating all of the first $10.5 * A_{10}$ to region 2 we have run into a 'dead end' which means that efficiency can only be achieved by reallocating protected area from region 2 to region 1.

It could be argued that we should consider total costs, C_{tot}, rather than the total increase in protected area, ΔA. However, Fig. 6 shows that total costs increase continuously and strictly monotonously with total protected area. In the case of weakly increasing marginal costs, C_{tot} and ΔA are even proportional. If we plot q_1 versus C_{tot} instead of ΔA, we obtain a curve identical to that in Fig. 5 ($e'/c_0=0.01$).

Fortunately, the problem demonstrated above only occurs if marginal costs increase weakly ($e'/c_0<<1$) and if $z>1$ but close to 1. The reasons are given below. If marginal costs increase more rapidly, the critical area is rather small (e.g., Fig. 5, $e'/c_0 = 0.02$: $\Delta_{cr}=2.5 * A_{10}$). Here the 'dead ends' are much 'shorter' and less protected area has to be reallocated to achieve efficiency. Imagine we have enough resources to increase total protected area by $\Delta A=\Delta_{cr}=2.5 * A_{10}$. Then all of this area should be allocated to region 2. Now assume there are enough resources to protect a further area of size $0.6\Delta_{cr}=1.5 * A_{10}$ (which is similar to the example above). The total area increase then is $\Delta A=1.6\Delta_{cr}=4 * A_{10}$. The question is now where to put the additional $0.2\Delta_{cr}=0.5 * A_{10}$. According to Fig. 5, a proportion of $q_1=0.375$ out of the total $\Delta A=4 * A_{10}$ should be in region 1. If we allocate all of the additional $0.6\Delta_{cr}=1.5 * A_{10}$ to region 1 we reach a ratio of $q_1=1.5/4=37.5\%$, which is exactly what is required. Therefore no reallocation from region 2 to region 1 is necessary.

Now consider the impact of the exponent z on the problem of 'dead ends'. For $z<1$ we could show analytically (eq. 15) that even for constant marginal costs ($e=0$) it is possible to allocate the protected area bit by bit (every amount $\Delta A \leq \Delta_{cr}$ is allocated to region 2 and once $\Delta A \geq \Delta_{cr}$ has been reached, any additional area is allocated evenly between region 1 and region 2). The same must be true for increasing marginal costs, because above we showed that increasing marginal costs reduce the magnitude of Δ_{cr} and the problem of dead ends. Lastly, if $z>>1$, we do observe a dead end problem as in Fig. 5 (solid line), but the corresponding Δ_{cr} are large compared to the initial amounts of protected area (A_{10} and A_{20}). In this case the dead end is reached only after the allocation of a very large amount of resources.

So far we have always assumed that the initial amount of protected area in region 2 is twice that in region 1. The effect of a different ratio can be seen in eq. (15). The larger the difference between the two regions, the larger the critical area below which all resources are allocated to one region.

5. Discussion of model results

The efficient allocation of resources between the two regions depends on the shape of the benefit function and the cost function which are assumed to be identical in both regions. The results are summarised in Table 1 and discussed below. If the benefit function increases less than proportionally with protected area, protected area should mainly be increased in the region that has the smaller initial amount of protected area. Above we have shown that benefit functions of this type may result from the island theory, in which species richness is the goal. It may also be appropriate when the focus is on individual species whose population size is subject to strong fluctuations ($v>1$ in eq. 2).

The situation is reversed when the benefit function increases more than proportionally with protected area, which is the case when the focus is on individual species with medium or weak fluctuations in population size ($v<1$ in eq. 2). Here protected area should mainly be increased in the region where the initial amount of protected area is large. If marginal costs are constant then all resources should be allocated to that region.

If benefits increase more than quadratically with protected area (individual species with weakly fluctuating populations, $v<2/3$), efficient allocation is independent of the cost function (assuming linearly increasing marginal costs). Here all resources should be invested in the region that has the largest initial amount of protected area (see above).

Below we consider benefit functions that increase less than quadratically with protected area ($z<2$ in eq. 1) and increasing marginal costs ($e>0$ in eq. 5). We find that if only a small amount of resources is available, then all resources should be allocated to one region which is determined by the exponent of the benefit function (see above). If the area that can be allocated exceeds some threshold Δ_{cr}, both regions should receive some proportion of the resources. The critical area Δ_{cr} gradually decreases if:

(a) the benefit function becomes proportional to protected area

(b) marginal costs increase more rapidly, or

(c) the initial amounts of protected areas in the two regions become similar.

Efficient allocation becomes more even if the critical area Δ_{cr} decreases or the amount of resources available to support conservation increases. These proportions become equal if the area that can be allocated becomes very large.

If marginal costs only increase weakly and if the benefit function increases slightly more than proportionally with protected area (z close to but greater than 1 in eq. (1)), there is a risk of running into a 'dead end'. This means that only a small change in the amount of area that can be allocated leads to a very rapid change in the efficient allocation ratio. If the total area that can be allocated is below the threshold Δ_{cr}, all area should be allocated to the region with the larger initial amount of protected area (see above), but as soon as slightly, say $\Delta_{cr}+\varepsilon$, units of area can be protected, the even allocation (of the total area $\Delta_{cr}+\varepsilon$) suddenly becomes efficient. This means that the piece-by-piece increase of protected area where the allocation of each bit is decided one after the other, may be inefficient compared to the situation where it is known exactly how much area can be allocated in total and allocation is based on this information. In other words, marginal optimisation may lead to an inefficient solution compared to a global one.

Our results can be regarded as an extension from what is well-known from ecological theory (e.g., den Boer 1968; Drechsler and Wissel 1998). If environmental variability is weak, the viability of a population is maximised if it is distributed over a single habitat patch. If environmental variability becomes strong, it may be more advantageous if the population is distributed over several habitat patches. This is the reason behind our finding that in the case of weak environmental variability, it is best to increase the larger protected area to obtain one large habitat patch while in the case of strong environmental variability it is best to increase the smaller protected area to obtain two habitat patches of medium size. This result, however, only applies if marginal costs are more or less constant. If we have increasing marginal costs, we find that the allocation of resources becomes less uneven between the two regions because uneven allocations are comparatively costly.

So far, we have assumed that benefits B are an adequate measure of society's utility U with respect to biodiversity (U~B). While in general this may be an adequate measure, we feel that it might be insufficient in the case of weak environmental variability, $v<<1$. Here, population lifetime increases very strongly with habitat size. A relatively small expansion may raise it to tens of thousands of years or more. Species with these lifetimes are regarded as 'safe' (IUCN, 1994). Given the aim of species survival, it might be argued that there is not much gain in making a safe species safer. In such a case expected lifetime (benefits) will still increase with habitat expansion, but utility will not. Therefore at small areas A where B is small we still obtain U~B, but at larger areas, U saturates at some level, leading to a sigmoid ('s-shaped') function. To demonstrate the behaviour of a sigmoid utility function, we choose a simple mathematical form (Fig. 7):

$$U = U_{max} * A^2 / (A^2+h^2) \qquad (16)$$

where U_{max} is the maximum utility achievable and h is some constant called the half saturation area, because at A=h half the saturation utility U_{max} is reached.

Most of the results for the sigmoid curve have already been captured above. Three cases can be distinguished in Fig. 7. Firstly, the initial protected area in both regions may be small compared to the half-saturation area h. Then we are in a situation in which benefits increase less than proportionally with protected area and the results are similar to those obtained for exponent $z<1$ above. Secondly, both initial areas may be small compared to the half-saturation area h. Then we obtain results similar to the case $z>1$, as long as ΔA is not too large. If it becomes very large ($\Delta A >> A_{10}, A_{20}$) we run into the saturating part of the benefit function. We found that this may result in rapid changes of the efficient allocation ratio (q_1), which may be much stronger than in Fig. 5 (solid line). This can be very extreme when we consider the third case possible in Fig. 7, namely where the half-saturation area h is close to the initial amount of protected area in region 2 (A_{20}). Here two critical areas can be observed, Δ_{c1} and Δ_{c2}. If $\Delta A < \Delta_{c1}$, all the area should be allocated to region 2. If $\Delta_{c1} < \Delta A < \Delta_{c2}$, all the area should be allocated to region 1. For larger ΔA the allocation becomes even, similar to Figs. 2 or 3. The likelihood of rapid changes of the efficient allocation ratio diminishes as marginal costs increase more rapidly, regardless of the underlying utility function. Therefore increasing marginal costs reduce the risk of 'dead ends' and the necessity of reallocation.

6. Spatial differentiation in existing programmes

We will now examine existing programmes to subsidise farming practices for conservational purposes with respect to spatial differentiation. We will show that spatial differentiation already exists and that existing types can be used to implement the policy recommendations of our model. The programmes analysed below are the implementation of EU Regulation 2078/92 in the German Federal States (Plankl, 1996). In all German states several programmes or measures exist. Each of them falls into one of the six categories distinguished in Table 2.[3]

Given the lack of information on the actual cost and benefit functions we are unable to evaluate whether the spatial differentiation in the individual programmes is efficient. However, we can analyse whether spatial differentiation would allow for the efficient allocation of resources in terms of our model results.

Some states only target their programmes at nature reserves or areas of similar value for biodiversity. These can be seen as representatives of region 2 in our model, as here the initial amount of protected area is higher than in region 1. Within the framework of our model assumptions, such a policy is efficient if marginal costs are more or less constant and the policy is targeted at individual species with medium or weak fluctuations in population size. Two states have employed the possibility to allocate more funds to regions of conservational

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[3] We did not consider demonstration projects, as their orientation to a certain area is caused by their preliminary

interest while not completely denying subsidies to areas with low nature value. These states pay higher subsidies if a measure is carried out in a nature protection area. Given the framework of our analysis this is an efficient policy in all cases in which our model suggests that some resources should be invested in both areas, but the majority of resources should be allocated to region 2 (increasing marginal costs and weak or medium fluctuations in population size). Only two states have a programme targeted at areas of low nature value, which is region 1 in our model. This represents an efficient allocation if the policy aim is to increase species richness or to increase the viability of individual populations subject to strong fluctuations.

Another possibility of spatial allocation chosen in some programs is orientation towards districts. This can be an adequate policy if the area of interest roughly corresponds with the districts. For example, there is a programme to protect common hamsters in Saxony-Anhalt which is concentrated on a few districts. These districts roughly represent the distribution of the common hamster (*Cricetus cricetus*) in this region. Some states have left the allocation of subsidies to nature protection agencies. In the context of the spatial allocation problem this can be an advantage where protected areas or districts do not spatially correspond to the ecologically relevant units. The nature protection agency is then fully empowered to spatially allocate subsidies in line with society's priorities.

While a spatial differentiation exists in some programmes, it is absent in the majority. Given the assumptions of our model, these programmes lead to a spatially even allocation of resources, which may be advantageous in particular situations, as shown above. However, we should bear in mind that most of the programmes established in the context of EU Regulation 2078/92 are not primarily targeted at biodiversity. Other aims include water protection from pesticides and nitrates as well as income support for farmers. These aims may conflict with the aim of efficient allocation with respect to biodiversity and might have been given more weight by the policy maker.

Our model has shown that the rapid reallocation of conservation efforts from one area to another may be necessary if we have run into what we call a 'dead end'. The reallocation of efforts is possible with all the programmes under review as they have a limited time horizon of mostly five years. However, reallocation might lead to additional costs, which have been

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character.

neglected in our model. In order to comply with the programmes, farmers might have to learn certain techniques and invest in certain machinery which is perhaps difficult to sell. This means that sunk costs exist for farmers. If a nature protection agency often changes its spatial orientation and farmers do not have the security that their investments can be used over their expected operational lives, they might add a risk premium to their costs. This implies that a given amount of subsidies (C_{tot}) leads to a smaller additional area available for conservational purposes (ΔA). Such problems are an argument for long-term conservation plans.

7. Conclusions and policy recommendations

With the aid of a spatial allocation model, we have developed guidelines for the efficient allocation of biodiversity-enhancing farming practices. Our model has shown that this allocation depends on the shape of the cost functions of farmers and the utility function of the policy maker. Pure economic studies usually put little effort on the establishment of realistic ecological benefit functions, whereas most ecological studies ignore the relevance of the cost function. We could show that both components are essential in the analysis of the spatial allocation of resources and conclude that interdisciplinary studies which combine ecological and economic theory open new perspectives. The present paper is a step into this direction.

Analysis of the spatial dimension of the implementation of EU Regulation 2078/92 in Germany has demonstrated that spatial differentiation as suggested by our model is feasible. However, when putting our results into practice, some additional aspects have to be taken into account. When our model suggests the reallocation of subsidies, it must be considered that farmers may add a risk premium to their costs. Taking this into account, reallocation might often be less attractive than proposed by our model.

Another problem arises if several goals are to be considered. If the policy aim is to protect not only one but several selected species, conflict may occur if their ecological characteristics differ. In addition, the policy maker might have other aims than enhancing biodiversity. These aims might sometimes be conflicting, leading to a policy differing from one which only pursues conservational aims. To consider such problems, multi-criteria analysis (e.g., Stewart 1991) is needed.

Although our benefit functions have a clear ecological basis, they are rather general and cannot take into account all the peculiarities of a real ecosystem. However, without abstraction, the development of general guidelines is not possible. We have sought a compromise between the generality of the statements and their applicability to specific situations.

Acknowledgements

We would like to thank Karin Frank, Volker Grimm, Helga Horsch, Irene Ring, Josef Settele, Birgit Soete and Christian Wissel for their helpful comments to the manuscript.

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Annex 1: Tables and Figures

Table 1: Summary of the model results. The proportion q_1 of resources that are allocated to region 1 in dependence of the increase in marginal costs (e'/c_0), the exponent z of the benefit function and the difference in the initial amount of protected area between region 2 and region 1, $A_{20}-A_{10}>0$. The critical area Δ_{cr} is defined such that if the budget allows to increase protected area only by an amount $\Delta A< \Delta_{cr}$, then all resources should be fully allocated to one region.

	$z \geq 2$	$1<z<2$ but not $z \approx 1$	$z>1$, $z \approx 1$	$z=1$	$z<1$
results valid for all e'/c_0	$q_1=0$: spend all resources in region 2	$q_1<0.5$: spend most resources in region 2	$q_1<0.5$: spend most resources in region 2	-	$q_1>0.5$: spend most resources in region 2
results valid only for $e'/c_0=0$	see above	$q_1=0$: spend all resources in region 2	$q_1=0$: spend all resources in region 2	any allocation q_1 is efficient	$\Delta_{cr} = A_{20}-A_{10}$
results valid only for $0<e'/c_0<<1$	see above	$\Delta_{cr} >> A_{20}-A_{10}$: spent practically all resources in region 2	Δ_{cr} is of the order of magnitude of $A_{20}-A_{10}$; existence of 'dead ends'	$q_1=0.5$: even allocation	$\Delta_{cr} < A_{20}-A_{10}$: more even allocation
results valid only for $e'/c_0 \approx 1$	see above	Δ_{cr} decreased compared to $e'/c_0<<1$: more even allocation of resources	Δ_{cr} is small: 'dead ends' are short; more even allocation	$q_1=0.5$: even allocation	Δ_{cr} decreased compared to $e'/c_0<<1$: more even allocation

Table 2: Spatial differentiation in programmes to subsidise farming practices with a positive impact on biodiversity.

German State	Programmes or measures exist only for protected areas, areas close to them or areas with high nature value	Programmes or measures exist where subsidies vary depending on the value of the area	Programmes or measures exist only for areas with low nature value	Programmes or measures exist that are geared towards certain districts	Programmes or measures exist where the nature protection agency freely allocates subsidies	Programmes or measures exist without spatial differentiation
Schleswig-Holstein	No	yes	no	no	No	yes
Hamburg	No	no	no	no	No	yes
Lower Saxony	Yes	no	yes	yes	No	yes
Bremen	Yes	no	yes	yes	No	yes
North Rhine-Westphalia	Yes	no	no	no	Yes	Yes
Hesse	No	no	no	no	Yes	Yes
Rhineland-Palatinate	No	no	no	yes	Yes	Yes
Baden-Württemberg	Yes	no	no	no	No	Yes
Bavaria	No	yes	no	no	No	Yes
Saarland	Yes	no	no	no	no	Yes
Berlin	No	no	no	no	no	Yes
Brandenburg	Yes	no	no	no	yes	Yes
Mecklenburg-Western Pomerania	Yes	no	no	no	no	Yes
Saxony	Yes	yes	no	yes	no	Yes
Saxony-Anhalt	Yes	no	no	yes	no	Yes
Thuringia	No	no	no	no	No	Yes

Figures

Fig. 1: Benefit functions $B \propto A^z$ (solid lines) with z=0.15, 0.65, 0.95, 1.35, 1.95 (from bottom to top). Dashed line: $B \propto \ln(A)$ (cf. eq. 2).

Fig. 2: Proportion of area that should be allocated to region 1 as a function of total increase in protected area. Total area increase is scaled in units of the initial amount of protected area in region 1 (A_{10}, see text). The five curves correspond to different marginal costs. From right to left: e'/c0=0.01, 0.03, 0.1, 0.3, 1.0. The benefit function is given in eq. (1) with z=0.15. The initial amount of protected area in region 2 is $A_{20}=2A_{10}$.

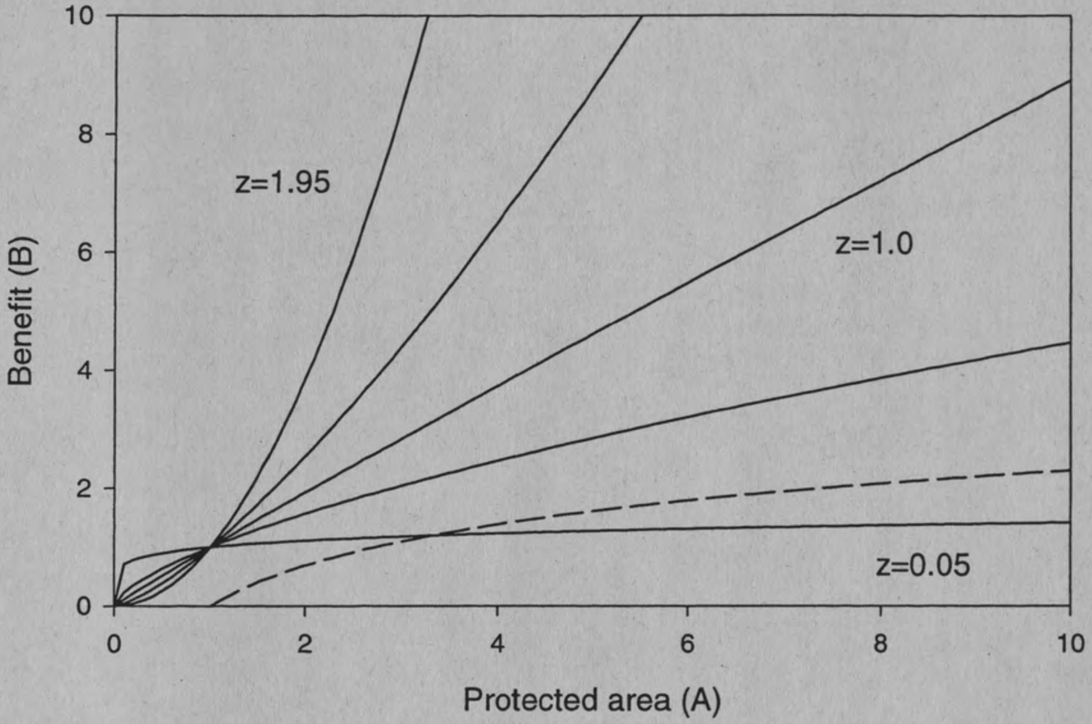
Fig. 3: See Fig. 2, but with z=0.95.

Fig. 4: See Fig.2, but with z=1.35 and $e'/c_0=0.3$ and 1.0 (from right to left).

Fig. 5: See Fig. 2 but with z=1.05.

Fig. 6: Total costs versus total increase of protected area. Model parameters as in Fig. 5. The curves correspond to different marginal costs (from bottom to top: e'/c0=0.01, 0.03, 0.1, 0.3, 1.0). Allocation is assumed to be efficient, i.e. given by Fig. 6.

Fig. 7: Sigmoid benefit function (eq. 16) with half-saturation area h=3. Benefits are scaled to their maximum value, B_{max}.



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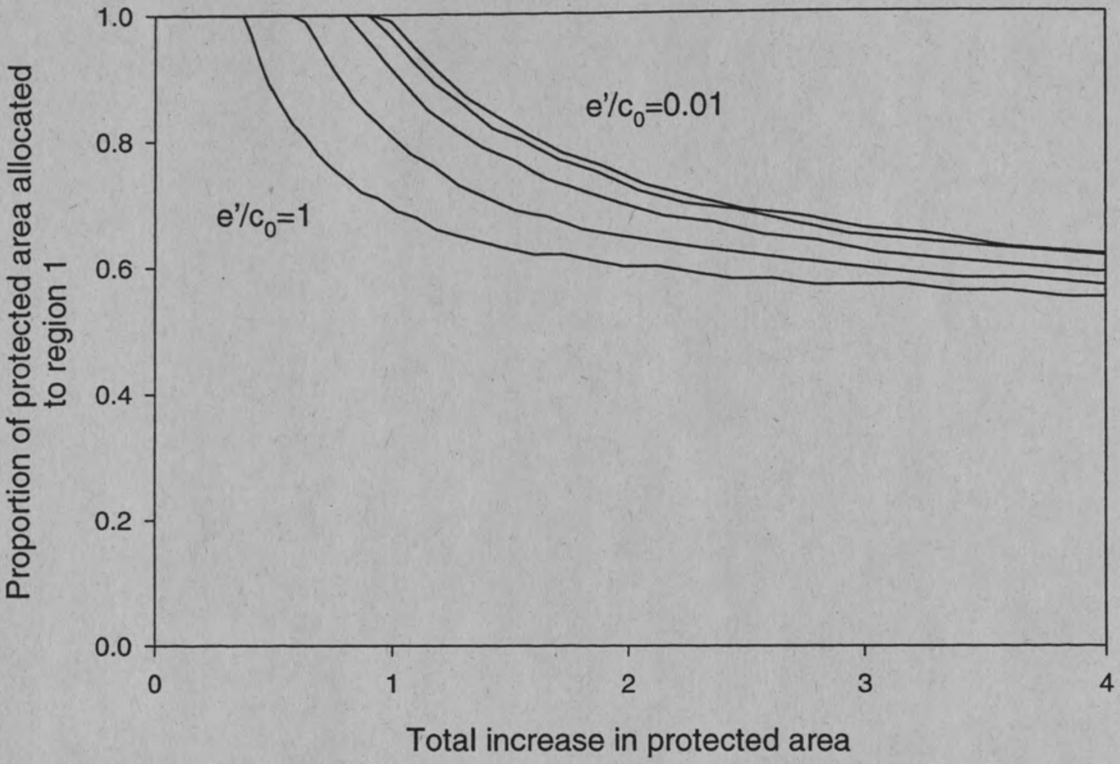

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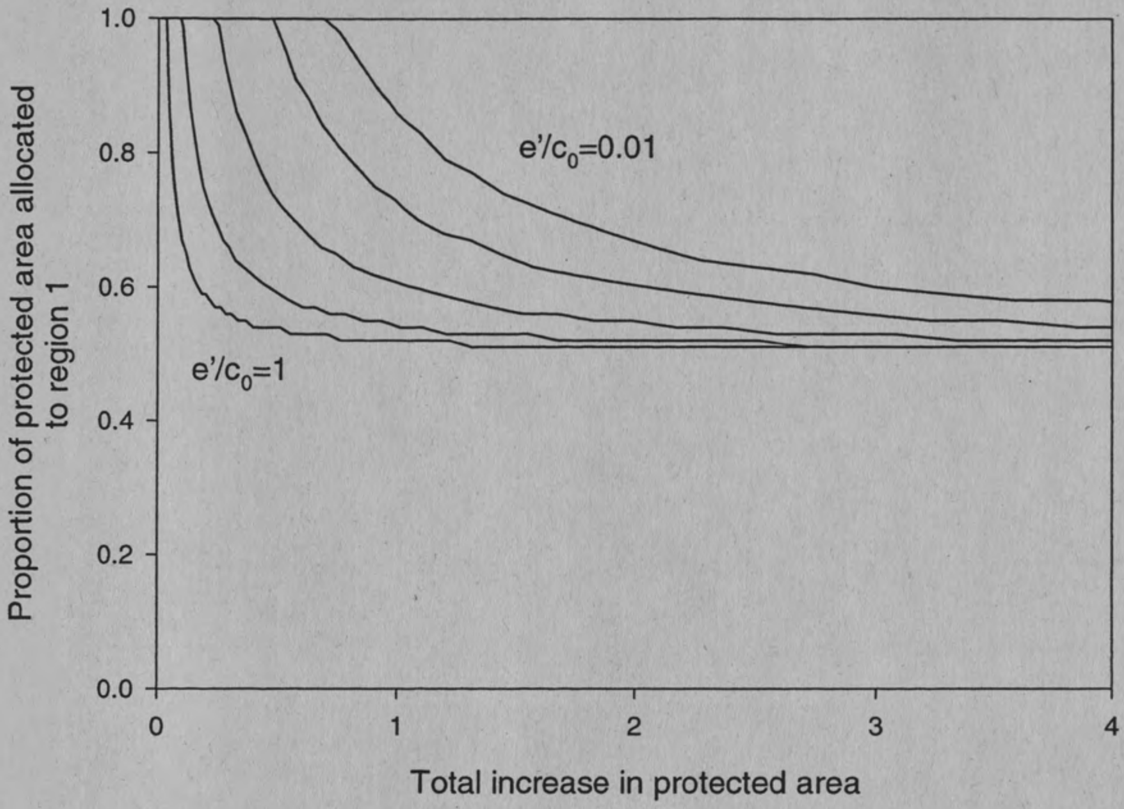


Fig. 3: See Fig. 2, but with z=0.95.

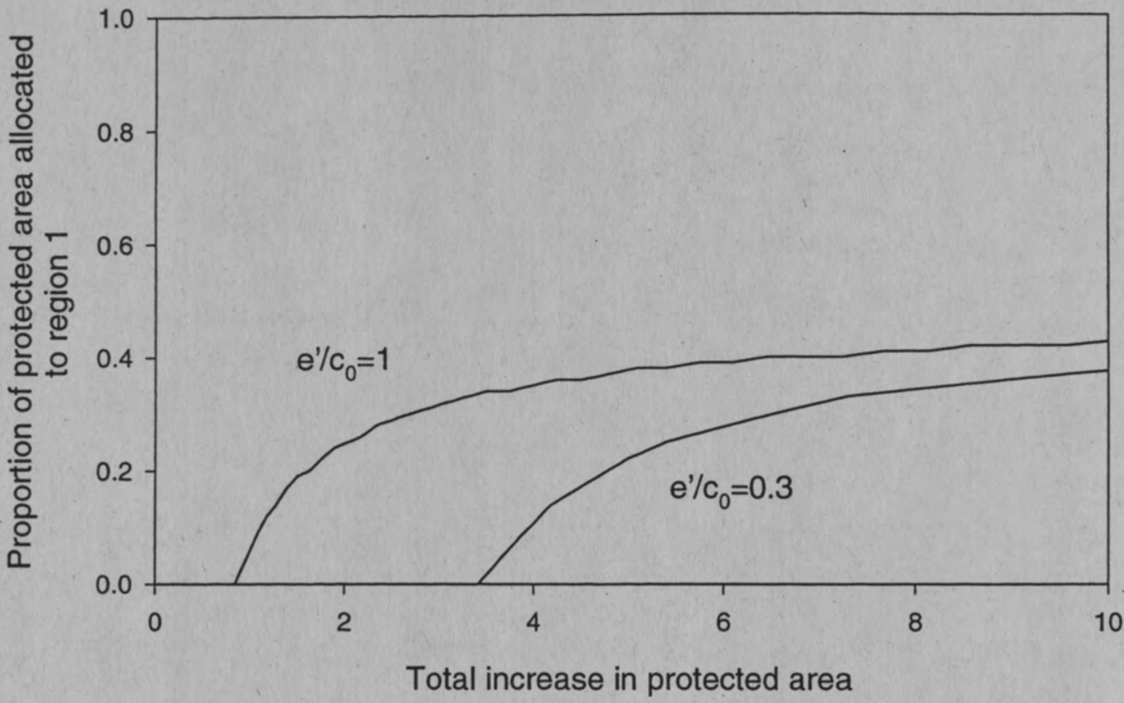


Fig. 4: See Fig.2 but with z=1.35 and e'/c_0=0.3 and 1.0 (from right to left).

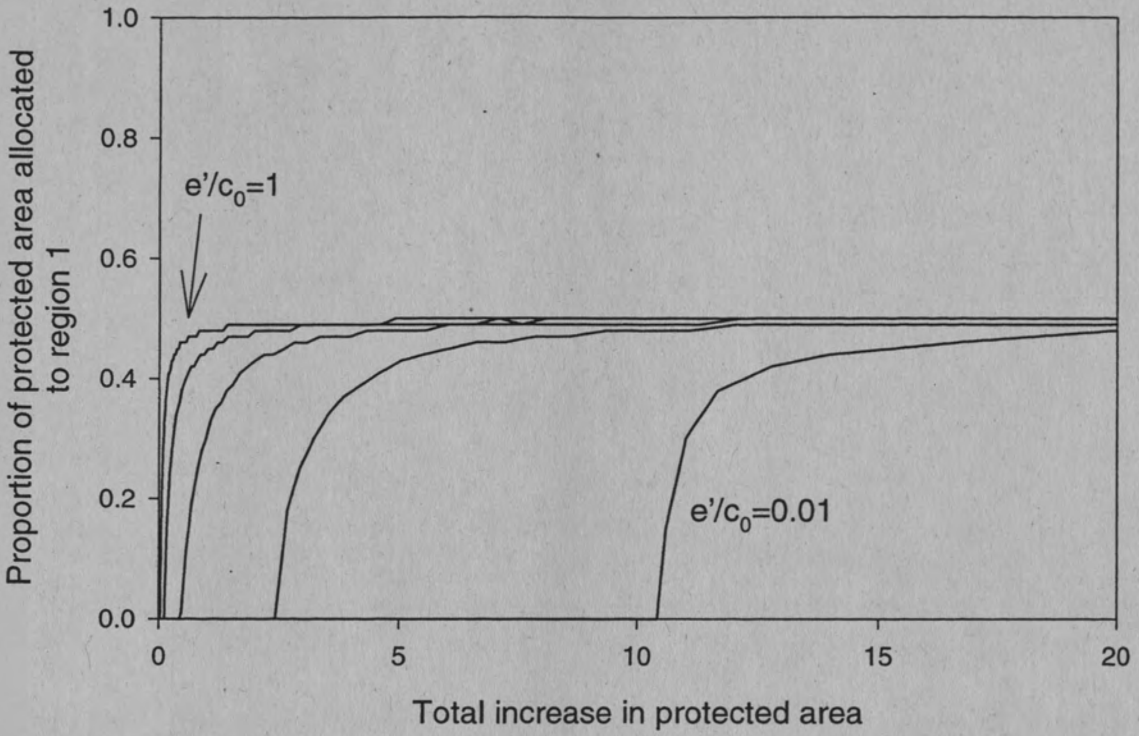
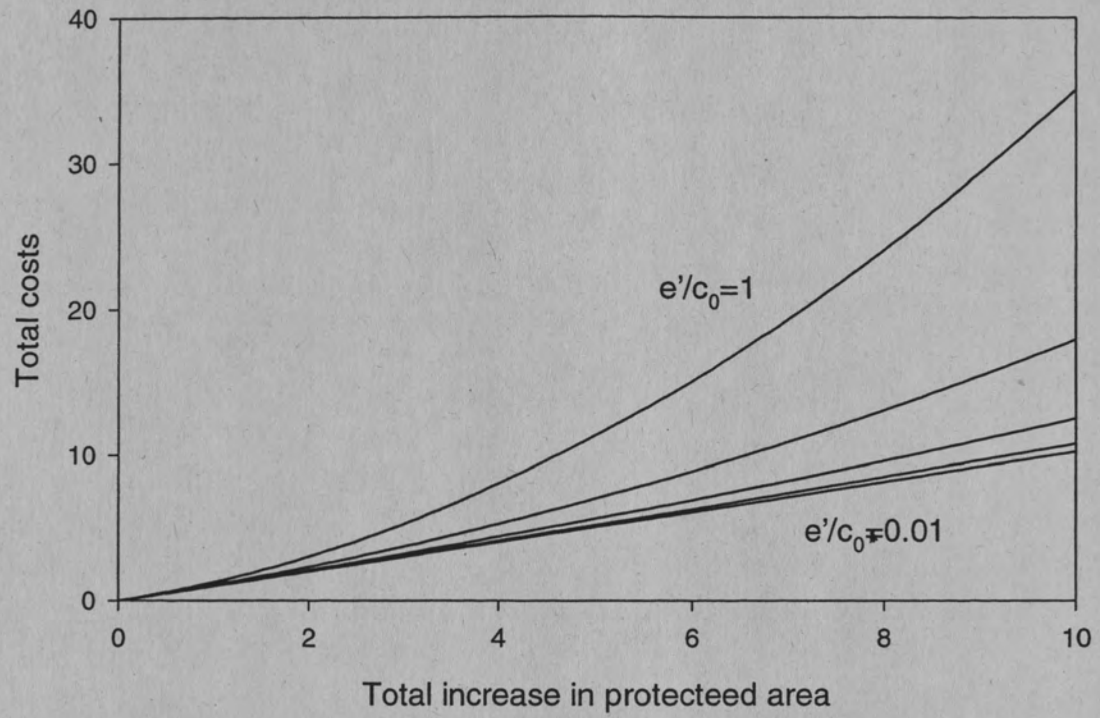


Fig. 5: See Fig. 2 but with z=1.05.



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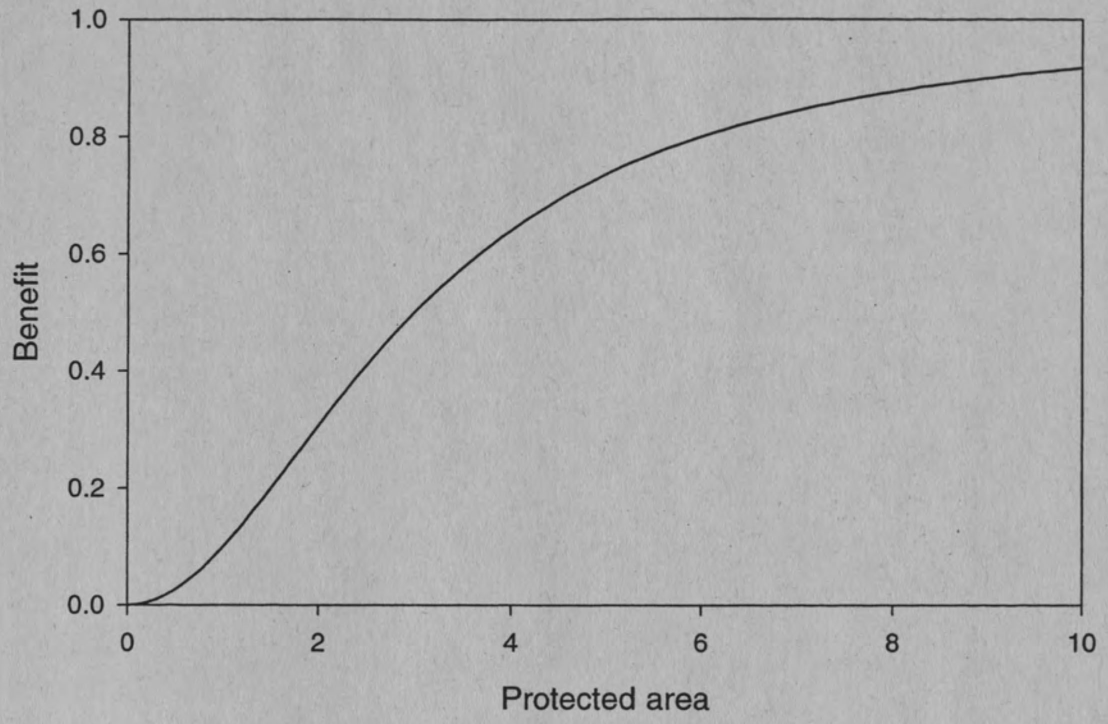

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