Performance differences and trade-offs in the provision of ecosystem goods and services

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Abstract

This paper approaches valuation of biodiversity and ecosystem services from a supply perspective utilizing the concept of trade-offs or opportunity costs. A new method is presented to provide spatial information on trade-offs between biodiversity and marketed and non-marketed ecosystem services at the spatial scale at which they are generated. With this method we are able to (a) assess regional performance differences in terms of the joint generation of biodiversity and ecosystem services in a region, (b) explain differences in regional performance by showing the importance of the conditions of the given environment, and to (c) estimate marginal rates of transformation or each region included in the analysis, which reflect the trade-offs between biodiversity and ecosystem services.

The method is based on a two-stage frontier approach. In the first stage, a non-parametric robust estimator is used to estimate the efficient frontier and determine relative performance with which regions generate biodiversity, ecosystem services and income. In the second stage, the estimated nonparametric frontier is approximated with a flexible translog production function such that opportunity costs can be derived.

The two-stage approach is illustrated with synthetic data for 1166 grid cells in 18 countries in middle and eastern Europe generated by the integrated assessment model IMAGE and biodiversity model GLOBIO. Based on the analysis, regional performance is evaluated and opportunity costs for biodiversity and ecosystem services and their dependence on income are assessed. It is observed that opportunity costs differ substantially between regions and that more developed countries generally combine ecosystem services and biodiversity in a more efficient way. In addition, carbon opportunity costs decrease with increasing carbon sequestration levels, exhibiting economies of scale characteristics. On the other hand, opportunity costs of biodiversity generally increase with increasing biodiversity, showing that reasonable levels of provisioning services and biodiversity can be combined.

Keywords: opportunity costs, ecosystem services, biodiversity, non-separability, non-parametric estimation, trade-offs.

JEL-Codes: C14, D61, O13, Q51, Q57.

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1. Introduction

Worldwide, biodiversity levels decline and ecosystem degrade (Millennium Ecosystem Assessment 2005; PBL 2010; Secretariat of the Convention on Biological Diversity 2010). Understanding the economic value of nature and the services it provides to humans has become increasingly important for local, national and global policy. [1] However, problems arise in that it is difficult to obtain meaningful values for goods and services which have no formal market, or are characteristically intangible. How to assess these values and at what aggregation level to properly evaluate in an informative way the ecological and economic effects of different land use decisions?

Trade-offs between the multitude of ecological and economic effects of land use decisions can be judged from a demand and supply side perspective. The larger part of the literature on environmental policy analysis adopts a demand side perspective in which environmental valuation methods are used to assess how people judge changes in biodiversity and ecosystem services (see e.g. Naeem et al. 2009; TEEB 2010). This judgment is reflected by estimates of the marginal rate of substitution which shows how consumers value trade-offs between ecological and economic changes. The use of these methods, however, has a number of backdrops. They do not always properly include interactions between ecosystem goods and services and the economic system (Montgomery et al. 1999; Batabyal et al. 2003) and face the problem that for unfamiliar goods and services preferences may be unstable (Dietz 2000; Plott and Zeiler 2005; Bateman et al. 2008; Bateman et al. 2011), for example, due to anchoring and framing effects (Ariely et al. 2003). In addition, the valuation methods often risk to double count the benefits from several ecosystem services (Fisher et al. 2008). These issues are particularly germane to cases involving supporting services which are of concern to policy makers but have no direct consumer appeal due to their unfamiliarity (Johnston and Russell 2011). As a result it often is unclear whether the estimates reflect actual values, and therefore whether the marginal rates of substitution truly reflect the way consumers value trade-offs. For those reasons values as estimated through demand side analysis remain controversial and difficult to serve as a sound basis for making decisions.

On the other hand, from a supply side perspective, integrated assessment studies show the effects of land use choices (Millennium Ecosystem Assessment 2005). Integrated assessment studies properly show the multitude of benefits provided by ecosystems in quantitative terms as well as the interactions and dependencies between the different ecosystem functions and services. A disadvantage is that these studies are often too aggregated in the spatial dimension or restricted to specific services or species to be sufficiently informative for judging trade-offs between ecosystem services and biodiversity or for judging overall performance of regions. They are, therefore, of limited informational value for direct policy decisions on changes in land use. Hence, there is a clear need for new methods which properly consider the ecological complexities and interactions and which show the inevitable trade-offs of land use changes at appropriate spatial scales (Polasky and Segerson 2009; McShane et al. 2011).

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[1] In the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005) *ecosystem goods and services* are defined as the benefits humans obtain from ecosystems. Usually four categories of ecosystem services are distinguished (see also Daily 1997): 1. provisioning services, e.g. food, wood, water and fiber, fuel;2. regulating services, e.g. climate regulation, flood regulation, water purification, disease regulation, pollination; 3. cultural services, e.g. aesthetic, spiritual, educational, recreational; and 4. supporting services, e.g. nutrient cycling, soil formation, primary production.

Against this background, the aim of this paper is to introduce a new, operational, type of valuation approach that starts from the supply side. This method traces out production frontiers showing the combinations of ecosystem services and biodiversity that can be generated in a given area. They enable the assessment of marginal rates of transformation of biodiversity and ecosystem services over a range of levels of supply of these goods at the spatial scale at which they are generated. The resulting trade-offs or opportunity costs - the value of the foregone alternative – reflect the (economic) implication of the biophysical and ecological effects of land use changes. They derive their economic meaning from the scarcity of the underlying resources and the jointness in the generation of ecosystem services. Thus the trade-offs reflect the underlying relationship between priced and non-priced ecosystem services and enable ecosystem service synergies to be covered without the risk of double counting. As the trade-offs are given in monetary terms, they provide particularly useful information for evaluating the economic consequences of land use changes. In addition, the method allows for an assessment of regional performance differences in terms of the effect land use decisions have on the joint generation of biodiversity and ecosystem services in a region. Our purpose is to assess the regions being more capable of producing various ecosystem services or, in other words, the Pareto-dominant regions. Moreover, we explain differences in regional performance by assessing the extent to which the operational environment, which is not under the control of the decision makers at least in the short run, affects performance. In addition we test whether regional performance exhibits an environmental Kuznets-type relationship, such that performance declines for increasing income levels until a threshold income level after which it starts to improve. The method developed in this paper is illustrated for a case study of eighteen countries in middle and eastern Europe and focusses on the generation of biodiversity and three ecosystem services viz provisioning services (agricultural income), cultural services and carbon sequestration with a spatial resolution of 50x50 km^2.

This supply side opportunity cost perspective developed in this paper is especially suited where current preference setting is ill-informed or lacking but where future generations are under consideration when decisions need to be made as is the situation with biodiversity and ecosystem services. The results provide relevant spatial trade-off information which is essential for supporting land use decisions by national and regional policy makers. More specifically, results from this paper are useful for the following four purposes. First, the results show national policy makers and multilateral organizations in which regions it may be cost-effective to further promote e.g. biodiversity conservation or agricultural production. Depending on the position of a particular area on the production frontier, it can be more cost-effective to specialize or to promote the joint generation of a bundle of ecosystem services. These insights support decisions where to start when intervening in land use to cost-effectively develop particular ecosystem services or where not to intervene to avoid excessive opportunity costs. Secondly, at lower spatial scales, the results show what opportunity costs a land use change will engender. With this information, national or lower level decision makers can then address the central question whether citizens are willing to bear these consequences of proposed land use changes. In other words, the trade-off information can be used to sharpen preferences, which in turn would allow for valuation studies to be able to properly evaluate preferences. Thirdly, for setting up systems of ecosystem accounting, a topic which recently gained renewed interest from several organizations and governments, our monetary estimates of opportunity costs of ecosystem services provide insight into the value of annual changes in ecosystem services provisioning in terms of foregone agricultural income. Using this, value changes for different regions and over several years can be compared. Finally, the results show that there is a lot of heterogeneity in the trade-offs between ecosystem services across different countries and areas. Thus, they show indirectly that the use of (benefit) transfer methods for evaluating marginal/opportunity costs of changes in ecosystem services, methods which are regularly applied in demand side valuation exercises and project appraisals, might be misleading, at least if the external factors are not controlled for.

This paper sits between ecological studies, which spatially evaluate trends in ecosystem services, and valuation studies, which search for how peoples' preferences can be translated into monetary values. This new perspective adds an extra dimension to ecological analyses by framing ecological research in economic terms. Moreover, it generates trade-off information which is essential but often missing in valuation studies. By combining economic and ecological insights and concepts, it therefore fills an important gap in the growing number of policy analyses searching for more efficient land use patterns. Methods for deriving this type of information are discussed in only a limited number of studies (Montgomery, Pollak et al. 1999; see e.g. Ferraro 2004; Naidoo et al. 2006; Polasky et al. 2008; Bostian and Herlihy 2010; Egoh et al. 2010; Macpherson et al. 2010). Closest to our approach is the study by Polasky et al. (2008). Where they adopt a bio-economic model to derive a two-dimensional efficiency frontier, however, we use parametric and non-parametric estimation techniques to estimate a multidimensional frontier. The multidimensional approach allows for the analysis of interdependencies between different services which may be missed if only two variables are investigated. The method adopted in this paper is derived from Florens and Simar (2005). Other recent examples which empirically analyzed the trade-offs between multiple environmental and economic indicators and inefficiency using parametric and non-parametric frontier methods include Bosetti and Buchner (2009) for an evaluation of climate scenario's, Ferraro (2004) for an analysis of the allocation of conservation funds across a spatially heterogeneous landscape, Hof et al. (2004), Bellenger and Herlihy (2010) and Macpherson et al. (2010) for an evaluation of environmental performance. Moreover, Cherchye (2001) and Cherchye et al. (2008) use frontier methods to derive aggregate indicators for macro-economic performance and human development. Similar methods are also applied in the energy and water sector for comparing efficiency of firms in a regulated market (see e.g. Thanassoulis 2000; Zhou et al. 2008; De Witte and Dijkgraaf 2010) or for eco-efficiency analysis where firms produce next to a number of desirable also a number of undesirable outputs like greenhouse gas emissions and waste (see e.g. Färe et al. 2007; Kortelainen and Kuosmanen 2007). Most studies using frontier methods especially focus on why particular regions or firms are inefficient. A novel feature of our approach is the focus on the marginal contribution of each indicator to performance and the way this trade-off information can be used in policy assessments (see e.g. Kuosmanen and Kortelainen 2007). Another feature of the method proposed in this paper is that it requires no prior assumptions about the functional form of the frontier, a criticism given to many parametric frontier methods (Florens and Simar 2005), and that no assumptions are required about the convexity of the frontier. This makes it particularly useful for testing whether the relationships between the ecosystem services under study are characterized by non-convexities, a feature of many ecosystems but an issue often ignored in economic studies (Chavas 2009; Brown et al. 2011) even though acknowledged by Dasgupta and Mahler (2003) to be a feature having important consequences for the functioning of the price mechanism. Assuming convexity relations where they do not exist may result in misinterpretations and false policy recommendations.

The remainder of this paper is set up as follows. In the next section, the theoretical framework is discussed, while section 3 presents our empirical approach. Section 4 discusses the data. The results of the analysis are presented in Section 5. Finally, a discussion on the method and results is given in Section 6.

2. Theoretical model

When various ecosystem services are derived from the same ecosystem, changes in their levels are physically connected through the basic biophysical function of the ecosystem. Different services are 'bundled' together and are thus affected negatively or positively, but often in a non-monotonous way, as one service such as food or biofuel production is increased or decreased. For that reason, an assessment of the trade-offs between biodiversity and ecosystem services should be based on specifications of the production structure and the production relationships involved. This includes the possibilities of input substitution between for example regulating services and capital inputs (e.g. biological or chemical pest control) and of changes in the proportion of biodiversity and ecosystem services generated. This also implies that specifications of the ecosystem-economic interactions should have the capability of integrating the biological and physical processes in a manner consistent with ecological insights (Wossink et al. 2001; Wossink and Swinton 2007). This means that the non-linear and non-convex relationships which characterize ecological systems should be properly considered (Chavas 2009; Brown, Patterson et al. 2011). Besides, in order to include effects of spatial differences in the biotic and abiotic environment, the analysis should be performed at a disaggregated level and be spatially explicit. Thus, only with an integrated ecological-economic framework the non-separability of the non-priced ecosystem services, the underlying supporting services and the ecosystem-economic interactions can be evaluated. A partial framework would not properly show the trade-offs, and synergies, between the different elements of the system.

Introducing multiple outputs raises interesting theoretical issues that have empirical implications. The relationship among outputs and in particular the degree in which these share the same inputs dictates the model to be used. As the different outputs are produced simultaneously and share several inputs, a simultaneous equation system or single equation production function with multiple outputs and inputs should be used.

The focus in this study is with the effect of land use choices on the generation of biodiversity and ecosystem services which can be divided into conventional marketed outputs, y, and non-marketed outputs, q, which jointly affect welfare.[2] This not only refers to the immediate effect on e.g. food production and recreational possibilities, but also the longer term effects on e.g. climate regulation. Variables y and q cover the different ecosystem services that can be distinguished in a given area which provide direct benefits or which serve as a proxy for longer term benefits. Variable y includes provisioning services and marketed cultural services (e.g. tourism). Variable q is defined as non-marketed cultural services and the regulating and supporting services which

[2] Next to the effect of land use choices, it would be interesting to analyze as well the effect of changes in inputs like labor, capital and intermediate ecosystem services. This would enable an analysis of the substitution between intermediate ecosystem services (especially regulating and supporting services) and capital inputs. Because of a lack of data on especially labor and capital inputs, these inputs are not considered here.

maintain benefits in the longer term. This includes e.g. carbon sequestration. Also biodiversity is included in *q*. It serves as a proxy for several intermediate services which are necessary for maintaining other services, like nutrient cycling, water purification and pest control. Several of the non-market services *q* are common pool resources. They are non-excludable and offer rival benefits. Non-excludability means that there is easy access to their use at zero marginal costs for the user. As a result, their marginal values are not properly revealed by price signals due to which supply and demand may not be Pareto optimal (Romstad 2008). The way land use choices affect marketed and non-marketed outputs is dependent upon a number of factors exogenous to the decision makers, like geographical location, soil type and regional income (which depends on population density and economic structure). These are covered by conditional variable *z*.

Consider a transformation function, $F(y,q|x,z)$, that describes how in a specific region marketed output *y* and non-marketed ecosystem services *q* are jointly produced using inputs *x* (including land) in a given environment described by the vector *z*. The transformation function can also be denoted as $x=F(y,q|z)$ which indicates the amount of the input bundle that will be used as a results of varying the quantity of *y* and *q*. The basic assumption underlying a transformation function is that the quantity of the inputs does not change.

Joint products *y* and *q* do not necessarily have to be produced in fixed proportions. Rather, this arises from land use choices made by humans – which crops to grow, cultivate large acreages or keep a landscape with scattered agricultural plots, deforest an area or keep it covered with trees, etc.? These choices can change the type, magnitude and relative mix of the services *q* and output *y* in the short and the longer term. Goods and services, provided through the market or not, are wanted because of the utilities they provide. The economic problem then is that of the allocation of scarce resources under the presumption that the objective is to get the greatest social benefit from these resources. Thus the region is viewed as a social planner, deciding upon land use so that it produces the combination of outputs *q* and *y* that maximizes social welfare denoted by regional utility *U* constrained by the transformation function and given input bundle x^0 – see also Figure 1.

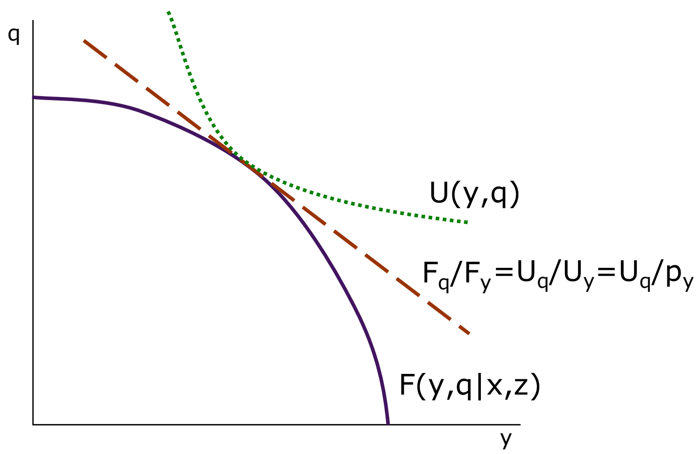

Figure 1: Representation of the social welfare problem for a situation with two outputs.

Summarizing the aspects above and omitting the time aspect, the joint utility maximizing model for a specific region with characteristics *z*, can be written as:

$$\underset{y,q}{Max}\left\{U(y,q) \mid F(y,q;z) \leq x^0, y,q \geq 0\right\} \tag{1}$$

Assuming a perfect market situation and the existence of an interior solution, the first order conditions for an optimal solution are given by:

$$U_y - \mu F_y = p_y - \mu F_y = 0 \tag{2}$$
$$U_q - \mu F_q = p_q - \mu F_q = 0 \tag{3}$$
$$x^0 - F(y,q|z) = 0 \tag{4}$$

where μ is the Lagrange multiplier for the technology constraint. In equation (2) and (3), p_y represents the prices of marketed ecosystem goods and services *y*, p_q represent the implicit prices of the non-marketed ecosystem services, while the partial derivatives F_y and F_q represent the change in the use of the input bundle *x* that arises from a change in the production of *y* and *q*, respectively. Thus F_y and F_q denote inverse marginal products. In addition, μ corresponds to the utility of the marginal product of *x* in the production of *y* and *q* when produced at their optimum combination.

Given the aim of our paper, we are particularly interested in how maximum utility will respond to a marginal increase beyond the optimal level of non-marketed ecosystems services, $\partial U^*/\partial q^*$. Using the envelope theorem and the first order conditions above, the marginal change in utility can be formulated as:

$$\partial U^*/\partial q^* = U_q = p_q = p_y\, F_{q^*}/F_{y^*} \tag{5}$$

where the expression F_{q^*}/F_{y^*} represents the slope of the transformation function at (y^*, q^*). It follows that at optimal levels of *y* and *q* and in a perfect market situation, the tradeoff between them, or their opportunity cost, is equal to the loss in utility from the reallocation of inputs (incl. land). So, the marginal rate of substitution, the slope of the isoquant, is equal to the marginal rate of transformation, the slope of the transformation function – see also Figure 1. In other words, at the optimum and in a perfect market situation, the value people attach to non-marketed goods (which is estimated in environmental valuation studies) is reflected by the marginal rate of transformation (which is estimated in this study). In an imperfect market situation, this not necessarily is the case, even though the marginal rate of transformation still reflects the opportunity costs, or the trade-offs that will emerge due to a change in one of the output variables.

To gain further insight, notice that F_{y^*} can be expanded as follows:

$$F_{y^*} = dF/dy = \partial F/\partial y^* + [(\partial F/\partial q^*)\,(\partial q^*/\partial y^*)] \tag{6}$$

where $\partial F/\partial y^*$ denotes the direct inverse marginal product and $[(\partial F/\partial q^*)\,(\partial q^*/\partial y^*)]$ denotes the indirect marginal product by way of the ecosystem services. F_q can be expanded in a similar fashion and so:

$$P_q = P_y \;\; [\partial F/\partial q^* + (\partial F/\partial y^*)\,(\partial y^*/\partial q^*)] \,/\, [\,\partial F/\partial y^* + (\partial F/\partial q^*)\,(\partial q^*/\partial y^*)] \tag{7}$$

Eqn. (7) shows how the implicit price of the non-marketed ecosystem services at the margin, p_q, is determined by non-allocatable inputs and technical interdependencies. For the maximizing regional planner, the trade-off between outputs *y* and *q* thus depends on the direct input requirement as well as the indirect effect on the joint product.[3] Moreover, as P_y is given in monetary terms, also opportunity costs P_q is derived in monetary terms.

Notice how the interactions between *y* and *q* determine the shape of the transformation function. The curvature of the transformation function can be investigated by means of the second order derivatives of F_y and F_q which measure the rate of change in the slopes (Tchale and Sauer 2007; Sauer and Wossink 2011). This refers to the concavity or convexity properties of the function in the neighborhood of points satisfying the first order conditions. The bordered Hessian as the matrix of second partial derivatives of the Lagrangian function corresponding to the maximization problem constrained by *F(y,q|x,z)* gives:

$$H = \begin{bmatrix} 0 & F_y & F_q \\ F_y & -\mu F_{yy} & -\mu F_{yq} \\ F_q & -\mu F_{qy} & -\mu F_{qq} \end{bmatrix}$$

The conditions for a local maximum is that for a point which satisfies the necessary conditions, the bordered Hessian is negative semi-definite (all its eigenvalues are non-positive). This implies the transformation function is quasi-concave at the point of evaluation or a convex input requirement set which is the classic case. However for bio-economic interactions as between *y* and *q* it is now understood that feedback effects from natural systems, *q* into social systems *y* may result in non-convexities (Brown, Patterson et al. 2011). In terms of the model above this means that marginal products from reallocation of x may be positive but non-decreasing due to the indirect effects through the joint output *q*. For locations on the transformation function where this applies the gradient F_{yq} would be positive.

To further investigate the impact of regional management, we introduce inefficiency. Regions whose output is not on the transformation function are also called inefficient regions.[4] For these regions, actual output is less than what would be expected given conditions *z* and resources *x*: *F*(*y,q*|*x,z*)<0. This deviation between actual and potential output is partly caused by interdependencies with variables not included in *y, q,*

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[3] The classic model for production of multiple products admits three principal potential product-product relationships: competitive, supplementary and complementary. Under ordinary circumstances outputs involve a trade-off such that more of one cannot be produced without less of the other. This competitive relationship is illustrated by the decreasingly concave section of the standard transformation function. An output is supplementary if some positive level of this output is possible without any reduction in the level of the other output. In that case, either the direct inverse marginal product or the indirect effect is non-positive but the net effect of the rearrangement is positive. An example is the use of natural borders of agricultural plots for which the negative direct effect of having smaller plots can be compensated by the indirect effect of higher yields due to improved pollination or natural pest management. For complementary products both the direct and indirect effect of an output change are positive and the complementary products can both be produced in increasing quantities.

[4] The use of the word 'inefficiency' is an issue contested by some economists ((e.g. Stigler 1976) as they argue that rational agents will not behave inefficiently. The inefficiency as observed in this analysis is caused by random noise due to missing or excluded variables that have a relationship with our output variables but which are not included in the analysis. For example, a region having more abundant water resources may have higher levels of several of the ecosystem services included than a region having similar characteristics except that it has scarce water resources. In our analysis, the water abundant region will be classified as being more efficient even though there might be factors that explain why the water scarce region can not reach the same performance level. As a result, inefficiency levels give an indication which regions are inefficient based on the variables used in the analysis, but they do not generally show that regions can increase their outputs or remove their underperformance for free. Moreover, the method in fact removes the effect of noise. This means that the interpretation of 'inefficiency' doesn't affect the estimation and interpretation of the efficiency frontiers.

x or z, or in other words by random noise which is removed using the distance approach Let the distance be denoted by $\lambda \geq 1$ such that $F(\lambda y,\lambda q|x,z)=0$. Thus, for a region not on the transformation function, increasing actual output by $100\cdot(\lambda\text{-}1)\%$, holding z and x fixed, would move the observation towards the transformation function and eliminate inefficiency. In the next section, this is discussed in more detail.

3. Two-stage robust conditional FDH for ecosystem services analysis

Following the theoretical model discussed above, we adopt the two-stage procedure as proposed by Florens and Simar (2005) to estimate the frontier of efficient indicator combinations and the opportunity costs of each of the indicators included in the analysis. In this method, in the first stage, using output oriented, robust conditional FDH, the efficient frontier and distances of the different observations to the frontier are determined (see also Daraio and Simar 2005; Daraio and Simar 2007; De Witte and Kortelainen 2009; De Witte and Marques 2010). In the second stage, using the distances, all observations are projected on the frontier, after which the frontier is estimated parametrically using a translog function, such that unique opportunity costs can be determined.

The first stage, is based on the non-parametric envelopment methods as proposed by Deprins et al. (1984), Charnes et al. (1978) and Färe and Grosskopf (2000). A production possibility frontier is determined representing the Pareto-optimal combination of observed biodiversity and ecosystem services levels. The distance of a region's observed outputs to the frontier are a measure for the efficiency improvement the region could in theory reach. The robust, conditional Free Disposal Hull (FDH) method developed by Cazals et al. (2002) and Daraio and Simar (2005) is adopted. The advantage of FDH is that, different from parametric and Data Envelopment Analysis (DEA) methods, it requires no prior assumptions about the convexity of the frontier. As ecosystem services generation is likely characterized by non-convexities (Chavas 2009; Brown, Patterson et al. 2011) prior convexity assumptions may lead to misleading policy recommendations. In addition, in comparison to traditional FDH, the robust (or order-m) FDH approach is much less sensitive to noise and outliers, since it allows some observations to be outside of the frontier. Moreover, the conditional FDH approach assures that only observations with similar characteristics are compared with each other (see Daraio and Simar, 2005; 2007). In our empirical analysis, we use output instead of input oriented robust FDH model because authorities can only to a limited extent influence land use decisions (the inputs into the model) but try to create circumstances such that biodiversity and ecosystem services (the outputs) are maximized.

In the second stage, the nonparametric frontier obtained in the first stage is approximated with a translog production function. The advantage of firstly doing the non-parametric analysis is that not the shape of the center of a cloud of observations is estimated, but the shape of the observations near the frontier (Florens and Simar 2005). Moreover, in contrast to standard parametric methods, this two-stage method can avoid critical homoskedasticity and distributional assumptions. Without this second stage, no unique shadow prices could be derived as FDH results in a stairway-shaped frontier of which no unique tangent exists. Based on the second stage, opportunity costs are determined for each output variable which represent the change in one output in terms of their effect on e.g. income.

For the first stage, introduce for each region a vector of outputs $y = (y^1,\ldots,y^M)$ (which cover y and q in the previous chapter), inputs $x = (x^1,\ldots,x^N)$ which cover the land use choices, and conditional variables $z = (z^1,\ldots,z^K)$ which are beyond the control of the decision makers. The feasible output set is defined as $\Psi = \{(x,y,z) \mid x$ can produce y given characteristics $z\}$. In empirical studies, Ψ should be estimated from a random sample of L observations $\{(x_i,y_i,z_i) \mid i = 1,\ldots,L\}$. The Free Disposal Hull (FDH) estimator for the production possibility set Ψ is (with bandwidth parameter h),

$$\Psi^{FDH}(x,y,z) = \left\{(x,y,z) \in \mathbb{R}^{M\ N\ K} \quad y \le y_l, x \ge x_l, z \in [z_l - h, z_l + h] \exists l = 1,\ldots,L\right\} \tag{8}$$

The FDH frontier is a stairway-shaped curve connecting the efficient observations. In Figure 2 line AB represents the FDH-frontier and region OAB the set of feasible outputs.

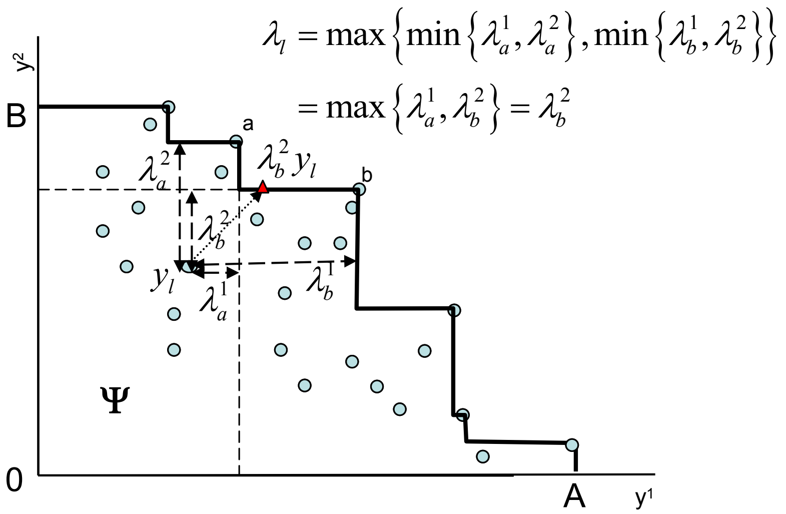

Figure 2: Representation of stage 1 showing the feasible output set Ψ and distance to the frontier of observation y_l which is equal to λ_l for an example with two outputs.

Note: Observation y_l can improve at most with λ^1_a before it reaches the frontier of the Pareto dominating observation *a* and with λ^2_b before it reaches the frontier of the Pareto dominating observation *b*. So, the observation can improve with $\max\{\lambda^1_a, \lambda^2_b\}$ before it reaches frontier AB. If $y_l=(y^1, y^2)$ improves with λ^2_b, the observation would move from y_l to $\lambda^2_b y_l$, which is located at the frontier.

Under the assumption of free disposability (see e.g. Färe and Grosskopf 2000, for an explanation of the assumptions), for each observation (x,y,z), the Farrell-Debrue measure of output-oriented efficiency can be defined as:

$$\lambda(x,y \mid z) = \sup\left\{\lambda \mid (x,\lambda y,z) \in \Psi\right\} \tag{9}$$

This function measures for each observation the distance of the output vector to the frontier – see also Figure 2. For the efficient observations on the frontier $\lambda = 1$. For the inefficient points, $\lambda > 1$, where $(1-\lambda)100\%$ measures the percentage output increase necessary to reach the frontier. The larger the distance, the more inefficiently the region combines the different outputs considered and therefore the lower the performance of the region. It is noted that the frontier gives the efficient observations and that performance is measured in terms of the Pareto improvement that can in theory be attained. Moreover, it is noted that inefficiency is partly caused by noise in the data caused by data not included in the analysis (see above).

In empirical studies, the question is how to estimate for each observation the distance (9). First consider a situation without conditional variables *z*. In that case, the estimator of (9) can be written in probabilistic format (Daraio and Simar 2005; De Witte and Kortelainen forthcoming):

$$\lambda\left(x_i, y_i\right) = \sup_{\lambda_i}\left\{\lambda_i \left| S_Y\left(\lambda_i y_i \middle| x_i\right) > 0\right.\right\} = \sup_{\lambda_i}\left\{\lambda_i \left| \frac{I\left(\lambda_i y_i \le y_l, x_i \ge x_l\right)}{I\left(x_i \ge x_l\right)} > 0, l = 1,\ldots,L\right.\right\} \tag{10}$$

for observation (x_i, y_i), with $S_Y\left(y|x\right) = H_{XY}\left(x,y\right)/F_X\left(x\right) = \Pr\left(y \le Y, x \ge X\right)/\Pr\left(x \ge X\right)$ the survivor function of Y, in which H_{XY} is the joint probability distribution function, F_X the cumulative distribution function of X and $I(\cdot)$ the indicator function.

Secondly, including the conditional variables and adopting the robust, order-*m* approach corrects for the disadvantage that (10) is sensitive to outliers (Cazals, Florens et al. 2002; Daraio and Simar 2005; De Witte and Kortelainen 2009). For each observation (x_i, y_i, z_i) a sample of size *m* is drawn with replacement from the original sample $\{(x_l, y_l, z_l)|l=1,\ldots,L\}$. Repeating this a large number of times and taking its expectation gives the order-*m* efficiency measure. Cazals et al. (2002) showed that the conditional order-*m* efficiency score is (see also Daraio and Simar 2005)

$$\lambda^m\left(x_i, y_i \middle| z_i\right) = \int_0^\infty \left[1 - \left(1 - S_Y\left(uy_i \middle| x_i, z_i\right)\right)^m\right] du \tag{11}$$

Estimating the conditional survivor function $S_Y(y|x,z)$ nonparametrically is more difficult than estimating (10) as smoothing techniques are needed such that the reference sample of size *m* is drawn in such a way that observations with comparable *z*-values have a higher probability of being chosen (see Daraio and Simar 2005; De Witte and Kortelainen 2009). For this, different from what is given in (10), $S_Y(y|x,z)$ changes into:

$$S_Y\left(y_i \middle| x_i, z_i\right) = \frac{\sum_{i=1}^{L} I\left(y_i \le y_l, x_i \ge x_l\right) K_h\left(\left(z_i - z_l\right)/h\right)}{\sum_{i=1}^{L} I\left(x_i \ge x_l\right) K_h\left(\left(z_i - z_l\right)/h\right)} \tag{12}$$

for all $l = 1,\ldots,L$ and with $K_h(.)$ a Kernel function with bandwidth parameter *h*.

These first stage efficiency scores can be used to target which regions perform better and which perform worse. Moreover, they are helpful for evaluating how much the different outputs in each region can theoretically improve before they reach their production potentials and which factors explain underperformance. Next to that, the results are used for testing whether the Kuznets-hypothesis applies for regional performance. The Kuznets-hypothesis purports that increases in income lead to negative effects for the environment, that is lower efficiency, until a certain threshold after which regions become more efficient. The idea behind this hypothesis is that countries first concentrate on development and use land for increasing production of provisioning services. Once development levels increase, countries pay more attention to biodiversity and ecosystem functioning and try to improve the balance between the different ecosystem services (Dietz and Adger 2003). Following Daraio and Simar (2007), to examine the effect of GDP on efficiency, we first derive efficiency scores for a situation with and a situation without GDP as conditional variable. Next, for each sub-region, the ratio of conditional inefficiency to unconditional inefficiency, δ(Y,Q|GDP)/δ(Y,Q), is non-parametrically regressed on GDP. For the output oriented approach, an increasing relationship implies that GDP is favorable to efficiency. GDP is some sort of freely available "extra" input and consequently conditional inefficiency δ(Y|GDP) is smaller than unconditional inefficiency δ(Y) for lower levels of GDP (Daraio and Simar 2005; De Witte and Kortelainen forthcoming).

In the second stage, following Florens and Simar (2005) and Daraio and Simar (2007), a we approximate the nonparametric frontier function with a flexible parametric production function. As derived below, this frontier function directly follows from the distance function which gives the distance from each observation to the frontier. Let $\delta(x,y|z)$ be the Shephard output distance function. The Shepard distance measure is equal to the inverse of the Farrell-Debrue distance measure introduced in (9) and (11), $\delta(x,y|z) = \lambda^{-1}(x,y|z)$. Introduce a parametric distance function $\varphi(x,y,z)$, which is homogenous of degree one in y, and with vector θ the unknown parameters.[5] The aim is to estimate the values of θ which give the best approximation of the multivariate output distance function $\delta()$, or in other words to solve in a similar way as for OLS-estimation,

$$\theta_0 = \arg\min_{\theta}\left[\sum_{i=1}^{L}\left(\delta\left(x_i, y_i \mid z_i\right) - \varphi\left(x_i, y_i, z_i; \theta\right)\right)^2\right] \tag{13}$$

Assume a translog production function,

$$\ln\varphi\left(y;\theta\right) = \alpha_0 + \beta'\ln y + \tfrac{1}{2}\ln y'\Gamma\ln y + \gamma'\ln z \tag{14}$$

where $\Gamma=\Gamma'$ is symmetric (see Daraio and Simar 2007). Due to homogeneity of degree one in y, it has to hold that $\beta'\cdot i_M = 1$ and $\Gamma\cdot i_M = 0$, with i_M the identity vector of size M. Define β_{-1} the (M-1)-vector of coefficients not containing β_1 and

$$\Gamma = \begin{bmatrix} \tau_1 & \tau_{-1}' \\ \tau_{-1} & \Gamma_{22} \end{bmatrix}$$

with $\tau = \left(\tau_1 \;\; \tau_{-1}'\right) \in \mathbb{R}$, τ_{-1} an (M-1)-vector and Γ_{22} an (M-1)x(M-1)-matrix. Due to the homogeneity assumption it follows that $\beta_1 = 1 - \beta_{-1}' \cdot i_{M-1}$, $\tau_1 = -\tau_{-1}' \cdot i_{M-1}$ and $\tau_{-1} = -\Gamma_{22} \cdot i_{M-1}$. For the translog function, (13) equals (with $\delta_i = \delta\left(x_i, y_i \mid z_i\right)$)

[5] Homogeneity of degree one in y implies that for all $\mu > 0$, $\varphi(x,\mu y,z) = \mu\varphi(x,y,z)$.

$$\theta_0 = \arg\min_{\theta}\left[\sum_{i=1}^{L}\left(\ln\delta_i - \left(\alpha_0 + \beta'\ln y_i + \tfrac{1}{2}\ln y_i'\Gamma\ln y_i + \gamma'\ln z_i\right)\right)^2\right]$$

$$= \arg\min_{\theta}\left[\sum_{i=1}^{L}\left(\ln\delta_i - \left(\alpha_0 + \left(1-\beta_{-1}'i_{M-1}\right)\ln y_{i1} + \beta_{-1}'\ln y_{i,-1} + \right.\right.\right.$$

$$\left.\left.\left.\tfrac{1}{2}\left(\ln y_{i1}\tau_1 + \ln y_{i,-1}'\tau_{-1}\right)\ln y_{i1} + \tfrac{1}{2}\left(\ln y_{i1}\tau_{-1}' + \ln y_{i,-1}'\Gamma_{22}\right)\ln y_{i,-1} + \gamma'\ln z_i\right)\right)^2\right]$$

$$= \arg\min_{\theta}\left[\sum_{i=1}^{L}\left(-\ln\tfrac{y_{i1}}{\delta_i} - \left(\alpha_0 + \beta_{-1}'\ln\tfrac{y_{i,-1}}{y_{i1}} + \right.\right.\right.$$

$$\left.\left.\left.\tfrac{1}{2}\left(\ln\left(\tfrac{y_{i,-1}}{y_{i1}}\right)'\tau_{-1}\right)\ln y_{i1} + \tfrac{1}{2}\left(\ln\left(\tfrac{y_{i,-1}}{y_{i1}}\right)'\Gamma_{22}\right)\ln y_{i,-1} + \gamma'\ln z_i\right)\right)^2\right]$$

$$= \arg\min_{\theta}\left[\sum_{i=1}^{L}\left(-\ln y_{i1}^{*} - \left(\alpha_0 + \beta_{-1}'\ln \tilde{\ } \quad \tilde{\ } \quad \tilde{\ } \right)\right)^2\right]$$

$$= \arg\min_{\theta}\left[\sum_{i=1}^{L}\left(-\ln y_{i1}^{*} - \left(\alpha_0 + \sum_{j=2}^{M}\beta_j\ln \tilde{\ } \quad \sum_{j=2}^{M}\sum_{l=2}^{M} \quad \tilde{\ } \quad \tilde{\ } \right)\right)^2\right]$$

with $y_{i1}^{*} = y_{i1}/\delta_i = y_{i1}\lambda_i$ the values of y_{i1} projected on the output efficient frontier and $\tilde{\ }$ $/\, y_{i1} = y_{i,-1}^{*}/y_{i1}^{*}$.

In words, to estimate the best parametric approximation of the multivariate output distance function, the output values are projected on the output efficient frontier using the distance values estimated in the first stage, after which the frontier function

$$\ln y_{i1}^{*} = -\left(\alpha_0 + \beta_{-1}'\ln \tilde{\ } \quad \tilde{\ } \quad \tilde{\ }\right) \tag{15}$$

is estimated using OLS – see also Figure 3. Using the conditions on β and Γ as given above, distance function $\varphi(x,y,z;\theta)$ immediately follows. According to Daraio and Simar (2007), one of the major advantages of this approach is that no restrictive homoskedasticity or distributional assumptions have to be made on the error term in $\varphi(\cdot)$. A disadvantage, because of the first-stage estimation, is that in the second stage standard errors should be obtained using a computationally intensive bootstrapping procedure (see Florens and Simar 2005).

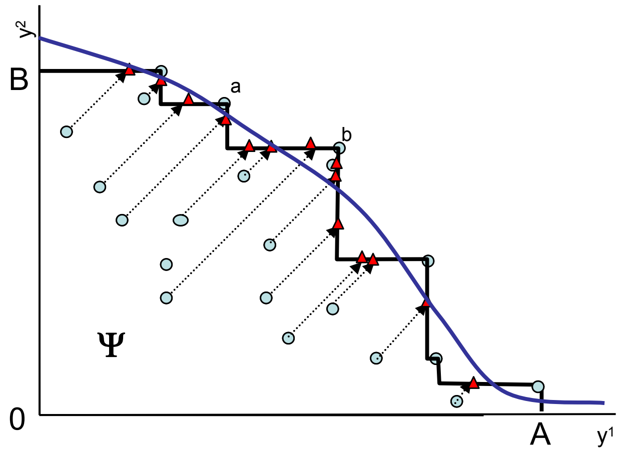

Figure 3: Representation of stage 2: project the observations on the frontier after which the smooth frontier function is estimated using OLS.

As a final step, opportunity costs or trade-offs between the input and output combinations are derived in physical and monetary terms using the frontier function (15) or using the output distance function. At each point at the frontier, the slope of the frontier function represents the marginal rate of transformation – see Figure 1. This gives the trade-offs in physical terms or the rate at which one output is lost in exchange for more of another. In equilibrium and for a perfect market situation, those physical trade-offs are equal to the shadow price ratios which represent the relative marginal value of each input or output to society (Bellenger and Herlihy 2010) – see also (5). In case of an imperfect market situation, the trade-offs reflect the opportunity costs, the output foregone due to an increase of one of the other outputs.[6] This opportunity cost ratio can be derived using the duality relationship between the benefit function and the distance function (Färe and Grosskopf 2000; Bellenger and Herlihy 2010). For output price $p \in \mathbb{R}^M$, the benefit function is defined as $B(p) = \sup_y \{p'y \mid (x,y,z) \in \Psi\}$, and consequently $B(p) \geq p'y$. Since $y/\delta(x,y \mid z)$ is also a feasible output vector, it also has to hold that $B(p) \geq p'y/\delta(x,y \mid z)$, from which it follows that

$$\delta(x,y \mid z) = \max_p \left[\frac{py}{B(p)}\right] \tag{16}$$

As a result, for a single observation and for $m = 1,\ldots,M$

[6] In the literature the terms opportunity costs and shadow prices are often used interchangeably. This may cause confusion, however. Where the definition of opportunity costs is clear, referring to the output foregone due to an increase in one of the other outputs, shadow prices may have different definitions. In micro-economics it often refers to the marginal value or marginal utility of the output for society, whereas in constrained optimization it refers to the increase of the value of the objective function due to a marginal relaxation of one of the constraints. If markets are perfect, indeed the marginal rate of transformation is equal to the marginal rate of substitution due to which trade-offs reflect marginal utility. In case of market imperfections, however, this not necessarily is the case. In that case, for a point at the frontier the marginal rate of substitution, i.e. the marginal change in utility, may differ from the marginal rate of transformation, i.e. the marginal change in output. In order to avoid confusion, we rather use opportunity costs instead of shadow prices when referring to trade-offs.

$$\frac{\partial \delta(x, y \mid z)}{\partial y_m} = \frac{p_m}{B(p)} \tag{17}$$

If the market price is known for one of the outputs, e.g. for the first output, it follows from (17) that opportunity costs for the other outputs are equal to

$$p_m = p_1 \cdot \frac{\partial \delta(x, y \mid z) / \partial y_m}{\partial \delta(x, y \mid z) / \partial y_1} \tag{18}$$

This reflects the slope of the production possibility frontier, i.e. the marginal rate of transformation. As a result, for the translog distance function derived under stage 2, [7] it follows that for the m^{th} element of y

$$p_m = p_1 \frac{y_1}{y_m} \left(\frac{\beta_m + \Gamma'_m \ln y}{\beta_1 + \Gamma'_1 \ln y} \right) \tag{19}$$

with Γ_m the m[th] row of vector Γ.

The effects of marginal changes in the output variables on the opportunity costs can be investigated using the indirect Morishima elasticity of transformation, which provides a measure for the curvature of the frontier (Blackorby and Russell 1989; Bostian and Herlihy 2010; Mundra and Russell 2010). The indirect Morishima elasticity of transformation is defined as the percentage change in the opportunity cost ratio due to a percentage change in the output ratio (Mundra and Russell 2010; Färe et al. forthcoming). It is a so-called two-price, one output elasticity in which only one of the outputs in the output ratio changes (Frondel 2011; Stern 2011). As a result, the elasticity is asymmetric, depending on which output changes. The Morishima elasticity of transformation, for a change in output y_i is defined as:

$$MET_{ij} = \frac{\partial \ln(p_i / p_j)}{\partial \ln(y_j / y_i)} = \frac{\partial \ln(p_j)}{\partial \ln(y_i)} - \frac{\partial \ln(p_i)}{\partial \ln(y_i)} \tag{20}$$

The *MET* shows how the opportunity cost ratio changes if one of the outputs changes with all inputs and the other outputs kept constant. It turns out that the change in the opportunity cost ratio depends on two quantity elasticities. A negative MET_{ij} implies that decreasing the quantity of i increases the shadow price of output i relative to that of output j, or the more negative MET_{ij}, the more costly it is to increase y_i. In that case, output j is a Morishima substitute to output i. Similarly, if $MET_{ij}>0$, output j is a dual Morishima complement to output i. For positive elasticities, it holds that the larger MET_{ij}, the less costly it is to increase y_i. Given (19), it follows that

[7] Note that $\partial y / \partial x = \partial \log(y) / \partial \log(x) \cdot y/x$.

$$M_{i1} = 1 - \frac{\tau_{ii}}{\beta_i + \Gamma_i \ln y} + \frac{\tau_{1i}}{\beta_1 + \Gamma_1 \ln y}$$

$$M_{1i} = 1 - \frac{\tau_{11}}{\beta_1 + \Gamma_1 \ln y} + \frac{\tau_{i1}}{\beta_i + \Gamma_i \ln y}$$

What does this second stage show us? First, if e.g. y_1 is defined as agricultural production and p_1 its market price, it gives opportunity costs of the non-monetary outputs in terms of revenues from provisioning services foregone. These opportunity costs show in a positive (not a normative) way the trade-offs between monetary and non-monetary outputs. These opportunity costs provide useful information for the decision making process on whether society is willing to make this trade-off. They, therefore, differ from the values estimated using environmental valuation methods. Different from valuation estimates, the opportunity costs show the effects of a land use change in income equivalents without any reference to the (largely unknown) trade-offs households are willing to make for these changes. Secondly, it shows which regions succeed in combining the different outputs in an efficient way and which do not. Those regions at the frontier all perform optimally; those not at the frontier are not Pareto optimal. This can be used to evaluate which regions do better and why. In addition, it gives information about potential efficiency gains, assuming the model assumptions are correct. Thirdly, it can be used to evaluate performance differences of certain scenarios of future change.

4. Data

The approach discussed above is illustrated for a case study of eighteen countries in middle and eastern Europe.[8] An important aspect is the choice of input, output and conditional variables. It determines the system analyzed and the types of conclusions that can be drawn. In order to be able to properly test the method discussed above, for this case study only a limited number of variables is included. This can be extended in later applications.

The distinction between supporting, regulating, cultural and provisioning services (see Footnote 1), even though a helpful categorization, is inappropriate for economic analyses and not helpful for deciding which variables are inputs and outputs (Wallace 2007; Fisher et al. 2009). Core in environmental economic analysis in general and the above method in particular is to differentiate between intermediary services (especially regulating and supporting services) and final services (especially provisioning and cultural services). The intermediary services are the inputs or processes necessary for producing the goods and services providing human benefits. Accordingly, Brown et al. (2007), and in a similar way Haines-Young and Potschin (2010) and de Groot et al. (2010), distinguish a) ecosystem processes or functions which are the physical and biological cycles maintaining the natural world (especially the supporting services), b) ecosystem services which result from ecosystem processes and relate to "improvements in the condition or location of things of value" (p. 331) (especially the regulating services), and c) ecosystem goods which are the tangible products resulting from ecosystem processes and services (especially the provisioning and cultural services, even

[8] This contains Albania, Estonia, Latvia, Lithuania, Belarus, Poland, Ukraine, Czech Republic, Slovakia, Hungary, Romania, Moldova, Bulgaria, Slovenia, Croatia, Bosnia and Herzegovina, Macedonia, and Serbia.

though the latter category is not tangible). In fact, in their definition, ecosystem goods are what Boyd and Banzhaf (2007) call final services.

For the current analysis, land is the only input variable included. Including inputs would enrich the analysis as it is not just intermediary ecosystem services but also human induced inputs that contribute to the provision of final ecosystem services. For example, labor, capital inputs, chemical fertilizers and pesticides affect land use intensity, may replace intermediary services, and thus do influence the final services generated. Even though data on pollination, erosion sensitivity and water use could be obtained, their inclusion only makes sense if substitution with human inputs can be shown. Because of a lack of data on land use intensity or other human inputs, it is decided only to include land as input variable. As a result, we do not analyze substitution possibilities between different inputs but only concentrate on competition between outputs.

Based on data availability, the outputs included in the analysis are provisioning services, cultural services, climate regulation and biodiversity. Due to the difficulty of properly defining and quantifying climate regulation, carbon sequestration is used as a proxy variable. The position of biodiversity in the economic model is debatable. In fact, it serves both as an input and as an output. On the one hand, higher biodiversity levels positively affect ecosystem services like nutrient cycling, pollination, pest control and recreation. On the other hand, biodiversity is affected by ecosystem services provisioning; e.g. improved water purification or nutrient cycling results in higher biodiversity levels, whereas more intensive food production usually leads to lower biodiversity levels (at least locally). Moreover, biodiversity affects human benefits through the insurance value of higher biodiversity levels (Folke et al. 2004; Quaas and Baumgartner 2008). We treat biodiversity as an output variable, serving as a proxy for the positive impact of several regulating and supporting services on ecosystems and as an indicator which is important in nature policies. Several indicators exist for measuring *biodiversity*, e.g. species richness, species abundance, status of key species or relative species richness. We measure biodiversity by the level of *mean species abundance*, i.e. the current mean abundance of species compared to their abundance in a pristine environment (Alkemade et al. 2009).

Conditional variables are included to assure a peer-to-peer comparison between cells when deriving the production possibility frontier. The variables included may affect the position of the frontier. We include per capita GDP, land cover, potential yield and historical and political typology. Regions having a different background, soil fertility, land cover or history will likely have a different production possibility.

Land use patterns originate from the GLC2000 land use map. Base data originate from the integrated assessment model IMAGE (Bouwman et al. 2006), biodiversity model GLOBIO (Alkemade, Oorschot et al. 2009), new estimates of ecosystem services on the level of grid cells of size 50x50 km^2 for the year 2000 (EC-JRC 2003; Schulp et al. forthcoming)[9] and data from the World Bank World Development Indicators and FAOstat. This results in 1166 observations. For the analysis, model data are applied because no field observations exist for the ecosystem services and biodiversity variables. The results

[9] IMAGE (Integrated Model to Assess the Global Environment) simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to explore the long-term dynamics of global change as the result of interacting demographic, technological, economic, social, cultural and political factors. GLOBIO (Global Biodiversity model) is used in the assessment of policy options for reducing global biodiversity loss and is based on the GLC2000 land use map. IMAGE results on cropping patterns (% of each cell covered with a particular agricultural crop) have been recalculated such that land cover type (% of each cell with grass, crop or forest cover) corresponds with the GLC2000 land use pattern.

from IMAGE and GLOBIO, however, give the state-of-the-art knowledge of the relationship between global land use decisions, a number of ecosystem and environmental indicators and biodiversity (the models are used e.g. in UNEP 2007; OECD 2008; Nelleman et al. 2009; Van Vuuren and Faber 2009; TEEB 2010).[10]

The following variables are included:

Output variables

1. Provisioning services: Agricultural revenues (in 2000 international $/km^2). For each cell total revenues for the production of temperate and tropical cereals, grass, rice, maize, pulses, roots, tubers, and oil crops are calculated based on land use data from the GLC2000 map, the cropping pattern from IMAGE, yield data and prices. Production data per cell for the year 2000 are based on FAO-data, which are allocated over the cells using IMAGE and GLC2000. Production is determined for grass, rainfed cereals, rice, maize, tropical cereals, pulses, roots and tubers, oil crops and biofuel crops (sugar cane, maize and woody biomass).[11] Prices per crop per country for the year 2000 are taken from FAOSTAT.[12] Note that for provisioning services, only crop revenues are considered and not other marketed provisioning services such as forestry and livestock products. The main reason is a lack of data on forestry outputs and prices (especially related to pulpwood, saw logs, veneer, fuelwood and charcoal) and on livestock outputs.
2. Cultural services: a composite index consisting of attractiveness for tourism and recreation and attractiveness for hunting and gathering activities. Tourist and recreation attractiveness is an index ranging from 0 (unattractive) to 1 (attractive) and depends on per capita income, percentage protected area, percentage land classified as urban and arable, distance to coast and geographic relief where flat and extremely mountainous areas are judged to be less attractive. Attractiveness for hunting and gathering activities is based on statistics from FAO and the European Forestry Institute. It depends on the regional potential for gathering wild foods, fruits, and mushrooms, catching fish and hunting game which depends on land cover and the potential population that can reach these activities within a reasonable time frame.
3. Biodiversity: mean species abundance (MSA) as determined by GLOBIO (see Alkemade, Oorschot et al. 2009). MSA depends among other things on land cover, habitat, % of the cell covered with certain vegetation, land use intensity, and distance to roads, villages and cities. It is an index indicating the level of disturbance compared to the maximally possible level for the particular habitat. An MSA equal to

[10] In selecting and calculating the variables used in our analysis, proper attention has been paid to prevent potential endogeneity problems. Most of the variables depend among other things on land use and crop choice, but none of them directly depend on any of the other variables included. Moreover, a risk of using model data is that the results simply replicate the model relationships and in fact confirm what has been put in the model. As our data originate from several models and as the model data are not directly input in our analysis but first used to estimate new indicators such that they all reflect land use as given on the GLC2000 land use map, this is less of a problem. Of course, the quality of our results depends on the quality of the underlying models. Given the widespread use of IMAGE and GLOBIO and the way in which results are validated, quality of these models is not a subject of discussion.

[11] In IMAGE a cell is either fully used for agriculture or does not produce any crops at all, whereas the GLC2000 map indicates which share of a cell is used for agriculture and for forestry. GLC2000 does not give cropping patterns but only acreages used for agriculture. For the agricultural cells from IMAGE, the estimated cropping pattern is projected on the agricultural acreage of the GLC2000 map. For the non-agricultural cells from IMAGE, cropping patterns are estimated such that they best fit total production and total cultivated area per country.

[12] For Albania, FAOSTAT prices are almost double the prices for the other countries. As there are no clear reasons which explain this, it is assumed that prices for Albania are equal to prices for Romania.

1 means that the land is not disturbed and is still in its virgin state. MSA is included as a proxy variable for several regulating and supporting ecosystem services that maintain the productive capacity of ecosystems.

4. Carbon sequestration: net biome productivity in tonnes C per km^2. Net biome productivity equals net primary production of carbon minus soil respiration minus the carbon stored in the biomass harvested. For respiration and sequestration factors long-term averages are taken to assure that annual sequestration doesn't change much e.g. due to age differences of forests. Data are based on the GLC2000 land use map and EURURALIS carbon model (see e.g. Schulp et al. 2008). In this model, sequestration depends on land cover in which arable, grass, wetlands and forests of different types and age are distinguished. Moreover, for arable and grass land, sequestration also depends on soil type. Results on a 1x1 km scale are aggregated to IMAGE cell size of 50x50 km. Carbon sequestration is a proxy variable for the ecosystem service climate regulation, which has a long term effect on production possibilities.

Input variables

5. The area of the grid cell: In IMAGE each cell is a square where cell size depends on the latitude; a cell at the equator has a size of 50x50 km^2 and for the other cells the size is corrected based on their latitude. Cell size also depends on the amount of open water present. Note that one could easily introduce other inputs here, but due to data unavailability we consider only land, as a fixed input, in our application. The other variables are all given per km^2 such that performance of smaller and larger cells can be compared with each other.

Conditional variables

6. GDP PPP per km^2 for the year 2000 (in international \$/km^2) – World Bank data on GDP per country which is allocated over the grid cells by considering differences between agricultural and non-agricultural income in order to properly distinguish between rural and urban cells. For this, non-agricultural income per cell is based on percentages of GDP earned in agriculture and percentages of the population working in agriculture. Income per cell is divided by area to correct for differences between large and small cells.
7. Share of arable and grassland: share of each cell used for production of agricultural crops and for grazing. In the analysis, a distinction is made between arable land (irrigated or rainfed), grassland (used for intensive or extensive grazing), forests (boreal, conifer, mixed or deciduous forest), shrub and herbaceous land and artificial surface. In order to distinguish between cells mainly covered with forest and those mainly used for agriculture, the share of arable plus grassland is included as conditional variable.
8. Potential yield: potential yield of temperate cereals in tonnes/ha based on climate, soil and slope characteristics. This variable is included to assure that only regions with similar biophysiological characteristics are compared with each other. Temperate cereals are chosen as it is the main crop grown (around 60% of the cropland is covered with temperate cereals).
9. Sub-region typology: categorical variable reflecting differences in historical, political and social development patterns which may affect the technical possibilities available to the regions. Four sub-regions are considered: 1. member countries to the

Commonwealth of Independent States (CIS) Belarus, Estonia, Latvia, Lithuania, Moldova and Ukraine, 2. Central European countries (CE) Czech Republic, Hungary, Poland and Slovakia, 3. the former Yugoslavian republics (YUG) Bosnia, Croatia, Macedonia, Serbia and Slovenia, 4. the south-eastern European countries (SE) Albania, Bulgaria and Romania (see, Fenger 2007)

Table 1 and Table 2 give some descriptive statistics. Appendix 1 shows maps with the base data. For some variables, the standard deviation is very large. This reflects differences in population density (urban vs. rural areas) and differences between average country development levels. Signs of correlation coefficients are as expected and related to land cover and land use. Agricultural production is higher in cells with higher percentages of agricultural land. MSA, cultural services and carbon sequestration are higher on areas with less cultivated plots and therefore in cells with lower agricultural production. Cultural services are higher in areas with higher MSA levels as these areas are more attractive for recreation and hunting. These are, generally, also the areas sequestering more carbon. The pattern of correlations between the ecosystem services is consistent with similar observations by Raussep-Hearne et al. (2010) for Canada. They are a sign that the joint generation of ecosystem services is non-separable. It is noted that the observed level of correlation coefficients does not affect estimates of the opportunity costs.

Table 1: Averages and standard deviations of the different variables included for the different sub-regions (standard deviations are given in brackets).

		Prov. services US$/km^2	MSA	Cultural services	Carbon sequest. Tonnes C/km^2	GDP US$/km^2	Pot. Yield ton/ha	% agric. + grass-land
Total	**Mean**	15,674	0.359	0.408	29.15	491,823	481	0.59
	St.Dev.	(11,394)	(0.128)	(0.102)	(29.14)	(774,723)	(109)	(0.21)
	Min - Max	0 - 83,928	0.133 - 0.929	0.144 - 0.900	-10 - 165	0 - 7,881,679	139 - 738	0.00 - 1.00
CIS	**Mean**	14,419	0.358	0.402	31.96	209,673	516	0.66
	St.Dev.	(11,089)	(0.130)	(0.093)	(26.10)	(372,633)	(108)	(0.22)
CE	**Mean**	14,982	0.349	0.457	20.21	1,082,414	431	0.56
	St.Dev.	(9,090)	(0.114)	(0.086)	(17.15)	(1,132,678)	(78)	(0.16)
YUG	**Mean**	14,677	0.365	0.358	16.43	629,314	384	0.50
	St.Dev.	(11,249)	(0.121)	(0.140)	(14.70)	(669,721)	(114)	(0.17)
SE	**Mean**	21,393	0.372	0.387	43.16	352,835	516	0.51
	St.Dev.	(13,826)	(0.147)	(0.089)	(47.37)	(503,458)	(80)	(0.22)

Table 2: Correlation coefficients of the variables included in the analysis

	1. Provisioning services	2. Mean species abundance	3. Cultural services	4. Carbon sequestration	5. GDP	6. Potential yield	7. %agric. +grass land
1. PS	1	-0.55	-0.39	-0.37	0.02	0.49	0.55
2. MSA	-0.55	1	0.50	0.55	-0.12	-0.33	-0.78
3. CS	-0.39	0.50	1	0.44	0.16	-0.21	-0.60
4. CAR	-0.37	0.55	0.44	1	-0.15	-0.12	-0.62
5. GDP	0.02	-0.12	0.16	-0.15	1	-0.12	-0.11
6. YLD	0.49	-0.33	-0.21	-0.12	-0.12	1	0.47
7. Agri	0.55	-0.78	-0.60	-0.62	-0.11	0.47	1

5. Results

The non-parametric method discussed in Section 3 is illustrated for the case discussed above. In this section, the two questions raised in the introduction, on differences in regional performance and on trade-offs between the different outputs, are discussed. The results, which are discussed below, lead to the following sequence of main conclusions.

1. Regional performance differences:

a. In the poorer sub-regions, cells differ more in the way they jointly produce the different outputs than cells do in the richer sub-regions. In most of the richer sub-regions, potential performance improvements are small.

b. Regional GDP has a significant influence on the inefficiency with which regions combine marketed and non-marketed outputs. Within each sub-region, higher income is associated with lower performance levels. For income levels exceeding a certain threshold, the relation between income and performance is insignificant.

2. Trade-offs between the different outputs

a. The production possibility frontier, showing the efficient output combinations, is non-concave. Even though inconvenient from an economic point of view, this is observed more often for ecosystem services.

b. The production possibility frontier for the richer CE sub-region is situated more outward than the frontier for the other sub-regions. This implies that the level of joint output for countries in the CE sub-region is potentially higher than that for the other regions. The frontier for the CIS-region is situated below that of the CE region. Combining this with the inefficiency scores for the countries in the CIS-region shows that these countries can reach high performance levels without large technical changes. The frontier of the YUG-countries is lowest. As their performance levels are relatively good, they require technical changes to improve their potential production.

c. Regional differences in trade-offs are large. Each country has regions with high and with low opportunity costs. Improving biodiversity, cultural services or carbon sequestration generally entails higher opportunity costs in areas with higher levels of provisioning services. On the other hand, improving carbon sequestration becomes cheaper in regions with higher carbon sequestration levels. Improving biodiversity, generally, becomes more expensive if levels of biodiversity increase.

Result 1a

Table 3 presents some descriptive statistics of the inefficiency levels as estimated using model (11). Figure 4 maps the inefficiency scores per cell and the average country inefficiencies. In total, 325 of the 1166 (28%) cells are classified as being efficient.[13] The average level of inefficiency is 10.1%. This implies that on average, the output variables can increase with 10.1%. These averages, however, hide considerable within country variation. The majority of the cells is only moderately inefficient and thus can improve performance only to a minor extent (see also column 5 in Table 3 and Figure 5). This is especially the case for the former Yugoslavian countries and the central European countries, except for Hungary. Multiplying the output values with the levels of inefficiency gives insight in the possible gain of becoming efficient. For all 18 countries, becoming efficient would increase production of provisioning services from $35,000 million per year to $39,000 million per year, an extra production worth $4,048 million per year. The amount of carbon stored would increase from 62.9 million tons per year to 66.7 million tons per year, an extra amount of 3.8 million tons per year. On average, mean species abundance would increase from 0.359 to 0.388.

Mean inefficiency values are affected by a small number of very inefficient cells. In general, the former Soviet republics (CIS) perform worse and the former Yugoslavian (YUG) and central European (CE) countries (except for Hungary) have better efficiency scores. Slovenia, Croatia and Czech Republic are among the best performing countries. Moldova, Hungary and Ukraine are among the worse performers. For Hungary and Ukraine, averages are affected by a few outliers. Moldova has low efficiency levels for all cells. Generally, the regions performing better have less agricultural land and higher biodiversity and carbon levels.

If inefficiency scores are compared between countries, it has to be reminded that scores are conditional on region. Therefore, the inefficiency scores of Estonia should only be compared with those of member states of the Commonwealth of Independent States (CIS) and the scores of Hungary only with those of the Central European (CE) countries. The higher average inefficiency score in the CIS countries means that cells in this region have on average a larger distance to their production possibility frontier than the cells in the former Yugoslavian countries (YUG). This implies that for the CIS-countries the difference between potential and realized production is larger than for the YUG-countries. This does not necessarily imply that the CIS-countries have lower joint output levels. If the production possibilities for the CIS-countries were higher than for the YUG-countries, the CIS-countries could still have a larger output despite of their higher level of inefficiency. So, we do not compare absolute levels of output, but in fact compare differences between the distributions of performance levels per sub-region – see Figure 5. Sub-regions having steeper distributions have converged more to a situation in which cells are more similar. Sub-regions with flatter distributions with larger tails are still more diverged, with larger variations between the cells.

The results show that inefficiencies are especially large in cells with above average percentages of agricultural land. Cells with a lower than average agricultural land cover (<59% agricultural land), have an average inefficiency of 4%. In contrast, for the cells mainly covered with agricultural land, the mean inefficiency level is 15%. Two reasons can be identified for this result. First, provisioning services are partly based on model estimates. To estimate crop fractions, regional agricultural production data observed

[13] Four cells can be classified as superefficiënt as they have an inefficiency level below 0%. This is possible because we adopt the robust order-m approach – see Section 3.

from FAO statistics are allocated over the cells. The resulting agricultural production in each cell not necessarily reflects optimally attainable production. As a result, the cells with more agricultural land can realize on average a larger Pareto improvement than cells with less agricultural land. So, the inefficiency levels should be interpreted with care. [14] Second, the results show trade-offs between provisioning services and the other three outputs (biodiversity, cultural services and carbon) which are positively correlated with each other. So, if one of these three outputs turns out to be low in a cell with a high level of provisioning services (and so with a high percentage of agricultural land) it is likely that also the other two outputs are low, making the level of inefficiency higher. This is the case in Hungary and Moldova with an above average agricultural production with below average levels of the other three output variables, some of which are extremely low.

The differences between the four regions can be exemplified by looking at the kernel density distributions of the inefficiency levels. Figure 5 shows the distribution of the inefficiency levels. The pattern is clear. The CIS-countries are most heterogeneous, with a distribution with the lowest peak and highest tails. In these countries, there is a number of good performing but also a substantial number of weak performing cells. For the YUG-countries, cells are most homogenous, having a distribution with the highest peak and lowest tail. Performance has converged to a level which only shows small differences between the cells and in which only few cells perform substantially worse than the others. Results of the Mann-Whitney test show that density distributions for the four regions differ from each other significantly, except for the distribution of the SE region with that of the CIS and of the CE region.

Swinnen and Vranken (2010) find a similar country pattern of efficiency in an analysis of the change of agricultural productivity for a number of Central and Eastern European and former Soviet countries during the transition period. They conclude that countries more advanced in the transition process have more efficient farms than the less advanced countries. According to their analysis, efficiency is strongly correlated with general institutional reform. The Central European and Balkan countries, in which pre-reform distortions were milder and which faster implemented reform policies, showed faster productivity increases than the former Soviet republics.

[14] Model (11) is run twice, once with the full set of cells and once with the cells which in IMAGE are classified as agricultural cells (680 out of 1166 cells). For those agricultural cells, IMAGE has estimated crop fractions. For the non-agricultural cells, crop fractions are based on an optimization model such that they best fit production and land use per country. This procedure is less sophisticated than the allocation procedure used in IMAGE. In both model runs inefficiency levels are higher in the cells with more agricultural land. The procedure applied to allocate production over the cells, therefore, does not seem to cause additional noise in the data.

Table 3: Descriptive statistics on the inefficiency scores, ordered per sub-region

	(1) Average inefficiency (%)[1]	(2) Standard deviation	(3) Number of inefficient cells	(4) Number of efficient cells	(5) Median inefficiency
Total	10.1%	12.6	837	325	4.9%
Belarus	6.7%	11.1	77	42	2.3%
Estonia	7.4%	12.8	17	17	0.0%
Latvia	4.2%	6.1	23	18	0.5%
Lithuania	11.6%	13.2	33	6	9.9%
Moldova	30.0%	10.7	16	0	33.5%
Ukraine	14.7%	14.9	267	52	10.5%
Czech	3.0%	4.9	24	20	0.2%
Hungary	17.5%	14.7	38	6	16.4%
Poland	9.0%	10.2	131	41	5.2%
Slovakia	3.2%	5.7	10	17	0.0%
Bosnia	3.4%	8.0	11	11	0.0%
Croatia	2.0%	4.3	10	24	0.0%
Macedonia	3.8%	7.0	6	7	0.0%
Serbia	12.4%	13.2	35	8	8.0%
Slovenia	0.0%	0.0	0	13	0.0%
Albania	6.7%	9.1	12	2	1.9%
Bulgaria	12.2%	11.9	47	6	8.5%
Romania	8.3%	8.8	80	35	6.1%

Notes: 1) An inefficiency of λ=1.101 implies that the level of inefficiency is (λ-1)*100%=10.1%.

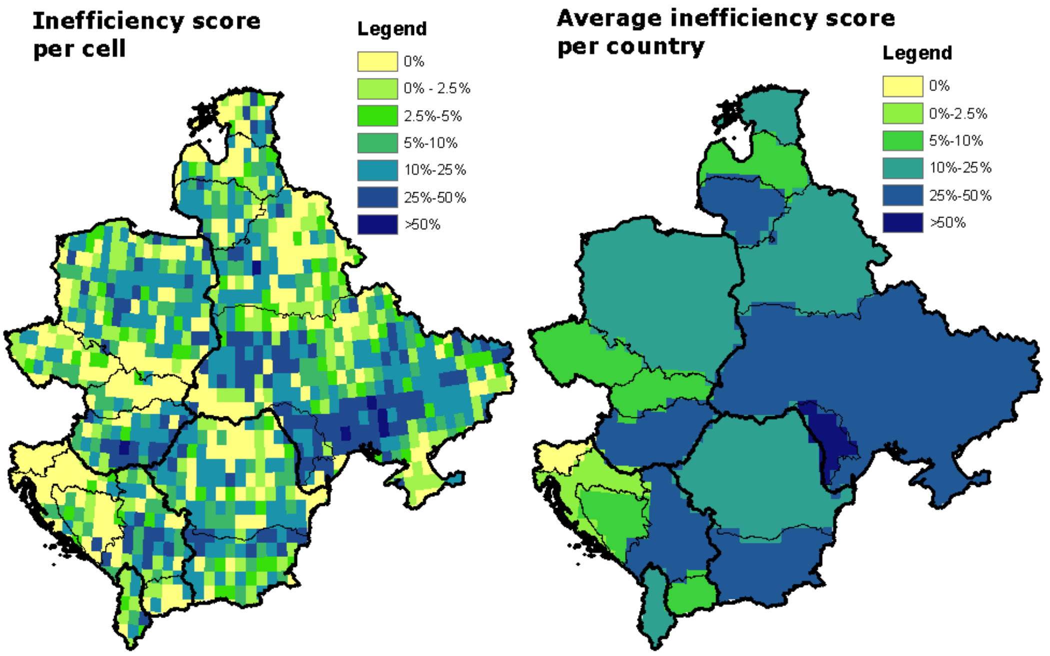

Figure 4: Maps of inefficiency scores per cell and averages per country

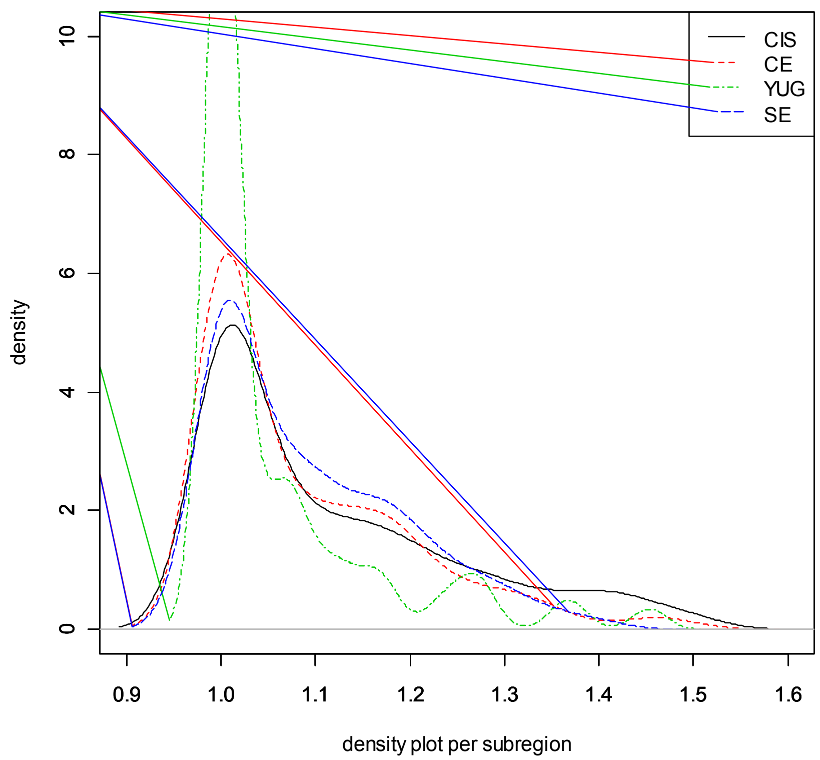

Figure 5: Kernel density plot of the inefficiency scores for the four sub-regions.

Result 1b

Does GDP have a positive or negative effect on efficiency? As explained above, the Kuznets-hypothesis purports that increases in income lead to lower efficiency, until a certain threshold after which regions become more efficient. This hypothesis is tested by non-parametrically regressing the ratio of conditional inefficiency to unconditional inefficiency, $\delta(Y,Q|GDP)/\delta(Y,Q)$ (Daraio and Simar 2007). This is done for the full sample and separately for each sub-region. For the output oriented approach, an increasing relationship implies that GDP is favorable to efficiency.

Figure 6 shows the relationship between $\delta(Y,Q|GDP)/\delta(Y,Q)$ and GDP and the partial regression line in which the other conditional variables are fixed at their mean values. Appendix 2 shows the relationships between the ratio of inefficiency levels and GDP separately for the different sub-regions. The left panel and the graphs in Appendix 2 show that on a cell level performance is affected by GDP. For low GDP levels, efficiency decreases with increasing GDP. Following the Mann-Whitney test, this decrease is significant at a 99% confidence level. For the graph in Figure 6, efficiency seems to increase again after a threshold GDP-level. This increase, however, is not significant and only based on a small number of observations. Also the graphs in Appendix 2, for each sub-region separately, do not show this increasing relationship. As a result, we cannot confirm that there is a Kuznets-type of relationship between efficiency and GDP. The right panel of Figure 6 shows the ratio of average conditional to unconditional inefficiencies per country regressed on per capita GDP per country. This graph also shows that at increasing income levels efficiency decreases. Following the Mann-Whitney test, this decrease is significant at the 95% confidence interval. This graph does not show the increasing part which is shown in the left panel. So, also at a national level, we do not see a Kuznets-type of relationship.

It follows that the first phase of the Kuznets-hypothesis can be confirmed; GDP does negatively affect efficiency. Poorer, less populated cells have less intensive agriculture due to which biodiversity, cultural services and carbon sequestration can reach higher levels. Increasing GDP levels result in agricultural intensification and consequently in a reduction of the other ecosystem services, but following from our analysis, overall efficiency reduces. The second phase of the Kuznets-hypothesis cannot be confirmed. Once regional income increases further and cells become more urbanized, combining the different ecosystem services is not done in a more efficient way. Also other Kuznets-type analyses find an indeterminate or weak relationship between biodiversity and GDP (Dietz and Adger 2003; Czech 2008; Mills and Waite 2009) and other efficiency analyses also point at the weak relationship between environmental efficiency and wealth (Zaim and Taskin 2000).

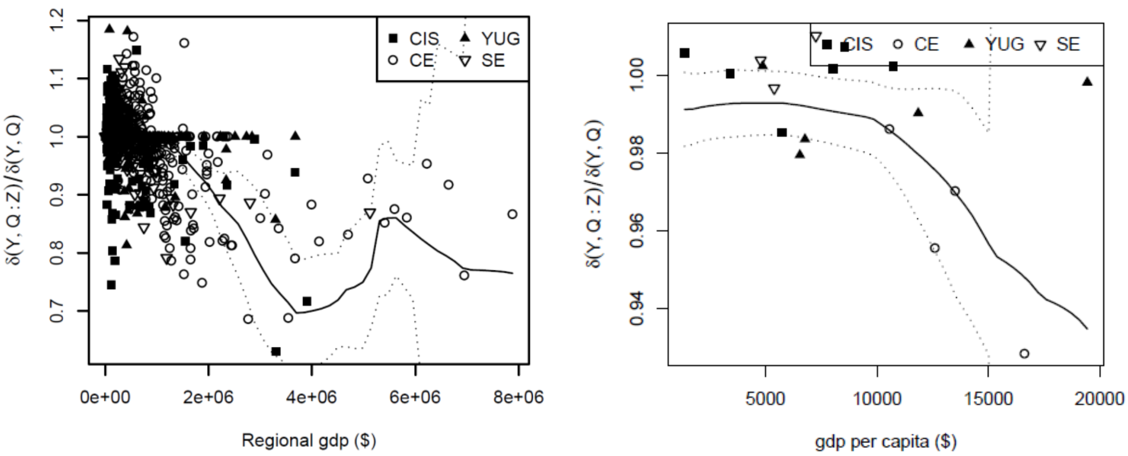

Figure 6: Partial regression plot of a) average regional GDP per cell and average δ(Y,Q|GDP)/δ(Y,Q) (left graph) and b) per capita GDP per country and average national δ(Y,Q|GDP)/δ(Y,Q) (right graph).

Note: The left panel show the non-parametric regression over all cells. The right one shows the ratio of average conditional and unconditional inefficiencies per country regressed on per capita GDP per country. The dotted lines give uncertainty ranges.

Result 2a

The next result tests concavity of the production possibility frontier. If this function is not concave, opportunity costs should be interpreted with care. Concavity of the production possibility frontier can be tested by checking quasi-convexity of the output distance function. For quasi-convexity, the bordered Hessian must be positive semidefinite, meaning all eigenvalues are non-negative - see Section 3. According to O'Donnell and Coelli (2005), only few studies test for convexity of the distance function. In fact, most studies estimating opportunity costs (or shadow prices) with frontier methods do not test for convexity but impose it by the particular choice of the functional form or by adding convexity constraints (see e.g. Färe et al. 2005; Bellenger and Herlihy 2010; Bostian and Herlihy 2010). In this way, the production possibility frontier is nicely concave, but one can wonder to what extent the resulting curvature and opportunity costs still reflect reality.

Curvature violations have consequences for the interpretation of the opportunity costs as the duality assumption between the distance function and benefit function, equation (16), no longer holds. For an observation at a concave frontier, opportunity cost

p_m in (17) is a benefit maximizing opportunity cost. For a downward sloping but convex frontier, however, it is a benefit minimizing opportunity cost. For a frontier which is convex nor concave, it is a local minimum or maximum. For all frontier shapes, however, the opportunity cost ratio (18) still reflects the change in y_1 due to a marginal change in y_m and therefore still reflects the trade-off between y_m and y_1 in the neighborhood of the observation y.

To test for concavity of the production possibility frontier, first, function (15), is estimated. As in many empirical applications, each of the continuous variables included is standardized. They are divided by their respective sample means such that each has a mean equal to one. The advantage is that coefficients estimated can directly be compared with each other. Moreover, non-monotonous observations are removed from the sample. The coefficients of the function $\ln\delta = \alpha_0 + \beta'\ln y + \frac{1}{2}\ln y'\Gamma\ln y + \gamma\ln z$ are listed in Table 4.

Table 4: Parameter estimates of translog function (15)

Coeff.(1)		Estimate	95% Confidence Interval(2)
α_0	Intercept	-0.211	(-0.252 - -0.144) *
β_2	Ln(*msa*)	0.374	(0.308-0.401) *
β_3	Ln(*cult.serv.*)	0.458	(0.371-0.496) *
β_4	Ln(*carbon*)	0.060	(0.035-0.089) *
Γ_{22}	½Ln(*msa*)Ln(*msa*)	0.622	(0.513-0.867) *
$\Gamma_{23} = \Gamma_{32}$	½Ln(*msa*)Ln(*cult.serv*)	-0.677	(-0.910--0.554) *
$\Gamma_{24} = \Gamma_{42}$	½Ln(*msa*)Ln(*carbon*)	0.045	(-0.032-0.093)
Γ_{33}	½Ln(*cult.serv*) Ln(*cult.serv*)	0.701	(0.549-1.034) *
$\Gamma_{34} = \Gamma_{43}$	½Ln(*cult.serv*)Ln(*carbon*)	-0.024	(-0.111-0.028)
Γ_{44}	½Ln(*carbon*) Ln(*carbon*)	-0.002	(-0.017-0.065)
γ_1	*GDP*	0.018	(-0.003-0.006)
γ_2	*Potential Yield*	-0.159	(-0.098--0.020)
γ_3	*Cover*	0.295	(0.121-0.200)
γ_{42}	Sub-region = CE(3)	-0.040	(0.012-0.098)
γ_{43}	Sub-region = YUG(3)	0.133	(0.032-0.133) *
γ_{44}	Sub-region = SE(3)	0.036	(-0.007-0.104)
β_1	Ln(*prov.serv*)	0.108	
Γ_{11}	½Ln(*prov.serv*)Ln(*prov.serv*)	0.008	
$\Gamma_{12} = \Gamma_{21}$	½Ln(*prov.serv*)Ln(*msa*)	0.010	
$\Gamma_{13} = \Gamma_{31}$	½Ln(*prov.serv*)Ln(*cult.serv*)	$-5.7\text{x}10^{-4}$	
$\Gamma_{14} = \Gamma_{41}$	½Ln(*prov.serv*)Ln(*carbon*)	-0.019	

Notes: (1) $\beta_1 = 1-\beta_2 - \beta_3 - \beta_4$, $\Gamma_{1i} + \Gamma_{2i} + \Gamma_{3i} + \Gamma_{4i} = 0$ for all i=1,2,3,4; (2) Variables marked with a * are significant at the 95% level. Confidence intervals are based on bootstrapping procedure with 200 runs. (3) The conditional variable sub-region is modeled as three dummy variables for the sub-regions CE, YUG an SE, where they have the value 1 if the respective cell is part of the sub-region considered and 0 otherwise.

The first-order derivatives of the distance function are positive for all observations. So, the distance to the frontier reduces if output levels increase. Similarly, at the frontier, higher levels of biodiversity, cultural services or carbon sequestration result in lower levels of provisioning services, showing that there is a trade-off between the different outputs (see (15)). In the inefficient cells it is, in theory, possible to have a win-win situation in which outputs increase without having negative trade-offs with the other outputs.

The distance function is not quasi-convex. For all observations the Hessian has both positive and negative eigenvalues implying that the frontier has a saddle point. This result is robust. The same result is also obtained for different formulations of the model, i.e. by removing one or more conditional variables, removing one output variable or formulating all conditional variables as categorical instead of continuous variable. As an illustration, Figure 7 plots for the sub-region SE the frontier in 3-dimensional plots, each time fixing one of the output variables at its mean value. As these plots in fact are extrapolations, they should be interpreted with extreme care, especially at the boundaries and the areas with only few observations. These plots also show that the frontier is not concave.

To conclude, the frontier is non-concave. Even though this result is inconvenient from an economic point of view, Dasgupta and Maler (2003), Brown et al. (2011) and Tschirhart (2011) argue that such non-concavities apply more often – see also Section 3, Dasgupta and Mäler (2004) and Crepin (2004).[15] Spillovers, positive externalities, species interactions and feedback effects from natural systems into social systems may result in non-concave frontiers. So, curvature violations most likely are part of the system and are not caused by data errors or wrongly specified models. The seemingly downward sloping, convex relationship between provisioning services and carbon sequestered may be caused by diseconomies of scope. A meta-analysis of data on land use change and carbon sequestration indicates that conversion from grassland to financially more attractive cropland results in a significant decline of soil carbon stocks and vice versa (Guo and Gifford 2002). Similarly, Boscolo and Vincent (2003) conclude that in forestry the joint production of timber and non-timber products may have a non-convex relationship. As a result, output specialization gives higher net returns than output diversification. Moreover, it implies that opportunity costs decrease for increasing output levels, indicating that for a fixed input level, increasing one output results in a reduction of the other outputs but at a decreasing rate.

Another interesting observation from Figure 7 is that for low enough levels of biodiversity it seems to be possible to improve biodiversity and provisioning services at the same time. We have to be careful drawing too strong conclusions on this, because it is based on only a few observations. Such a complementary relationship, however, is a

[15] Dasgupta and Mahler (2003) argue that " the word "convexity" is ubiquitous in economics, but absent from ecology. There is a reason for each. As prices are prominent in modern transactions, it is but natural that we would wish to uncover the ways in which the price system is capable of functioning as a resource allocation mechanism. ... We now know that the price system can be an efficient allocation mechanism if transformation possibilities among goods and services – in and over time – constitute a convex set. However, in non-convex environments, we still do not have a clear understanding of the mechanisms by which resources are allocated except in the case of specific partial economic systems. So we economists continue to rely on the convexity assumption, always hoping that it is not an embarrassing simplification. ... Ecologists have no comparable need to explore the structure of convex sets [as they don't optimize anything]. They are interested in identifying pathways by which the constituents of ecosystem interact with one another and with the external environment. A large body of empirical work has revealed that those pathways in many cases involve transformation possibilities among environmental goods and services that, together, constitute non-convex sets. Often the non-convexities reflect positive feedbacks in Human-Nature interactions. ...The price mechanism is especially problematic in economic systems characterized by positive feedback processes. We now know that in such environments it may prove impossible to decentralize an efficient allocation of resources by means exclusively of prices." The Dasgupta & Mäler article is an introduction to a special issue of Environmental & Resource Economics published in 2003. The papers in this special issue give detailed attention to time but not to space. There has been little improvement in this respect since 2003. This is a major limitation in particular with respect to ecosystems services association with terrestrial ecosystems. These services are modulated by biophysical interactions (both present and from the past) at and between (usually but not necessarily nearby) locations. An additional complication is that the utility derived from these services by humans may also be modulated (present, past and also future). So, that may give non-convexities in the utility function as well. These complexities may have serious consequences for valuation studies attempting to estimate demand functions for ecosystem goods and services. In case of such non-convexities, it may well be that the estimates or demand functions produced by these valuation studies are not utility optimizing but only provide at best a local maximum but maybe even a minimum. We don't know of work any that properly analyzed these issues in detail.

plausible result as for biodiverse poor areas, increasing biodiversity also supports biotic processes which are beneficial for agricultural production as well. The lower agricultural production due to a loss in agricultural land can be compensated by the positive externalities of higher biodiversity. Once biodiversity exceeds a certain level, the positive externalities can not compensate for the loss in land. Likewise too high levels of biodiversity may also harm agricultural productivity.

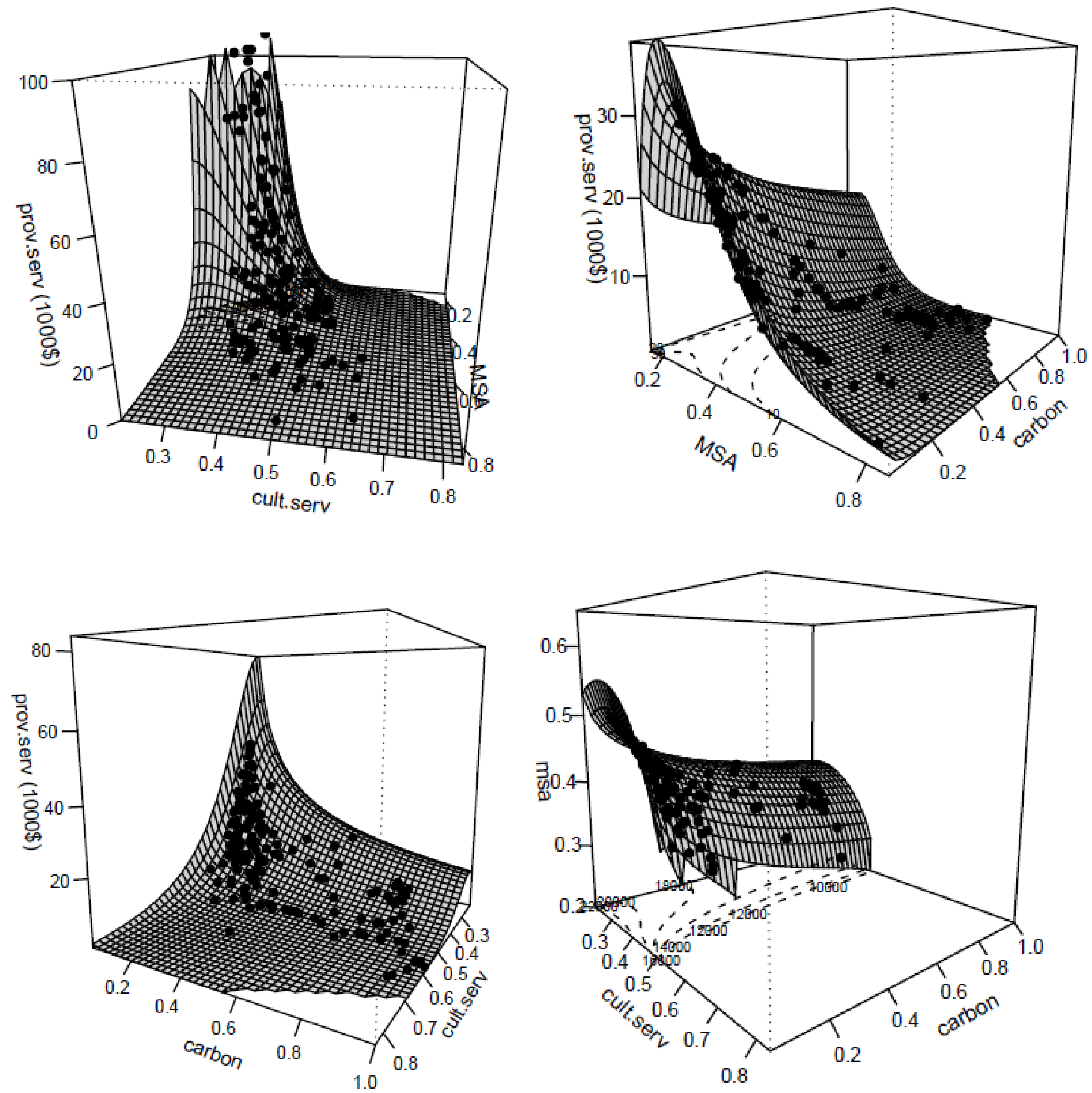

Figure 7: 3-dimensional plots of the frontier for the sub-region SE.

Note: The plots for the other three sub-regions are similar. Contour plots are given on the x-y plane. The dots on the frontier are the observations on which the regression is based projected on the frontier. To draw the different plots, the output not given in the plot and the conditional variables are fixed at their mean values. For the range of values given by the x-y coordinates, the corresponding level of z-values is determined using (15).

Result 2b

On average, performance in the CIS-countries is shown to be lower than in most of the other sub-regions – see Table 3. This, however, does not mean that their average production levels are lower. Inspection of the frontiers shows that the production possibility frontier of the CE sub-region is above the frontiers of the other sub-regions.

The coefficients γ_{42}, γ_{43} and γ_{44} prove that the frontier for the CE sub-region is the highest and the one for the YUG sub-region is the lowest, even though the YUG-countries had the lowest levels of inefficiency. The frontiers for the SE and CIS sub-regions are close to each other – see also Figure 8.[16]

This result implies that in the year 2000, the CE sub-region, being by far the richest sub-region in our sample, had higher potential joint production levels than the other sub-regions. Most countries from the CE-region, except for Hungary are already close to this frontier as they have relatively low inefficiency levels. For the CIS-countries, potential production is relatively high as well, but, given the high levels of inefficiency, many cells are still far from this frontier. For the YUG-countries, potential production is still relatively low, but most cells are already close to the frontier. For these countries, further productivity increases require technical improvements that make it possible to shift the frontier outwards. For the CIS-countries productivity increases seem to be feasible without many technical changes.

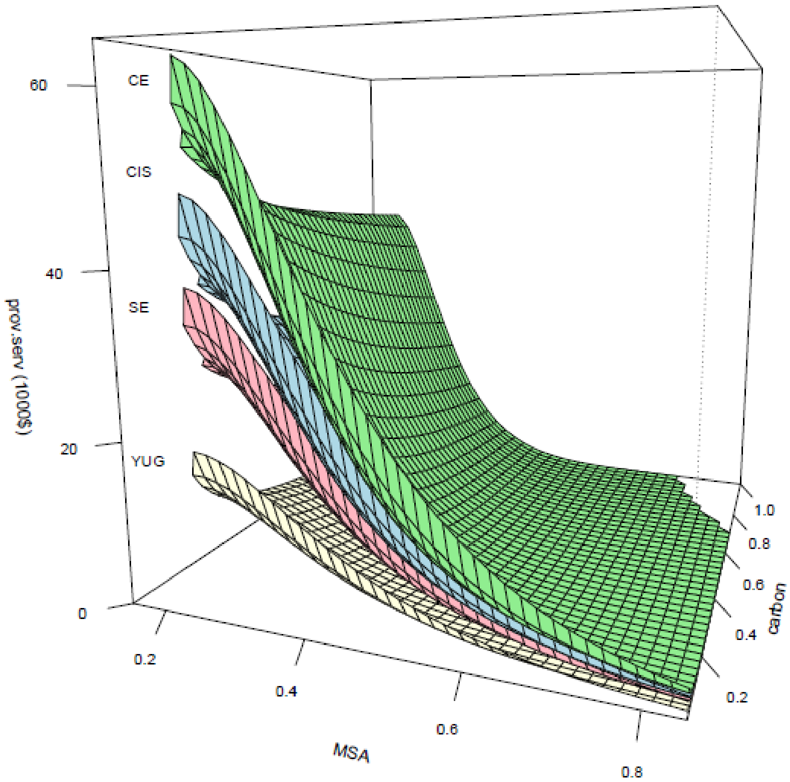

Figure 8: 3-dimensional plot of the frontiers for the four sub-regions in the biodiversity – carbon – provisioning services plain.

Note: The value for cultural services is fixed at its mean value. One should take care when interpreting the shape of the frontier beyond the range covered by the observations. For that reason, the increasing part of the frontier for low MSA levels (see the second plot of the previous figure) is not shown in this figure.

Result 2c

The final result concentrates on opportunity costs. Opportunity cost ratios are estimated using (19). The opportunity cost ratio is the ratio of the output's marginal performance to the marginal performance of provisioning services. Here marginal performance refers to the output's marginal contribution to reducing inefficiency. So, for

[16] Note that the function estimated, function (15), is $-\ln(y_1) = f(y_2, y_3, y_4, z_1, z_2, z_3)$, such that a positive coefficient for dummy variable Z_3 implies that the frontier is shifted inwards.

each observation, the opportunity cost ratio reflects the relative value of the outputs relative to the gross value of provisioning services.

It should be kept in mind that the opportunity cost ratios reflect the marginal rates of transformation at the frontier, i.e. when output is technically efficient – see (19). This marginal rate of transformation reflects the gross benefits from provisioning services foregone due to a change in any of the other output variables. Those regions not on the frontier in theory underemploy the available labor, physical and natural capital and could in theory increase one output without sacrificing another (see also footnote 4). For those cases, opportunity costs are zero.[17] The frontier reflects the Pareto optimal production possibilities, given current input levels, income and technological possibilities. As explained in Section 2, in case of a perfect market situation, they would be equal to the marginal rate of substitution and therefore also reflect society's priorities and be allocatively efficient, i.e. be the welfare optimizing points. In case of externalities, market imperfections or public goods, as in our case, this not necessarily is the case. Even if an observation is technically efficient, non-marketed ecosystem services may be under- or oversupplied if their levels do not reflect preferences. The opportunity costs presented here do not reflect these preferences, nor do they reflect the willingness to pay for having more or less of a certain ecosystem service. They, in fact, represent the willingness to supply an additional unit of a certain ecosystem service and reflect the gross revenues from provisioning services to be sacrificed to supply one extra unit of another ecosystem service. Due to the non-concavity of the frontier, the opportunity costs may not reflect the revenue optimizing price ratio. They do, however, still show the trade-offs resulting from a marginal change in any of the outputs.

Based on the coefficients given in Table 4 and equation (19), the opportunity cost ratios for the different outputs are derived and presented in Table 5, Table 6, Figure 9 and Figure 10. The effects of small output changes on opportunity costs are exemplified using the Morishima Elasticity of Transformation (MET) which provides a measure for the curvature of the frontier– see (20). Estimates of the MET are given in Table 7 and Figure 11. The opportunity costs are given in terms of the reduction of gross benefits from provisioning services due to a 1% change in the output value. They are also given per kg of wild food hunted or gathered (fish, fruit, game and mushrooms), per tourism point and per ton of carbon sequestered. Due to the particular interpretation of the opportunity costs, it is difficult to directly compare them with other studies. This is especially the case for the cultural services indicator, which is composed of a tourism index and hunting and gathering index which are constructed especially for this project. Also the opportunity cost for mean species abundance is difficult to compare with other studies as there are hardly any studies estimating opportunity costs for biodiversity on agricultural land (Polasky and Segerson 2009; Tschirhart 2009) and when it is attempted, most often trade-offs between biodiversity and agriculture are modeled in stylized integrated ecological-economic models (Brock and Xepapadeas 2003; Eichner and Pethig 2006).

For interpreting the carbon index, remember that an increase in carbon sequestration refers to changing land use from e.g. agriculture to a land cover sequestering more carbon. A switch from arable land to extensive grassland would yield 0.3-0.8 ton carbon per ha per year; a switch to forest would increase sequestration

[17] Note that the opportunity costs are estimated for each observation. For the observations not on the frontier, these values reflect the trade-offs for the situation in which they moved towards the frontier. As these opportunity costs at their current level of efficiency are zero, there are (in theory) no foregone benefits from provisioning services if they move towards the frontier.

more, but this would be very costly changes. Antle et al. (2003), construct a marginal opportunity cost curve for sequestering carbon in the soil. This curve is based on an analysis of the farm opportunity costs per ton of soil carbon for five cropping system in the US in which annual carbon rates range from 0.06 to 0.68 ton per hectare per year (for those having positive rates). The resulting marginal farm opportunity costs, which reflect effects on net farm revenues, range from $20 to $100 per ton carbon. Similarly, MacLeod et al. (2010) estimate for the UK a carbon abatement cost curve for agricultural emissions from crops and soils. They estimate a shadow price of carbon of £35 per ton CO_2 ≈ £128.24 per ton carbon ≈ $198.74 per ton carbon for 2022 and argue that 11.5% of emissions from agriculture can be abated at a marginal abatement cost of £46 per ton CO_2 = £168.54 per ton C ≈ $261.20 per ton C. For higher abatement levels, marginal abatement costs far exceed the estimated shadow price. Note that these values reflect effects on gross farm revenues.

The average opportunity cost of $263 per ton of carbon sequestered as estimated above are in line with the estimates from MacLeod et al. (2010). To compare the estimate with results from Antle et al. (2003), the opportunity cost estimate of $263 of gross farm revenues foregone per ton of carbon must be transformed to net farm revenues foregone. For this, the gross benefits have to be multiplied with the social profit rate, which relates the value added of an economic activity to the value of gross output of this activity at world prices. Hughes and Hare (1994) provide an estimate of the average medium run social profitability of agriculture for a selection of eastern European countries of 7.25%. Using this rate, our average opportunity cost of $263 of gross benefits lost due to an extra ton of carbon sequestered implies a loss of net benefits of $19, which is in line with the order of magnitude of the estimates from Antle et al. (2003).

As shown by the results and especially Figure 10, opportunity costs differ substantially between the different countries but also within country differences are large. On average, opportunity costs are lowest in the more wealthy CE countries and higher in the poorer countries (especially the YUG and CIS countries). Each country, however, has regions with high and low opportunity costs.

Further analyzing the opportunity cost function shows that carbon opportunity costs increase with decreasing levels of carbon, biodiversity and cultural services and with increasing levels of provisioning services. So, the higher the level of provisioning services, the higher the provisioning services forgone to store an extra unit of carbon. Next to that, one extra unit of carbon stored has a higher opportunity cost for low levels of carbon sequestration than for higher levels. Moreover, as shown by the positive but decreasing Morishima elasticities, these opportunity costs decrease with a decreasing rate; so very fast for low carbon levels and slowly for higher carbon levels. In other words, it becomes cheaper to increase carbon sequestration when sequestration levels increase, but at a decreasing rate. This pattern is also observed in Figure 7. For low carbon levels, an extra unit of carbon stored will result in a larger loss of provisioning services (i.e. has a larger opportunity cost) than when carbon levels are higher. If sequestration is higher, a larger part of the cell will be covered with forest and agricultural production will already be low. Sequestering somewhat more will not demand a huge sacrifice from the provisioning services. This implies that we have a situation with increasing returns to scale in which it is more cost-effective to sequester more carbon in areas already having high levels of carbon sequestration and in areas less interesting for agricultural production. Areas currently covered with more forest may be less suitable for agriculture due to which transforming land from agriculture to other land uses may result in relatively low agricultural benefits foregone. It also implies it may be cost-effective to have a certain level of specialization per cell, in which particular cells are more focusing on provisioning services and others more on carbon sequestration. Looking at Table 6 and the maps in Appendix 1, it follows that opportunity costs are higher in the countries having above average agricultural production and below average carbon sequestration and biodiversity, like Macedonia, Molodova and Hungary. Each country, however, has its areas with higher and lower levels of provisioning services, making it possible within each country to find the most cost-effective locations for increasing carbon sequestration.

The picture for the opportunity costs for biodiversity and cultural services is more mixed. For both outputs, their opportunity costs increase with higher levels of provisioning services. So, the higher the levels of agricultural production, the higher the revenue from provisioning services foregone when biodiversity or cultural services increase. As a result, increasing biodiversity is more cost-effective in areas with low agricultural production than in the high production areas. The relationship between biodiversity levels and their opportunity costs, however, is more complex. The same applies for cultural services. The Morishima elasticities are negative for most and positive for some observations. As a result, it depends on the cell characteristics, whether increasing biodiversity becomes more expensive or not. It follows that the relationship between provisioning services and biodiversity is concave at first but becomes convex after a certain threshold level of biodiversity. The level at which this kink is observed depends on cell characteristics like provisioning services, carbon sequestration and land cover. The higher carbon levels, the higher the threshold level. Moreover, the higher the levels of provisioning services, the higher opportunity costs for biodiversity are and the higher the rate at which these opportunity increase with rising biodiversity levels (very negative Morishima elasticities). This implies that in general, and especially so for regions having high agricultural production, it becomes more expensive to increase biodiversity if biodiversity levels are higher (even though at a decreasing rate). However, after a certain threshold level, which is cell specific, opportunity costs start to decrease again. Moreover, combining high levels of biodiversity with high levels of agricultural production is difficult. For cultural services, more or less the same pattern is observed as for biodiversity.

It is interesting to observe that increasing carbon sequestration becomes cheaper with higher levels of carbon, whereas increasing biodiversity continues to become more expensive for most observations. Increasing carbon sequestration can be done at low (opportunity) costs, but at the same time increasing biodiversity is more difficult. For increasing sequestration transforming agricultural land to extensive grassland or monoculture forests may be enough. Improving biodiversity demands more effort. Only when a certain biodiversity level is realized (which is already rather high), further increasing biodiversity becomes easier. In those cases external pressures are low and ecosystem processes support instead of compete each other.

Another interesting observation is that correlation coefficients may hide the relations between the variables due to which conclusions based on correlation coefficients alone would lead to flawed conclusions. For example the correlation coefficients between opportunity costs and output variables show that regions with higher levels of provisioning services and lower levels of biodiversity, cultural services and carbon sequestration generally have higher opportunity costs than regions with lower output levels. For carbon this result also follows from analyzing in detail the features of the opportunity cost function. For biodiversity and cultural services, however, the correlation coefficients would lead to the conclusion that for regions with lower biodiversity levels it would be more expensive to improve biodiversity than for regions with higher biodiversity levels. In other words, we would have a situation with increasing returns to scale. The above analysis, however, showed that this relationship is more complex and also depends on other cell characteristics like the level of provisioning services and carbon sequestration in the cell. Increasing returns to scale for biodiversity may apply, but not for the full range of possible biodiversity levels; only if agricultural production is low. Simply taking correlations may hide some of the relationships as not all effects are controlled for, which is done in the opportunity cost function (19).

To conclude, the maps shown in Figure 10 show in which regions it is expensive to improve biodiversity, cultural services or carbon sequestration – also compare the maps in Appendix 1 showing the values of the output variables within each cell. There is considerable variation within each country, but each country has regions in which improving any of the output variables is cost-effective. Figure 11 show to what extent it becomes more or less expensive to further increase outputs. Especially in regions having high negative Morishima elasticities, further increasing the variables becomes more expensive very fast. If these regions already have high opportunity costs, these regions are least suitable for further improvements. Cost-effectiveness is higher in the regions with lower opportunity costs and low negative or positive Morishima elasticities. So, these maps are helpful for prioritizing conservation policies.

Table 5: Mean opportunity cost ratios

	Mean	Median	Standard deviation	Min	Max
MSA ($ per % MSA index)	1,276	1,027	1,029	1	8,846
Cultural services ($ per % cult.serv index)	1,865	1,368	1,706	0.3	12,587
Wild fish ($ per kg)	415	305	380	0.1	2,802
Wild fruit ($ per kg)	76	56	70	0.01	513
Wild game ($ per kg)	8,857	6,499	8,102	1.5	59,777
Wild mushrooms ($ per kg)	81	59	74	0.01	543
Tourism ($ per tourism point)	4,998	3,668	4,572	0.8	33,736
Carbon ($ per % carbon index)					
($ per ton C)	263	202	220	1.4	1,986

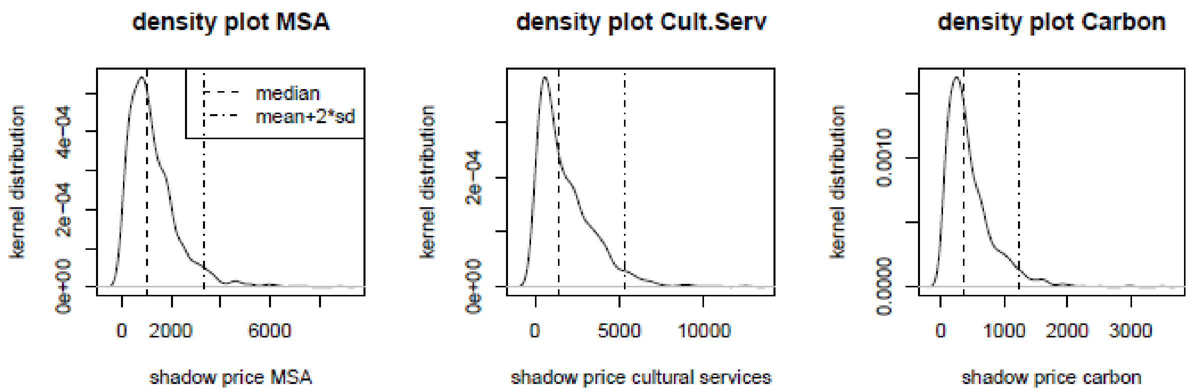

Figure 9: Density distribution plots of opportunity costs

Table 6: Median opportunity cost ratios and standard deviations per country

	MSA ($ per % MSA)		Cultural services ($ per % cult.serv index)		Carbon ($ per tonne carbon)	
	Median	St.Dev.	Median	St.Dev.	Median	St.Dev.
Total	1,027	1,029	1,368	1,706	202	220
Belarus	1,008	597	666	503	125	55
Estonia	247	310	233	339	62	65
Latvia	667	482	699	587	139	89
Lithuania	702	254	1,234	510	211	78
Moldova	1,534	707	2,633	1,664	490	151
Ukraine	1,184	944	2,323	1,878	220	190
Czech	363	486	1,103	1,149	246	170
Hungary	1,308	543	2,286	1,741	342	232
Poland	792	615	1,329	1,110	224	183
Slovakia	521	831	560	1,364	110	97
Bosnia	1,904	2,344	694	2,031	284	134
Croatia	870	772	934	1,414	222	108
Macedonia	1,817	770	1,412	1,243	1,169	419
Serbia	1,206	833	1,159	2,043	374	151
Slovenia	111	312	314	539	66	67
Albania	1,208	1,046	1,577	1,204	315	260
Bulgaria	1,635	779	1,947	960	347	181
Romania	2,064	1,439	2,464	2,440	155	294

Table 7: Morishima elasticity estimates

	mean species abundance			cultural services			carbon		
	mean	median	st.dev.	mean	median	st.dev.	mean	median	st.dev.
Total	-6.50	-0.80	144.73	-2.12	-0.40	24.09	0.87	0.87	0.04
Belarus	-0.15	-0.11	0.36	-4.60	-1.24	21.58	0.84	0.84	0.02
Estonia	-0.67	-0.52	0.74	-1.09	-0.65	1.91	0.83	0.83	0.02
Latvia	-0.89	-0.56	1.35	-19.12	-0.57	116.76	0.84	0.85	0.04
Lithuania	-2.50	-1.42	4.37	-0.31	-0.21	0.38	0.87	0.87	0.01
Moldova	-1.68	-1.84	0.87	-0.34	-0.11	0.60	0.90	0.90	0.02
Ukraine	-2.15	-1.27	4.00	-0.89	-0.21	7.45	0.87	0.88	0.05
Czech	-5.37	-2.48	11.38	-0.16	-0.09	0.26	0.88	0.88	0.02
Hungary	-9.15	-1.21	30.23	-0.37	-0.25	0.44	0.89	0.89	0.03
Poland	-2.69	-1.22	5.93	-0.42	-0.26	0.53	0.87	0.87	0.03
Slovakia	-183.80	-0.81	931.40	-0.68	-0.44	0.82	0.84	0.84	0.04
Bosnia	-0.04	0.17	0.60	-5.03	-3.75	4.28	0.87	0.87	0.02
Croatia	-2.02	-0.67	5.02	-1.46	-0.50	3.37	0.87	0.86	0.03
Macedonia	-0.56	-0.23	0.74	-2.18	-1.28	2.37	0.91	0.90	0.01
Serbia	-4.92	-0.34	11.59	-1.66	-0.85	1.96	0.89	0.88	0.04
Slovenia	-3.12	-2.14	2.86	-0.25	-0.12	0.50	0.83	0.83	0.02
Albania	-1.67	-0.70	1.97	-0.90	-0.49	1.54	0.88	0.88	0.02
Bulgaria	-0.61	-0.37	0.88	-0.94	-0.78	0.74	0.87	0.88	0.02
Romania	-1.04	-0.58	2.34	-2.84	-0.51	10.00	0.86	0.87	0.07

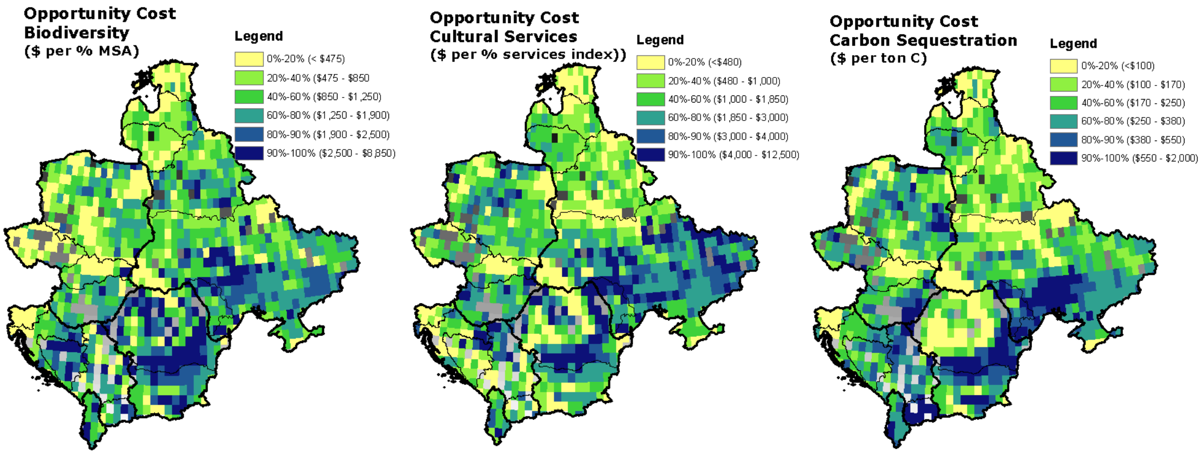

Figure 10: Maps of opportunity costs per cell for a) mean species abundance ($ per % MSA), b) cultural services ($ per % cultural services index) and c) carbon sequestration ($ per tonne carbon).

Note: Classification of the cells is such that each color corresponds with 10% or 20% of the observations. Grey cells are non-monotonic observations or outliers.

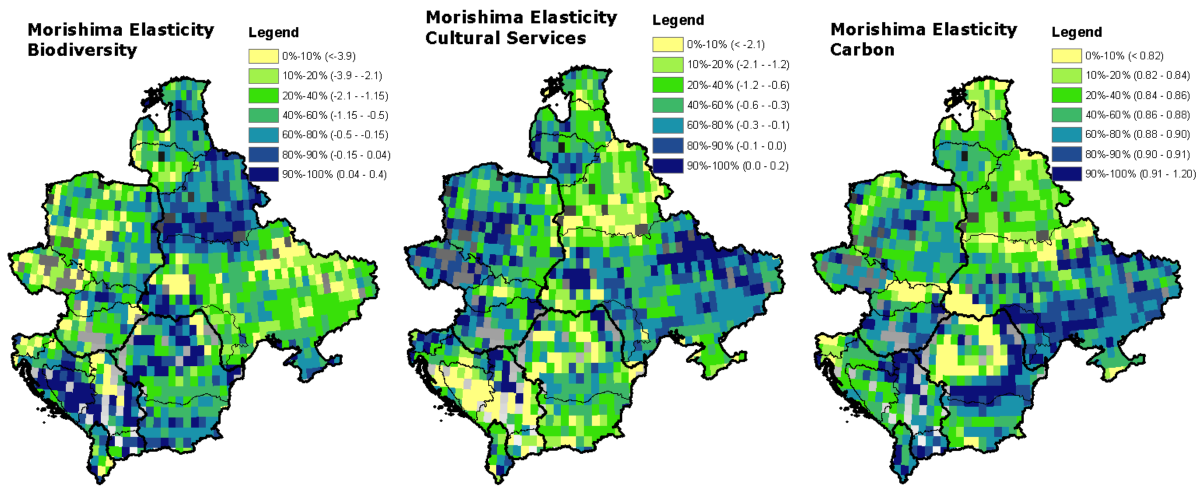

Figure 11: Maps of Morishima elasticities of transformation for a) mean species abundance ($ per % MSA), b) cultural services ($ per % cultural services index) and c) carbon sequestration ($ per tonne carbon).

Note: Classification of the cells is such that each color corresponds with 10% or 20% of the observations. Grey cells are non-monotonic observations or outliers.

6. Discussion

This paper presents a new approach to 1) assess differences in regional performance in the generation of income, biodiversity and ecosystem services and to 2) estimate trade-offs between ecosystem services, biodiversity and income. To the literature on integrated assessments, our approach adds an economic interpretation of the ecological relationships observed; what are opportunity costs of changes in ecosystem services and to what extent do they differ per region? Moreover, we provide an objective judgment on the overall performance of a region and give policy relevant information about possible directions of Pareto improvements and factors affecting performance. These insights are helpful for prioritizing the regions requiring attention and for searching cost-effective policies. Moreover, given insights in the location of a region on the frontier, i.e. the combination of ecosystem services generated in the region, it can be questioned whether this corresponds with what people want or whether another combination of services is preferable. The frontier information shows what is possible and which opportunity costs changes bring about.

The paper also adds to the growing literature on environmental valuation the insight that trade-offs explicitly depend on the biophysical interactions between biodiversity and ecosystem services. Currently, the valuation of ecosystem services and biodiversity receives ample attention.[18] By estimating a monetary value of the welfare effects of changes in levels of biodiversity and ecosystem services, financial effects of interventions can be weighed more easily with the associated biodiversity and ecosystem services effects. Valuation of ecosystem services is especially used within cost-benefit analysis (CBA) for making the welfare consequences of the different effects of an intervention more easily comparable. If all effects, including those on ecosystems, are shown in the same unit, comparing interventions or policy measure becomes easier and more transparent. Even though we do not want to underscore its usefulness, CBA and especially the use of valuation methods have their limits (see e.g. Gatto and De Leo 2000). Especially when also the ecological and environmental impacts as such of decisions are important to the decision makers, summarizing all effects in one monetary value does not provide sufficient information. Using cost-effectiveness analysis (CEA) is useful in those cases. In a CEA, trade-offs between ecological or environmental impacts and costs are presented. Three reasons for doing a CEA for the analysis of ecosystem services are the following:

1. First, in principle, from a demand side perspective, environmental valuation attempts to value human preferences for environmental changes. For many ecosystem services, however, preferences are not yet well-developed or unstable because people lack information about their importance. So, it is not clear what is measured and to what extent the estimated values reflect the true welfare effect. In addition, valuation in economic parlance can fail to capture non-economic motivations which may be written in the much more narrative language of obligations, virtues or culture. As remarked in TEEB (2010), "if we ask people their willingness to pay for biodiversity, it is likely that people actually state their willingness to pay for biodiversity", without capturing non-utilistic and non-individual motivations. A review of recent studies on ecosystem services indicates a lack of attention for the social dimension (Menzel and Teng 2010; Chan et al. forthcoming).
2. Secondly, and related to the first point, still much is unknown about ecosystem functioning and the importance of particular species or processes. As a result, it is unclear whether valuation studies provide an underestimate because not all processes are included or an overestimate because the importance of some processes is exaggerated. Showing trade-offs between processes and services helps to understand the interlinkages, to inform people and in the long run to shape and sharpen preferences. It shows, given regional characteristics, which changes can be expected when land use is adapted.

[18] Overviews and in-depth discussions of the methods to value ecosystem services were initiated in the USA by the National Academy of Sciences (National Research Council 2005) and the US Environmental Protection Agency (US Environmental Protection Agency 2009). Recently, the TEEB study (the economics of ecosystems and biodiversity) provided an overview of the state-of-the-art knowledge on valuation methods and marginal values of ecosystem services for ecosystems around the globe (TEEB 2010). TEEB is based on an evaluation of the environmental valuation literature of the last decades. As a follow-up of this, several European governments are planning to perform or finalizing a TEEB-like study for their own country in order to get a better idea of the importance of their natural resources for their economy (see e.g. UK National Ecosystem Assessment 2011).

3. Thirdly, especially the regulating and supporting services do not provide human benefits themselves, but they are necessary for producing those services that provide human benefits (Wallace 2007; Fisher, Turner et al. 2009). This does not mean they are not valuable. Rather, their value is embodied in the value of final ecosystem services (Boyd and Banzhaf 2007). If values of intermediate and final services are estimated separately and then aggregated, as is often done, one runs the risk of double counting values (Fisher, Turner et al. 2008). Moreover, showing aggregate values of ecosystem services hides the biophysical information, which is also relevant for decision making. The trade-off estimates shown above embody the importance of the intermediate services and therefore properly show from a supply side perspective the effects of changes in the generation of ecosystem services.

Due to the problem that human preferences on biodiversity and ecosystem services are not stable yet, it is important to learn more about the biophysical interactions between the different ecosystem services and the opportunity costs of particular changes before attempting to put monetary values on them. Actually, the results of this study serve as input in the process in which human preferences on ecosystem services and biodiversity are gradually shaped and sharpened. It therefore fits the ideas proposed by Polasky and Segerson (2009) who discuss the opportunities and challenges for integrating insights from economic and ecological research for public decision. If normative methods are controversial or not yet appropriate, it may be preferable to adopt positive methods to show the trade-offs of effects of public interventions. Due to the discussions surrounding normative methods (incl. valuation methods), it may be preferable to use positive methods first and learn more about the trade-offs of public interventions.

The method presented here has a number of advantages in comparison with valuation studies and other efficiency analyses. Comparing it to valuation studies on biodiversity and ecosystem services, the method used, despite of its data requirements, is less data intensive than many other (especially stated preference) valuation techniques. Moreover, it does not require any strong assumptions on people's preferences or their stability which plague valuation studies on the same topic. On the other hand, comparing it to other efficiency studies adopting stochastic frontier methods or data envelopment analysis, no prior concavity assumptions on the frontier (or convexity assumptions on the production possibility set) have to be made. Even though this also affects interpretation, one can wonder what results mean if concavity assumptions are made and in reality the biophysical relations show non-concavities. They may show erroneous trade-off relationships and therefore lead to wrong policy recommendations.

It has to be noted, however, that the opportunity costs presented here, reflect effects of marginal changes. As valuation studies can not be used for estimating the value of full ecosystems or of large changes but only for marginal changes, also the opportunity costs can not be used for evaluating effects of large changes. This implies that the method can not be used to evaluate for example whether it is better to organize land use in a country such that some parts are specialized in provisioning services and other parts in other services or such that ecosystem services are balanced in all cells. For that, other methods are necessary.

Even though we have to be careful drawing policy conclusions due to data incompleteness, the current analysis results in a number of interesting policy insights. First, the richer countries, containing the Czech Republic and the former Yugoslavian republics have the lowest inefficiency levels, indicating that most regions are close to their potential. Hungary is a special case as large differences are observed within the country. The richer countries, Central European countries like Czech Republic, Slovakia, Poland and Hungary, currently, have a higher potential than the other countries. Moreover, the YUG-countries, currently seem to have lower capabilities than the other countries. Considering the result that their efficiency levels are high, improving production implies that technical improvements are necessary to shift the frontier outwards. The CIS-countries, on the other hand, have relatively high capabilities, but many regions are still far from their potential. In these regions it is, in theory, possible to improve e.g. biodiversity without sacrificing agricultural output. In principle, performance could be improved in a relatively large number of regions without too many sacrifices.

Secondly, the relation between regional performance and GDP is decreasing. At low income levels an increase of income does result in a deterioration of performance levels. After a certain threshold income level is reached, the relation between efficiency and income is insignificant. This implies that performance improvement requires active involvement of policy makers and clear priority setting. Without policy interference, efficiency will deteriorate and improvement in one output variables will result in a decline of another output variable. The trade-off analysis can be used as input in cost-benefit analysis to derive the possible gains and losses of policies to improve performance.

Thirdly, a result which is important for many economic analyses on ecosystem services is that the production possibility frontier, exhibiting the possible interactions between the different ecosystem services, is non-concave. As a result, frontier functions as estimated in the current paper should be interpreted with care. The same applies, mutatis mutandis, for demand functions estimated using stated or revealed preference methods. With non-concavity, it is unclear whether the resulting prices refer to utility maximizing output levels; they may as well refer to utility minimizing levels or to local optima. This caveat carries over to any further study using these results, such as cost-benefit analysis. More analysis is needed to properly evaluate this apparent violation of basic economic convexity assumptions. Even though it is a rather unpleasant result for economic analyses, it is of no surprise for ecologists who are not interested in optimizing economic behavior but in observing interacting species.

Fourthly, opportunity cost information shows that trade-offs differ substantially between regions. On average, higher income countries have lower opportunity costs than the poorer countries in our sample implying that in richer countries land use changes will entail lower opportunity costs. Within country variation, however, is large and countries have regions in which trade-offs are high and regions in which they are low. Given this variation, one has to be careful using benefit transfer methods which are used more and more often to generalize results from environmental valuation studies. Generally, opportunity costs increase for higher levels of provisioning services. For most regions, they also increase for higher levels of biodiversity levels and cultural services, but they decrease for higher carbon levels. Carbon levels are higher in areas with low agricultural productivity than in areas with higher agricultural productivity. So, increasing carbon sequestration in areas with low carbon levels will result in a large loss of agricultural production, which explains its high opportunity cost. Carbon sequestration has economies of scale characteristics. On the other hand, increasing biodiversity and cultural services will be more costly if areas are targeted with higher levels of biodiversity or cultural services, even though at a decreasing rate. Only after a certain threshold biodiversity level, further increasing biodiversity may be done at lower costs. So, until a certain biodiversity level, biodiversity and agricultural production have economies of scope characteristics. For higher levels, specializing becomes more cost-effective.

The approach presented here can potentially be applied in other related fields of research as well. The opportunity cost information obtained from the current analysis, especially if extended for multiple regions, multiple ecosystem services and multiple years, can serve as useful input in for example studies on sustainable national income. The results clearly show the dependence of opportunity costs on current levels of ecosystem services and the loss or gain of income if biodiversity or ecosystem services levels change. Traditional national accounting methods do not include the loss or gain in non-marketed goods; the opportunity costs estimated here can serve as proxies. For this purpose, however, more services would need to be included and trade-offs evaluated in terms of net benefits instead of gross benefits as in the current analysis.

The number and type of policy implication offered by future analyses will benefit from fewer restrictions on data availability. Obviously, if more outputs are modeled, more trade-offs can be analyzed. If provisioning services from forest cells are included, effects from deforestation can be shown. Moreover, a richer analysis will follow if inputs are included. This not only refers to regulating and supporting ecosystem services affecting the provisioning and cultural services, like pollination, erosion prevention, water infiltration and natural pest management. It also refers to inputs reflecting land use intensity, like fertilizer and pesticide use, labor input and capital input. By including both types of inputs, trade-offs between natural and modern inputs can be analyzed in more detail. Finally, if other socio-economic indicators are included, also trade-offs between for example poverty, ecosystem services and the millennium development goals can be analyzed in more detail. For this, however, detailed data on a finer spatial scale level are absolutely necessary, but do not yet exist.

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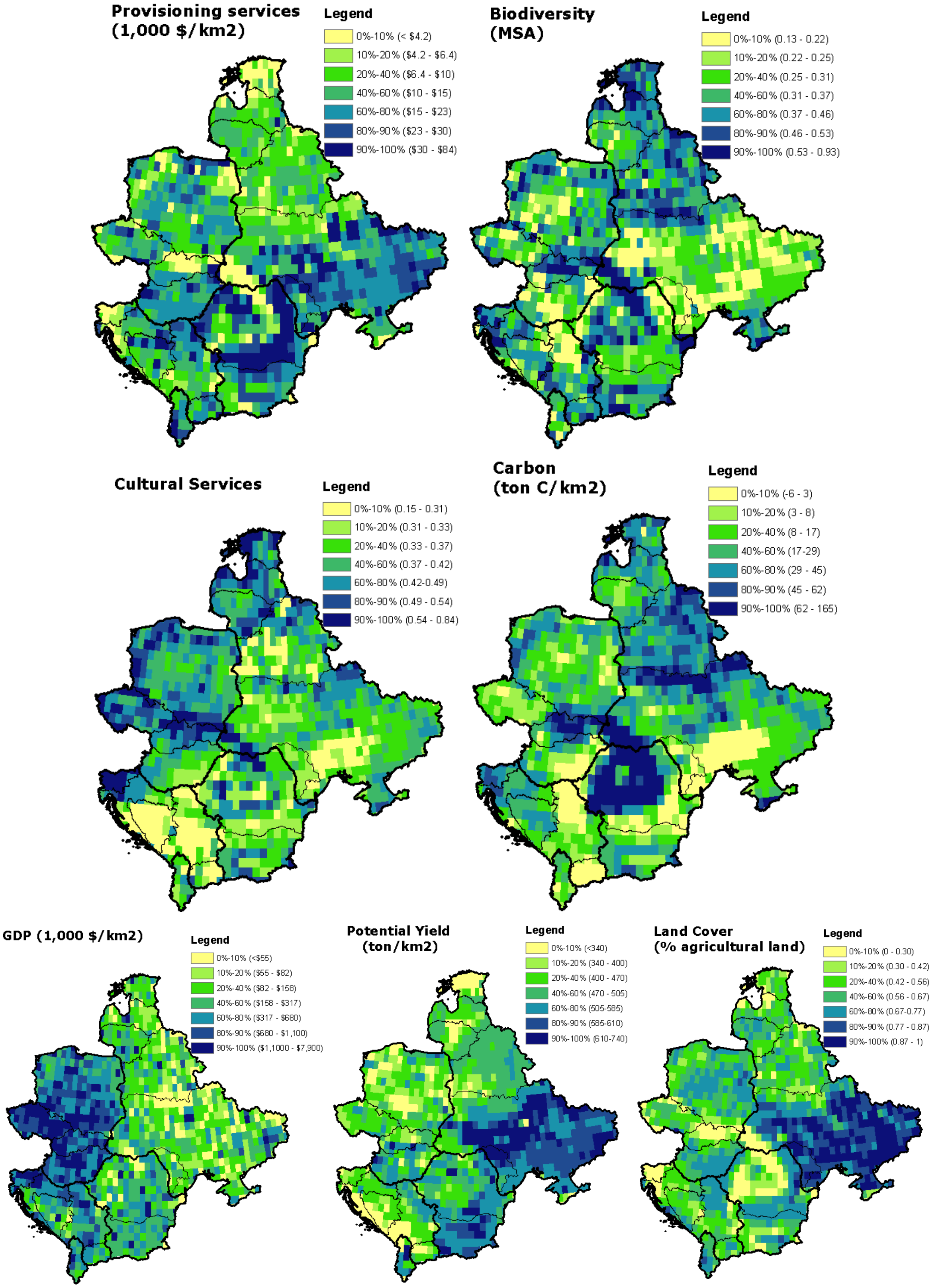
Appendix 1: Maps of base data



Map 1: Maps of the base data: a) provisioning services in $ of agricultural output per km^2; b) biodiversity (MSA); c) cultural services; d) carbon sequestration (tonnes C/km^2); e) GDP ($/km^2); f) potential yield (ton/km^2/yr) and g) land cover (% agricultural land)).
Note: Classification of the cells is such that each color corresponds with 10% or 20% of the observations.

Appendix 2: Maps of base data

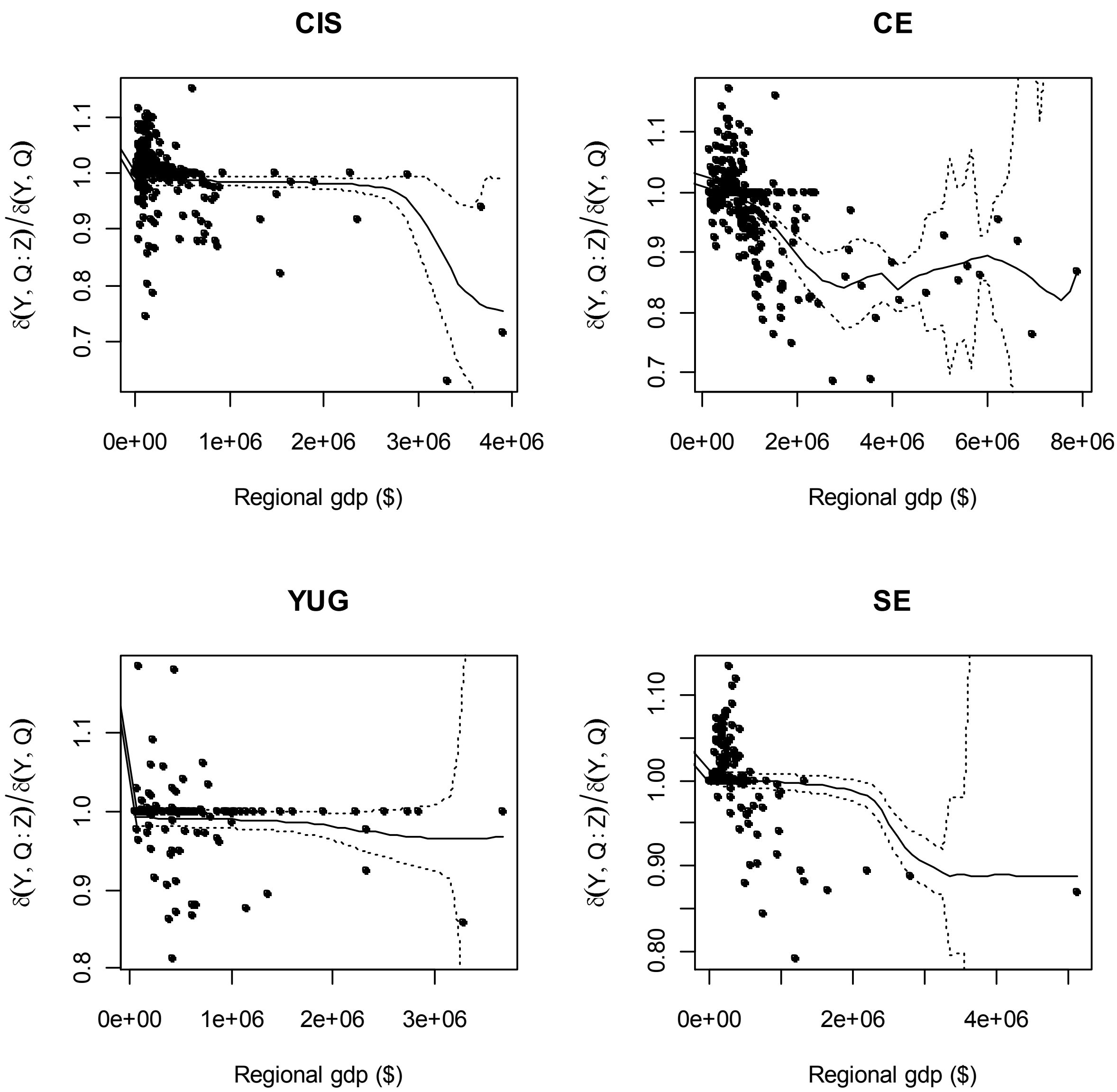


Figure A2: Partial regression plots of average regional GDP per cell and average δ(Y,Q|GDP)/δ(Y,Q) for the four sub-regions.