A production function approach to regional environmental-economic assessments

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ABSTRACT

Numerous difficulties await those creating regional-scale environmental assessments, from data having inconsistent spatial or temporal scales to poorly understood environmental processes and indicators. Including socioeconomic variables further complicates the situation. In place of empirical or process-based regional environmental assessment models, we propose a nonparametric outcomes-based approach using a directional distance function from the efficiency and productivity analysis literature. The regional environmental-economic production function characterizes the relative efficiency of geographic units in combining multiple inputs to produce multiple desirable and undesirable socioeconomic and environmental outputs. This production function makes no assumptions about the functional relationships among variables, but by quantifying the extent to which desirable outputs can be expanded and inputs and undesirable outputs can be contracted, the production function can help decisionmakers identify the most important broad-scale management and restoration opportunities across a heterogeneous region. A case study involving 134 watersheds in the Mid-Atlantic region of the United States indicates that, depending on which outputs are specified as desirable in the models, a quarter to a third of the watersheds are efficient in producing desirable outputs and minimizing inputs and undesirable outputs. Including socioeconomic indicators tends to reduce watershed efficiency as compared to models that only use environmental indicators. Efficiency levels also appear to be correlated with Ecoregions.

Keywords: environmental assessment, production function, efficiency, nonparametric modeling, Mid-Atlantic

1. Introduction

Regional-scale environmental assessments require integrating data sets from a variety of sources collected for diverse purposes and having inconsistent spatial or temporal scales. Moreover, the environmental processes and the relationships among variables in the assessment tend to be poorly understood. Including socioeconomic variables only exacerbates the situation. Regional assessments often use multivariate statistics to describe the relationships between these variables, but multivariate analyses frequently reduce data dimensionality (James and McCulloch, 1990; Tran et al., 2006) and can be difficult to interpret by both the analyst and the intended audience (planners and managers).

Many regional environmental assessments focus on reductions or losses of ecosystem services without consideration for the economic and social pressures that lead people to use or consume environmental resources or services (Wainger et al., 2004). Models capable of evaluating economic and environmental trade-offs while taking into account economic factors that may compensate for environmental losses would likely become valuable decisionmaking tools.

The model described in this paper may be a step towards addressing the challenges of performing regional assessments. Using a directional distance function from the efficiency and productivity analysis literature (Färe et al., 1989; Färe and Grosskopf, 2004; Färe et al., 2007a), the model creates a regional environmental-economic production function (REEPF) that characterizes the relative efficiency of geographic units in combining multiple environmental inputs to produce multiple desirable and undesirable environmental and economic outputs. The REEPF relies on a flexible, nonparametric specification of production relationships, making no assumptions about the functional relationships among inputs and outputs. This characteristic dramatically simplifies the modeling requirements of a regional assessment, while retaining the ability to integrate data sources across media and scales. By quantifying the extent to which desirable outputs can be expanded and inputs and undesirable outputs can be contracted, the REEPF can help decisionmakers identify the most important management and restoration opportunities across a heterogeneous region. This paper presents the conceptual underpinning of the REEPF, the assumptions related to using the approach in a regional assessment context, and a case study using variables related to resource conditions and socioeconomic activities in 134 watersheds in the Mid-Atlantic region of the United States.

2. Methods

For the regional environmental-economic assessment, we assume there are three types of variables: desirable outputs, undesirable outputs, and inputs. The outputs are split into desirable and undesirable outputs to reflect the likelihood that many productive activities create byproducts, pollution, or other external effects that incur environmental or economic costs. For example, electricity generation is frequently examined in the efficiency and productivity literature in this manner, with inputs such as coal, capital, and labor combining to produce the desirable output, electricity, while simultaneously producing a variety of undesirable outputs, such as NO_x and SO_2 emissions (Färe et al., 2007a, b). In the general case, both inputs and undesirable outputs are costly, either directly to producers or to society as externalities. Decisionmakers therefore seek to minimize the use or production of inputs and undesirable outputs, respectively, while maximizing the production of desirable outputs. The model described in this article extends this premise to regional-scale land use planning. For example, community planners permit land use conversion for development activities (such as transportation, residential, and industrial infrastructure) that produce desirable economic benefits such as housing, employment, commercial, and recreational opportunities. However, development simultaneously produces undesirable consequences, such as habitat loss, water quality degradation, and air pollution. In the regional assessment context, we seek to identify the decisionmaking units which are most efficient, that is the watersheds using fewer inputs to produce more desirable outputs relative to undesirable outputs.

It is important to discuss the different nature of the decisions being modeled in the regional assessment case as compared to the decisions being made in the firm-level production that is frequently modeled using the directional distance function approach. The production literature assumes that all relevant variables are captured in the model, regardless of whether the variables are under the full discretion of the decisionmaking unit. Clearly, in a regional assessment application, regional land use planners and environmental managers will not have full control of the inputs, and many variables may be missing or unobserved in the production relationship. However, given that the objective is to help target investments in increasing the joint production of economic and environmental benefits, and assuming that the points of management leverage are well-specified, then putting aside the assumption that the model fully describes the system is reasonable. The intent is to help decisionmakers prioritize investments, rather than describe a highly complex, coupled environmental-economic system.

2.1 Theoretical Foundation of Efficiency Analysis

In the model, the *N* inputs are written $x = (x_1, ..., x_N)$; the *M* desirable outputs are written $y = (y_1, ..., y_M)$; and the *J* undesirable outputs are written $b = (b_1, ..., b_J)$. We assume a production relationship between inputs and outputs. In the efficiency and productivity literature, this relationship is generally referred to as the production *technology* and, where $P(x)$ equals the output set, is written as $P(x)=\{(y,b): x \text{ can produce}(y,b)\}$. This statement says that each input vector *x* can produce a combination of desirable and undesirable outputs (y,b).

A series of axioms typically apply in efficiency analysis, which is sometimes called axiomatic production theory (Färe and Grosskopf, 2004). In the application of the model to regional environmental and economic assessment, six axioms merit special attention, roughly following Färe *et al.* (2007a).

1. **Compactness:** $P(x)$ is compact for all x, which means that finite inputs produce finite outputs.

2. **Inactivity:** Inactivity is always possible, or $\{0\} \in P(x) \forall x$. The implication of this axiom is that it is possible to produce none of the specified outputs for any given vector of inputs. While this axiom makes sense for, say, a power plant, it makes little sense when the unit of analysis is a region where the existence of environmental and socioeconomic outcomes, for better or worse, is assured. In our regional assessment case, then, the mathematical meaning of this axiom is maintained, even if its interpretation in a typical production context is not strictly held.

3. **Free disposability of inputs:** Inputs are freely disposable, which is mathematically stated as $P(x') \subseteq P(x)$ if $x \geq x'$. Free disposability of inputs means that a decisionmaking unit can increase the quantity of any given input while holding other inputs constant and not reducing output.

4. **Strong disposability of outputs**: Strong disposability of outputs implies that undesirable outputs can be disposed into the environment without incurring a cost in reduced desirable production, or if $(y,b) \in P(x)$ and $(y',b') \leq (y,b)$ then $(y',b') \in P(x)$. Another way of saying

this axiom in an environmental decisionmaking context is that the private costs of pollution are zero for a decisionmaking unit. As such, unregulated decisionmaking units are often modeled under the axiom of strong disposability. In contrast, the axiom of weak disposability is based on the existence of private cost associated with reducing the disposal of undesirable outputs in the environment. Under weak disposability, a decisionmaking unit can reduce desirable and undesirable outputs proportionally by θ, or that $(y,b)\in P(x)$ and $0\leq\theta\leq 1$ imply $(\theta y,\theta b)\in P(x)$, indicating that a reduction in undesirable outputs must be achieved at a cost of a reduction in desirable outputs, because resources must be reallocated from the production of desirable outputs to the reduction in the production of undesirable outputs. Weak disposability is sometimes considered an approximation of a decisionmaking unit operating within a regulated environment (Färe and Grosskopf, 2004; Färe et al., 2007a). In the regional assessment context, we assume strong disposability because, while some of the components of the system may in fact be regulated, there are no specific regulatory mechanisms that regulate overall production at the watershed scale.

5. **Null-jointness:** The use of the directional distance function to evaluate the joint production of desirable and undesirable outputs typically draws upon the axiom of null-jointness. Null-jointness states that $(y,b)\in P(x)$ and that $b=0$ implies $y=0$, or that if no undesirable outputs are produced, then no desirable outputs are produced. While we maintain that socioeconomic benefits (*i.e.,* desirable outputs) will always come at the cost of undesirable outputs, it is possible that some but not all undesirable outputs can be eliminated or, as we shall see in the case study, not be produced by one or more decisionmaking units.

With these preliminaries in place, we are now able to present the directional distance function that constitutes the regional environmental-economic production function. First, let

$g=\left(g_y,-g_b,-g_x\right)$ represent the directional vector. The directional vector indicates the direction and relative preference we are trying to move the inputs and respective outputs. Note that the elements of the vector corresponding to undesirable outputs and inputs are negative; this indicates we wish to reduce undesirable outputs and inputs while increasing the quantity of desirable outputs. For the case study that follows, we let $g=\left(g_y,-g_b,-g_x\right)=(1,-1,-1)$, which also implies we are equally weighting all inputs and outputs.

The objective of the environmental-economic production function is to find the maximum expansion of desirable outputs in the g_y direction with the largest feasible proportional contraction in inputs and undesirable outputs in the $-g_x$ and $-g_b$ directions, respectively, or:

$$\begin{aligned}&\vec{D}\left(x,y,b;g_y,-g_b,-g_x\right)=\sup\left[\beta:\left(y+\beta g_y,b-\beta g_b\right)\in P\left(x-\beta g_x\right)\right]\\&\text{where }\ \vec{D}\left(x,y,b;g_y,-g_b,-g_x\right)\geq 0\Leftrightarrow\left(y,b\right)\in P(x).\end{aligned}\tag{1}$$

Here, β is an expansion factor that measures the maximal feasible proportional expansion of desirable outputs and contraction of inputs and undesirable outputs for a given decisionmaking unit. In other words, if a decisionmaking unit is completely efficient in maximizing desirable outputs and minimizing inputs and undesirable outputs, then the decisionmaking unit is producing desirable outputs on the production possibility frontier, and β is zero. Consequently, β may be considered a measure of the decisionmaking unit's inefficiency, and $1-\beta$ a measure of its efficiency.

The directional distance function can be visualized in Figure 1, which for simplicity is reduced to two dimensions by assuming the input vector is held constant while the objective is to maximize a single desirable output y and to minimize a single undesirable output b. Under strong disposability of outputs, the feasible production space is described by the square 0EBCD.

Meanwhile, under weak disposability, the feasible production is described by the polygon 0ABCD. Note that under weak disposability, after a point, reducing *b* leads to reductions in *y*, showing how reductions of undesirable outputs come at the cost of reduced desirable output. Suppose now that a decisionmaking unit is producing at (*b,y*). Under both weak and strong disposability of outputs, the decisionmaking unit is overproducing *b* and underproducing *y*. The objective of the model described in (1) is to contract *b* in the g_b direction and expand *y* in the g_y direction, as shown in the directional vector in Figure 1. Given a directional vector, the inefficiency measure β gives the distance from the observed performance of the decisionmaking unit to the production frontier at the boundary of the feasible production set in the direction of the directional vector under the relevant output disposability axiom. For weak disposability, the decisionmaking unit would have to move to $\left(b-\beta' g_b, y+\beta' g_y\right)$ to be 100% efficient (*i.e.*, $\beta = 0$), and for strong disposability, to $\left(b-\beta^* g_b, y+\beta^* g_y\right)$.

We can identify β for the decisionmaking unit *k'* using the following linear program familiar from the data envelopment analysis literature (Färe and Grosskopf, 2004; Färe et al., 2007a):

$$
\begin{aligned}
& \vec{D}\left(x^{k'}, y^{k'}, b^{k'}; g_y, -g_b, -g_x\right) = \max \beta^{k'} & & \\
\text{s.t.} \quad & \sum_{k=1}^{K} z_k y_{km} \geq y_{k'm} + \beta^{k'} g_{y_m} & & m = 1,\ldots,M \\
& \sum_{k=1}^{K} z_k b_{kj} \geq b_{k'j} - \beta^{k'} g_{b_j} & & j = 1,\ldots,J \\
& \sum_{k=1}^{K} z_k x_{kn} \leq x_{k'n} - \beta^{k'} g_{x_n} & & n = 1,\ldots,N \\
& z_k \geq 0 & & k = 1,\ldots,K
\end{aligned}
\tag{2}
$$

where the variable z_k is a weighting variable. This program constructs the production frontier by searching for a decisionmaking unit or weighted combination of units producing equal or more desirable outputs, equal or fewer undesirable outputs, while using equal or fewer inputs than the unit under analysis, k'. If β equals zero, the unit resides on the production possibility frontier. This model is run once for each observation in the dataset to identify the inefficiency levels for all decisionmaking units.

While the ability to model production without imposing a specific function form on the production relationships is a major advantage of this directional distance approach, it is important to note that the expansion factor β is sensitive to the measurement units and magnitude of the variables. One approach to manage this sensitivity, which we adopt in the case study below, is to transform variables to the ratio of the observed value and the maximum in the dataset for each variable in the dataset, or:

$$y_k^* = \frac{y_k}{y_{\max}}, b_k^* = \frac{b_k}{b_{\max}}, \text{ and } x_k^* = \frac{x_k}{x_{\max}} \ \forall k \tag{3}$$

Under this transformation, β is equivalent to the maximum increase (decrease) in desirable outputs (inputs and undesirable outputs) as a percentage of the maximum observation for each variable in the dataset (Picazo-Tadeo et al., 2005).

The technology in this model exhibits constant returns to scale. In an article that uses data envelopment analysis to allocate conservation contracts within a watershed, Ferraro (2004) explains that it is misleading to compare firms with land parcels—watersheds in the current study—because each parcel is unique and cannot be replicated, whereas replication of a firm is an idea central to constant returns to scale. That said, a variable-returns-to-scale approach in our case would subset the data into sets of watersheds with similar returns to scale, potentially leading to watersheds considered efficient within their peer groups that are dominated across all attributes by watersheds within other scaled peer groups (Ferraro, 2004). In this article, we maintain the assumption that watersheds exhibit constant returns to scale to avoid this problem.

2.2 Case Study

The case study draws upon a dataset developed by the U.S. Environmental Protection Agency's Regional Vulnerability Assessment (ReVA) program as part of its Mid-Atlantic Assessment. Numerous articles have been published based upon this work, including a series of articles exploring multivariate and fuzzy logic approaches to regional environmental assessment (Smith et al., 2004; Tran et al., 2006; Tran et al., 2007; Tran et al., 2008). The economic and environmental variables used in the ReVA assessment were drawn from a wide variety of sources and inevitably do not represent the same spatial or temporal scales. ReVA estimated each variable for 134 watersheds at the HUC8 scale that constitute the Mid-Atlantic region. The Mid-Atlantic region spans 10 states across five Level II Ecoregions (Secretariat of the Commission for Environmental Cooperation, 1997): (1) Atlantic Highlands; (2) Southeastern USA Plains; (3) Mixed Wood Plains; (4) Mississippi Alluvial and Southeast USA Coastal Plains; and (5) Ozark, Ouachita-Appalachian Forests (Figure 2).

The ReVA estimates were chosen for this study because they represent well the disparate types of information available for regional assessments. Additionally, the advantages of the flexible, nonparametric directional distance function are highlighted by its ability to meaningfully model information from disparate sources. For this case study, we use four inputs, four desirable outputs, and six undesirable outputs that are shown in the first column of Table 1. See Smith *et al.* (2004) for a detailed discussion of the variables. We selected the 14 variables from a larger set to illustrate the use of the REEPF. While no single authority exercises complete control of the four inputs in this model, these four were chosen because they could be influenced by land use planning/policy and by conservation efforts, and because, in terms of environmental quality, lower values typically are considered good for all four. The desirable outputs chosen reflect a mix of socioeconomic and environmental variables, increases in which can be argued to be good. The undesirable outputs reflect environmental problems (pollution and exotic species) that planners and environmental managers typically try to minimize. While this model specification lacks the clarity of the input-output relationship of a typical model in production economics, the complexity of evaluating joint environmental-economic production in regional landscapes will always make model specification an untidy process.

To show a range of results that are sensitive to regional management objectives, we present the results of four different models. In each of the four models, the inputs and undesirable outputs remain the same, but the desirable outputs are varied. The desirable outputs for each model follow:

Model 1: per capita income, population density, percent wetland, and percent interior forest.

Model 2: per capita income, percent wetland, and percent interior forest.

Model 3: population density, percent wetland, and percent interior forest.

Model 4: percent wetland and percent interior forest.

3. Results

Table 2 presents descriptive statistics on the estimated inefficiency ratings across the four models. Results of Models 1 and 3, which both include population density, were similar. Meanwhile, the results of Models 2 and 4 were similar as well. In Model 1, which contains all four desirable outputs, a little more than one-third of the observations were considered efficient, with an average efficiency of 99.1 percent (β = 0.009) and a minimum efficiency of 93.6 percent (β_{max} = 0.064). Recall that β is equivalent to the maximum increase (decrease) in desirable outputs (inputs and undesirable outputs) as a percentage of the maximum observation for each variable in the dataset. Consequently, a watershed that is 99.1 percent efficient (β =

0.009) should be able to increase desirable outputs and decrease inputs and undesirable outputs by 0.9 percent. It should also be noted that while the efficiency values in Table 2 may appear to be quite high, when translated into physical measures, small changes in efficiency can result in significant changes in environmental quality.

Removing population density as a desirable output decreased the efficiency of the watersheds in the dataset: only 26 percent were found to be efficient, the average efficiency was 96.2 percent, and the least efficient watershed in the dataset had an efficiency of 71.2 percent. Removing per capita income and retaining population density for Model 3 returned results similar to Model 1 in that about a third of the observations were found to be efficient, with an average of 99 percent efficiency and a minimum efficiency rating of 93.3 percent. The final model, with just percent wetlands and percent interior forest as desirable outputs, returned the lowest rates of efficiency, with 25 percent of the observations being efficient, average efficiency of 95.6 percent, and a minimum efficiency of 65.2 percent.

The spatial variation of the results can be seen in Figure 3, which depicts results in five groups, with darker shading for watersheds with lower efficiency ratings. Figure 4 presents the average inefficiency results across Level II Ecoregions for all four models. In comparing the averages across Level II Ecoregions, it is important to note that the analysis of variance must account for the fact that the groups are of unequal size and, in the case of this analysis, of unequal variance, according to Levene’s test for homogeneity of variance. Because of the unequal group size and unequal variance, inter-group statistical differences were determined using Tamhane’s post-hoc test at a 95 percent confidence level. For both Models 1 and 3, Tamhane’s post-hoc test showed that inefficiency levels were lower in the Atlantic Highlands than in Mixed Wood Plains and the Ozark, Ouachita-Appalachian Forests. For Models 1 and 3, efficiency levels in Mississippi Alluvial and Southeastern USA Coastal Plains were higher than in Mixed Wood Plains. For Models 1 and 3, all comparisons between Level II Ecoregion group averages were not statistically different. Similarly, there were no significantly different efficiency levels across all Level II Ecoregions in Models 2 and 4. This implies that the presence of population density as a desirable output in Models 1 and 3 may dampen the variation in watershed efficiency across ecoregions.

Inspecting the results depicted in Figure 4, there is a notable segmentation in the Ozark, Ouachita-Appalachian Forests Ecoregion. Using a southwest-to-northeast line to roughly bifurcate the region, relatively high efficiency levels are found south and east of that line and relatively low efficiency levels are found north and west of that line. These results correlate well with the more detailed Level III Ecoregions, with the Central Appalachian Ecoregion to the Southeast and Western Allegheny Plateau Ecoregion to the Northwest, and may result from greater population and industrialization in the areas north and west of the southwest-to-northeast line.

Table 3 shows the average maximum desirable output production across all 134 watersheds for each of the models and, similarly, values for the average minimum inputs and the average minimum undesirable outputs when inefficiency is hypothetically removed from each observation. A watershed's maximum production depends on which desirable outputs are included in the model, which indicates the trade-offs involved in adopting different regional management objectives. For example, Model 2 yields a higher average maximum per capita income than Model 1, which includes population density.

To evaluate the watersheds' relative change in rank order as desirable outputs were varied, the watersheds were divided into quartiles based on their efficiency rating for each model. In the case of ties at the quartile breaks, tied watersheds were placed in the higher efficiency quartile. Overall, 81 of the 134 watersheds (60 percent) are in the same quartile across all models, demonstrating the relative stability of the rank ordering of the watersheds. The same 36 watersheds (27 percent) are in Quartile 1 for each model, and all 36 watersheds were rated as 100 percent efficient for all four models, meaning that these 36 watersheds were performing on the production possibility frontier for all models Meanwhile, 12 watersheds (9 percent) stay in Quartile 2, 14 (10 percent) stay in Quartile 3, and 19 (14 percent) stay in Quartile 4 across all four models. Of the remaining watersheds, relatively few exhibit volatile performance across models.

4. Conclusions

This article presents an approach to evaluate the environmental-economic performance of regions in producing desirable outputs in the presence of undesirable outputs and costly inputs using a directional distance function. This approach to developing a regional environmental production function offers several advantages for developing regional assessments. The flexible, nonparametric approach is capable of incorporating a wide variety of information and imposes no functional form upon the relationships among the variables in the assessment, offering a strong advantage when dealing with very complex systems. The production function provides information that can help environmental decisionmakers prioritize environmental investments and also establish reasonable expectations about the amount of improvement that may be expected.

In contrast to the usual application of data envelopment analysis to evaluate firm-level efficiency, the regional environmental-economic production function approach necessarily assumes that decisionmaking is not vested with any singular management authority. The assessment is also unlikely, if not unable, to incorporate all relevant variables, which steers the production function presented here away from the traditional econometric view of production functions, which assumes all relevant factors are included in the model. In this, the use of the directional distance function in this study is similar to its use in cross-country comparisons of productivity, such as Lozano (2008) and Kumar (2006), in which the production problem is presented at the same level of decisionmaking abstraction. It is also possible in the regional assessment context that there are no clear distinctions between inputs and outputs, which necessitate that the assessment analyst takes great care in properly specifying the model.

We created several models reflecting different management objectives by varying the desirable outputs used to calculate efficiency. Our results indicated that, depending on which desirable outputs are specified in the models, a quarter to a third of watersheds are efficient in producing maximal desirable outputs with minimal undesirable outputs and input use. Our results show that across all watersheds, average efficiency ratings range from 99.1 percent to 95.6 percent, depending on which desirable outputs are selected for the analysis. When socioeconomic indicators (*e.g.*, per capita income and population density) are used, model efficiency ratings are higher than when just environmental measures (*e.g.*, percent of the landscape in wetlands or interior forest) are used. Efficiency levels are also correlated with eco-regions, with Atlantic Highlands and Southeast Coastal Plains tending to be more efficient than Mixed Woods, Southeastern Plains, and Appalachian Forests.

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Table 1. Variables used in the analysis

	Average	Std. Dev.	Min.	Max.
Inputs				
Percent edge forest (2 ha scale)	30.6	9.9	7.9	52.5
Percent impervious surface	3.7	3.6	0.9	25.1
Riparian agriculture (percent of stream-length with adjacent agricultural land cover)	15.0	9.2	0.0	45.7
Road density (m/ha)	19.7	8.3	9.2	59.0
Desirable outputs				
Per capita income (1996$)	22 592	4 504	15 110	41 528
Population density (people/ha)	243	421	16.6	2590
Percent wetland	5.9	10.6	0.0	58.1
Percent interior forest (2 ha scale)	60.1	16.0	0.1	91.5
Undesirable outputs				
Exotic aquatic species (no.)	11.9	6.4	2.0	34.0
Exotic terrestrial species (no.)	11.3	1.8	8.0	16.0
Total nitrogen in streams (kg/ha/yr)	3.4	0.5	2.3	5.1
Nitrogen deposition (kg/ha/yr)	8.8	1.6	6.4	12.3
Ozone design values (ppm-hours)	85.9	3.8	79.1	98.0
Particulate matter 2.5 ($\mu g/m^3$)	14.8	1.0	12.4	17.2

Note: See Smith *et al.* (2004) for discussion of variables.

Table 2. Efficiency levels for 134 Mid-Atlantic Watersheds

	Model 1	**Model 2**	**Model 3**	**Model 4**
Number efficient (β = 0)	49	37	46	36
Percentage efficient	34%	26%	32%	25%
Average efficiency (1- β)	99.1%	96.2%	99.0%	95.6%
Std. dev. of avg. efficiency	1.3%	5.2%	1.4%	6.4%
Maximum efficiency (1- β)	100%	100%	100%	100%
Minimum efficiency (1- β)	93.6%	71.2%	93.3%	65.2%

Table 3. Maximum production of desirable outputs and minimum use of inputs and production of undesirable outputs (means)

	Actual	Model 1	Model 2	Model 3	Model 4
Inputs					
Percent edge forest (2 ha scale)	30.6	30.1	28.7	30.1	28.3
Percent impervious surface	3.7	3.5	2.8	3.5	2.6
Riparian agriculture (percent of stream-length with adjacent agricultural land cover)	15.0	14.5	13.2	14.5	13.0
Road density (m/ha)	19.7	19.2	17.5	19.1	17.1
Desirable outputs					
Per capita income (1996$)	22,592	22,976	24,150	—	—
Population density (people/ha)	243	267	—	268	—
Percent wetland	5.9	6.4	8.1	6.5	8.4
Percent interior forest (2 ha scale)	60.1	60.9	63.5	61.0	64.1
Undesirable outputs					
Exotic aquatic species (no.)	11.9	11.6	10.6	11.6	10.4
Exotic terrestrial species (no.)	11.3	11.2	10.7	11.2	10.6
Total nitrogen in streams (kg/ha/yr)	3.4	3.3	3.2	3.3	3.2
Nitrogen deposition (kg/ha/yr)	8.8	8.7	8.4	8.7	8.3
Ozone design values (ppm-hours)	85.9	85.0	82.2	85.0	81.6
Particulate matter 2.5 ($\mu g/m^3$)	14.8	14.7	14.2	14.6	14.1

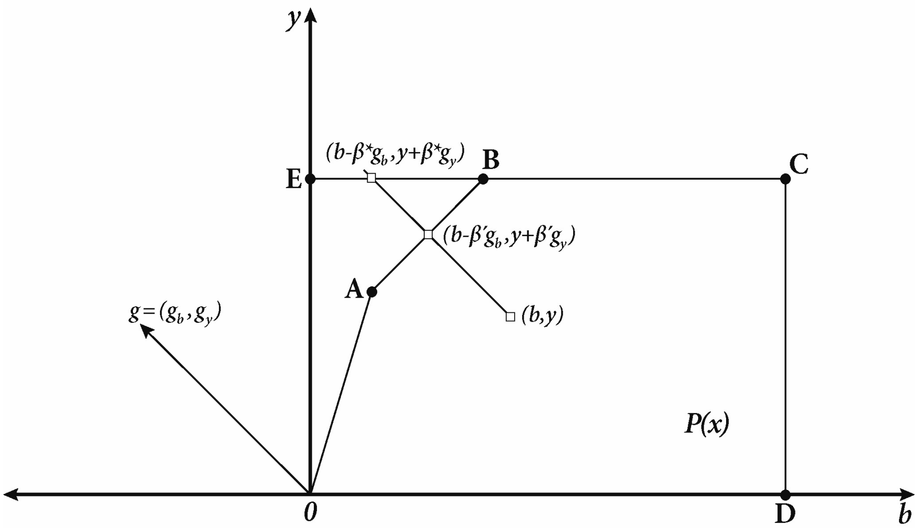
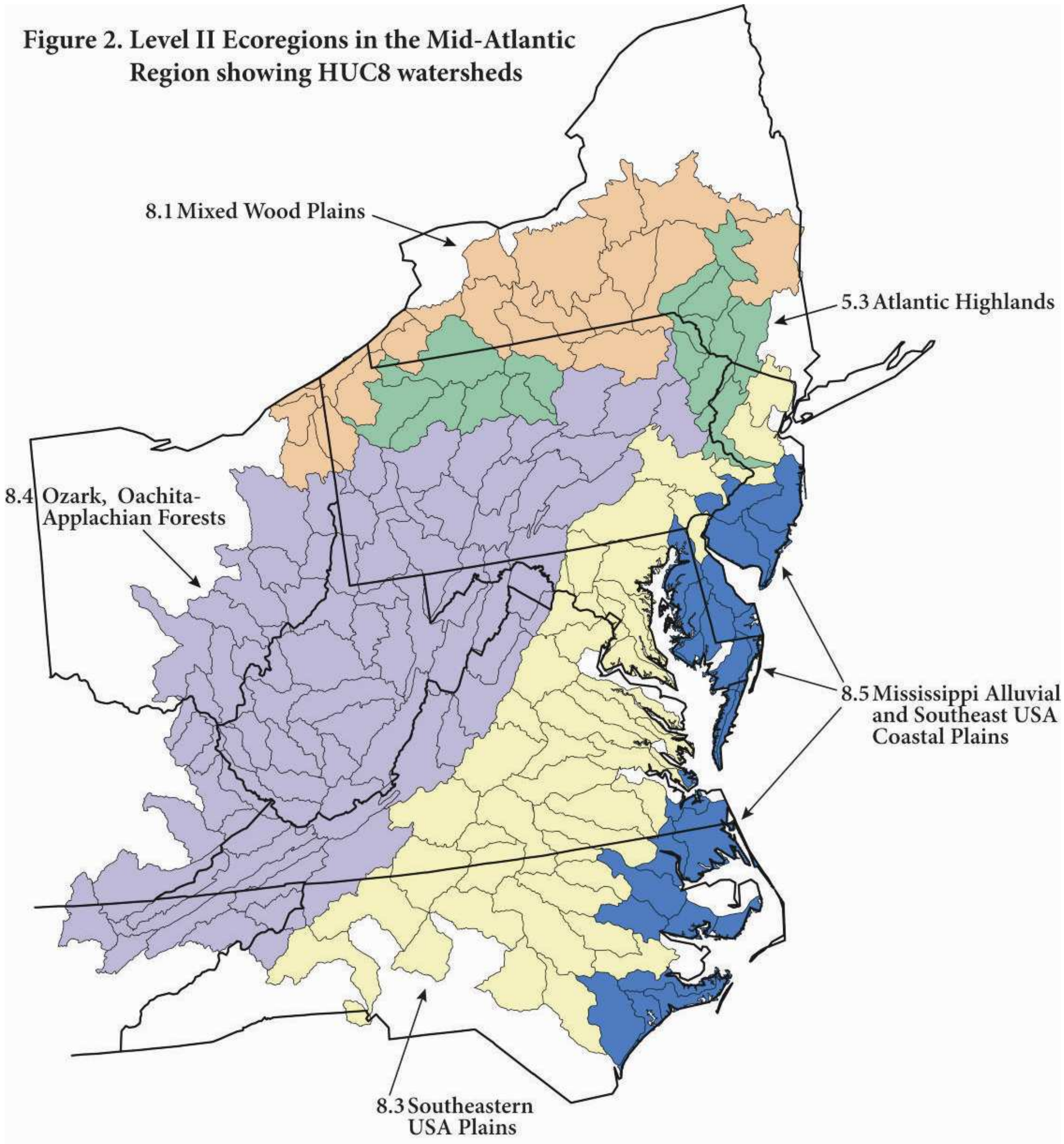


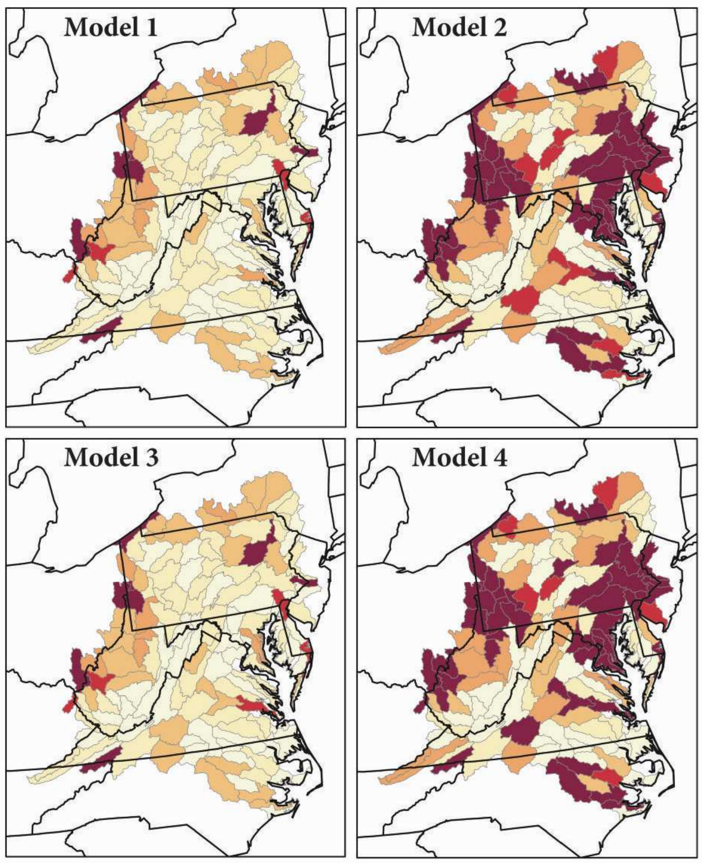
Figure 1. Production technology and directional distance function (adapted from Färe *et al.* 2007)

Figure 2. Level II Ecoregions in the Mid-Atlantic Region showing HUC8 watersheds



Map colors accessible by vision-impaired; based on http://www.ColorBrewer.org, by Cynthia A. Brewer, Pennsylvania State University.

Figure 3. Efficiency ratings from four models for 134 Mid-Atlantic watersheds



* Map colors accessible by vision-impaired; based on http://www.ColorBrewer.org, by Cynthia A. Brewer, Pennsylvania State University.

Figure 4. Average efficiency ratings from four models for five Level II ecoregions