

# Valuing ecosystem services in general equilibrium\*

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## Abstract

We explore the consequences of treating the multiple, non-market benefits associated with improvements in ecosystem health and the market economy from which damage to these ecosystems stems as an integrated system. We find that willingness to pay measures of use-based ecosystem services are impacted by the changes in demand for complementary market goods. Demand for these goods shifts due to the introduction of pollution regulations that deliver improvements in ecosystem services. As a result, partial equilibrium estimates of these use values may be measured with substantial error if they fail to account for the general equilibrium adjustments caused by the regulation. We also find that the basic physical/biological connections between the resources underlying use and non-use values for ecosystems may have important implications for the measurement of these values.

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# 1 Introduction

In this paper, we report on the results of experiments designed to explore the consequences of treating the multiple, non-market benefits associated with improvements in ecosystem health and the market economy from which damage to these ecosystems stems as an integrated system.

Forty years ago Ayres and Kneese (1969) launched the transformation of the modern economic perspective on environmental externalities. At that time, economists treated externalities as exceptional cases that could be adequately addressed through “simple *ad hoc* arrangements.” Today, there is a much greater appreciation of the pervasive nature of some externalities. The debate about climate change and policies to control greenhouse gases has helped to provide a tangible, widely recognized, example of the implications of materials and energy balances for widespread externalities resulting from production and consumption activities that Ayres and Kneese highlighted. Nevertheless, it would be a mistake to conclude that economists fully appreciate the implications of the general equilibrium perspective Ayres and Kneese advocated or the quantitative tools needed to act on their insights.

Two years earlier, Krutilla’s (1967) call for a revision of the economic criteria used to evaluate preservation versus development decisions broadened the scope for evaluating environmental externalities in a different way. His paper challenged the conventional view of how consumption should be represented in preferences. He identified a distinction between consumption as “use” and services that contribute to utility but do not require any type of use. His discussion was quite general and he argued that some people might have preferences for protecting unique natural environments, species, or ecosystems simply to assure they would “exist.” This led to considerable literature aimed at reconciling the

practical and conceptual challenges implied by existence values with methods for measuring the benefits of improving environmental quality that continues to this day.

What is sometimes overlooked in these discussions is that the services involved need not be limited to unique natural environments or “cute critters.” In the context of climate change or biodiversity loss, the science suggests that the integrity of fundamental, background services delivered by large-scale physical and biological systems may be at stake. Without raising the specter of disaster, changes to these systems could result in important changes to the level of resources required to maintain market and non-market services at a level consistent with current living standards. At the same time, the values that people place on these background services are not easily captured using the standard techniques employed by environmental economists to measure changes in environmental quality.

In particular, existence values need not have any observable demand signal in the market economy to document the fact that people would be willing to sacrifice resources to protect or enhance these services. As a result, we cannot rely solely on revealed preference techniques for assessing these trade offs. Modeling how these services contribute to utility in formal preference structures requires the use of separability restrictions to specify how the trade offs between market goods and services (including the uses of environmental resources) are affected by non-use or existence consumption.

As an illustration of the issues that are at the center of our analysis, suppose an individual derives utility  $U$  from a vector of marketed consumption goods,  $x$ , leisure,  $l$ , and a vector of services derived from an ecosystem,  $q$ . If the individual has both use and non-use values for the ecosystem then  $q$  enters the utility function in at least two places:

$$U = V(c(Q(q), x, l), h(q)) \quad (1)$$

$q$  enters here in a subfunction  $c(Q(q), x, l)$  where services associated with the ecosystem are combined with market goods and leisure time to create use-based values.  $q$  also enters as a weakly separable element,  $h(q)$ , which captures the non-use components of ecosystem value.<sup>1</sup>

Two aspects of any analysis of the role of ecosystem services in economic activity become clear when use and non-use values are viewed in this way. First, the value of some ecosystems to the individual will, in general, depend on the prices of market goods and the labor/leisure choice. When a pollution regulation is put in place, for example, the increase in prices of pollution-intensive goods and the corresponding decrease in the real compensation for labor implies a lower demand for these market goods and higher demand for leisure. To the extent that non-market goods exhibit special relationships with these goods or the overall cost of living is affected in important ways by these price changes, the value of non-market services will also be affected.

Second, the two components of ecosystem value will be related to each other. While changes to the level of non-use services,  $h(q)$ , will have no impact on the observed pattern of consumption, they will affect the value of other market and non-market services.<sup>2</sup> When the two sets of services are derived from the same ecosystem, *changes in their levels are physically related to each other through the basic physical/biological functions of the ecosystem*. This last feature of ecosystem values parallels the logic set out by

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<sup>1</sup>Hanemann (1988) first proposed a variation on this definition. Originally, non-use value was defined by including an additively separable term to preferences, where  $U = V(c(Q, x, l)) + h(q)$  (with  $Q$  and  $q$  unrelated). This format implies that a composite of market goods and non-market, use-related services are perfect substitutes for the non-use contribution to well-being. Yet another alternative, implying that there are average substitutes for non-use services would be the same as equation (1) but exclude the links between  $Q$  and  $q$ . Our formulation in equation (1) maintains the essential idea in non-use value — revealed preference information alone will not provide all the information necessary to understand the importance of changes in  $q$  for people's well-being.

<sup>2</sup>The exception to this statement is the special case in which non-use value is a perfect substitute for all other consumption.

Ayres and Kneese in which the physics of materials and energy balances makes the assets associated with the ultimate deposition of byproducts of production and consumption and its relationship to the various capacities of the environment to assimilate residuals from these activities so important to the performance of the joint economic/environmental system.

In a general equilibrium, these relationships influence how the non-market consequences of production and consumption choices feed back to alter individuals' demands (and supplies) for all goods and services. To the extent that non-market goods affect leisure demand, for example, they may have influence throughout the market economy through changes to labor supply. To the extent that changes in pollution-intensive activities are affected by these changes, they may also feed back to determine the equilibrium level of pollution and services delivered by the ecosystem.

In short, a general equilibrium framework is needed to evaluate the connections between ecosystem services and related market activities. Moreover, it must jointly represent the connections between the relevant parts of the market economy as well as reflecting the role that ecosystem services play in contributing simultaneously to the use and non-use components of preferences.<sup>3</sup>

In this paper, we propose to begin the process developing a new generation of general equilibrium models that incorporate these insights. We illustrate our ideas with an application to the impacts of acidic deposition on ecosystem services in the Adirondacks. The purpose of the application is to demonstrate the challenges associated with calibrating such a model to non-market valuation information and assessing the quantitative signifi-

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<sup>3</sup>Ayres and Kneese emphasized the first part of these relationships — the physical linkages in production and consumption to residuals and the physical properties of natural systems. They overlooked the potential for these linkages to produce feedback effects via consumer preferences. This is where Krutilla's analysis contributes to the overall structure of our argument.

cance of representing the benefits of environmental regulations as an integrated part of a general equilibrium system.

The specific example we use is acidic deposition from nitrogen oxides and sulfur dioxide. Three ecosystem services are assumed to be affected — freshwater fish populations, scenic vistas and tree cover, and a composite impact that is intended to reflect existence service stemming from concerns about the damages to the habitat for the other two, use-related, environmental resources (i.e. the fish and trees) as well as other related species without direct uses from acidic deposition. Our characterization of the concentration/response functions and measures of economic values for these services are loosely based on the existing literature. As a result, our model is not intended to be a serious policy evaluation of acidic deposition. Rather, our objective is to describe how multiple feedbacks can arise from non-market services and influence the demands and supplies of market goods.

We have another objective as well. The connections that ecologists describe linking the functions of ecosystems to the services economists identify as important to people depend on the spatial scale. The scale for their analysis often does not match the scales for most economic analyses. This issue of scale relates to both geography (or the spatial scale) and the definitions for what are exogenous influences and endogenous responses as we discuss below. Both are important and influence our ability to use the existing literature in environmental economics to calibrate a general equilibrium model that includes ecosystem services.

Section 2 develops the background for our research. It discusses how the early public economics literature made assumptions that precluded the inclusion of important feedback effects from externalities. This perspective has dominated much of the literature on general equilibrium evaluations of environmental policy. We close this background by describing how the composite of Ayres and Kneese and Krutilla's contributions identified the issues

central to the importance of non-market feedbacks for general equilibrium policy evaluation. Section 3 shows how existing market and non-market information can be used to calibrate a computable general equilibrium (CGE) model with multiple non-market resources. Section 4 describes our model and 5 discusses the results for a representative policy scenario — reducing emissions of nitrogen oxide and sulfur dioxide by 43%. Our primary objectives are to demonstrate how partial equilibrium welfare measures for non-market services might be modified by a general equilibrium approach and to describe how virtual prices signal the importance of strategic modeling assumptions for non-market feedbacks. Finally the last section discusses the implications of our analysis for developing more complete CGE models with the types of extensive non-market interactions called for in Ayres and Kneese’s seminal paper.

## **2 Background**

### **2.1 Early Literature**

At the time they were writing, Ayres and Kneese noted that externalities were an inevitable consequence of consumption and production activities because the effects of alternative residuals management policies were largely ignored. They illustrated this point diagrammatically (see Figure 1 in their paper) and analytically, noting in their framework that

there are three classes of physical exchange for which there exist no counterpart economic transactions. These are: (1) private use for production inputs of “common property” resources, notably air, streams, lakes, and the ocean; (2) private use of the assimilative capacity of the environment to “dispose of” or dilute wastes and residuals, and (3) inadvertent or unwanted material inputs to

productive processes — diluents and pollutants. All these goods (or “bads”) are physically transferred at zero price. . . because there exists no social institutions that permit the resources in question to be “owned” and exchanged in the market (p. 291)

They suggest that the influence of a market might be simulated using shadow or virtual prices for the services and that the monetization of these services would provide a type of virtual income. However, when they introduced them into the model they placed them as arguments that give rise to incremental social costs *on the supply side of the economy* (represented by their equation (7)). Ayres and Kneese are specific in suggesting that demands for private goods carry over unchanged. This specification implies the feedback effects of changes in the quality of the environment on the demands for private goods are not reflected in consumers’ behavior.

Shortly afterwards, Diamond and Mirrlees (1973) also argued for restrictions on these feedback effects to avoid anomalous outcomes. The issue in their case arises because aggregate demand in a market exhibiting an externality might change in what they considered to be counterintuitive ways with a move from an unregulated equilibrium to an efficient allocation. The anomalous case is problematic because, as Diamond and Mirrlees suggested, it seems to imply an upward-sloping demand function. However, Cornes (1980) clearly dispels this case, noting that their concerns were due to a failure to properly decompose the responses leading to the efficient outcome.<sup>4</sup> He notes that:

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<sup>4</sup>All of the literature describes this issue as arising from a consumption externality. One individual’s consumption affects others and those others affect that person. This characterization is misleading. Pollution from production arises because some agents consumed the production involved. The real issue here is non-separability and what we have identified as feedback effects, not the fact that one agent’s consumption adds or detracts from the well-being of others. Pollution from production activities could be described in these terms as well. Our point is simply that the labeling of these cases has distracted attention from the more fundamental point exposed by the Buchanan-Kafoglis example.

In the absence of real income or welfare effects, aggregate demand may vary positively with prices. This is because in addition to the conventional compensated price responses, there are compensated responses once thought to be perverse or anomalous, once the role of compensated quality responses is isolated and clearly understood (p. 317, emphasis added)

The explanation lies in different patterns of complementarity and substitution between a private consumption good and the external effect among agents. These interactions lead to adjustment in each agent's Hicksian demands for the consumption good such that aggregate demand changes in unanticipated ways. The basic insight is that the structure of non-separabilities across agents can lead to unanticipated changes in the demands for market goods and their corresponding non-market outcomes.

To illustrate this point, consider a simple adaptation to the Diamond-Mirrlees structure. We have added a second private consumption good. Each of the two individuals' preferences are separable in the two private goods but not in the externality, and one of each person's private consumption choices has an own contribution to the externality as well as a "pure" external effect. Equations (2) and (3) state the amended Diamond-Mirrlees preference functions —  $u()$  for individual one and  $v()$  for individual two — with  $\mu_1$  and  $\mu_2$  the numeraire goods,  $x_1 = x_{11} + x_{12}$  and  $x_2 = x_{21} + x_{22}$  the two private goods ( $x_{ij}$ ,  $i = \text{good}$ ,  $j = \text{individual}$ ), and  $\beta$  and  $\alpha$  the external effects arising from the individuals' consumption. These relationships are defined in (2) through (5).

$$u(x_{11}, x_{21}, \mu_1, \beta) = A_1(x_{11}, \beta) + A_2(x_{21}, \beta) + \mu_1 \quad (2)$$

$$v(x_{12}, x_{22}, \mu_2, \alpha) = B_1(x_{12}, \alpha) + B_2(x_{22}, \alpha) + \mu_2 \quad (3)$$

$$\beta = \beta(x_{11}, x_{12}) \quad (4)$$

$$\alpha = \alpha(x_{21}, x_{22}) \quad (5)$$

The characterization of the externality creates the appearance of a non-separability in individual one's choices even though his preferences are specified as separable. For example, in the case of individual one, these effects arise through the influence of  $x_{21}$  on the second individual (via  $\alpha$ ) which in turn "feeds back." The link causes a separable consumption choice ( $x_{21}$ ) by individual one to have an effect on his consumption of  $x_{11}$ . This link takes place because  $x_{11}$  has an external effect on individual two and that individual's choices ( $x_{12}$ ) influence individual one's trade offs. Thus, even though  $x_{11}$  and  $x_{21}$  are specified to be separable consumption choices for individual one, feedbacks outside the market make them non-separable.

Of course, as Sandmo (1980) noted in his commentary on Diamond and Mirrlees, the significance of these relationships for policy is an empirical matter.<sup>5</sup> To evaluate them, we must make decisions about how to represent economic activities in a model, how to account for the natural systems receiving the residuals identified in Ayres and Kneese, and how to link the physical responses of these systems to the services people want from the environment. The latter effectively defines the points of contact between these two systems.

## 2.2 General Equilibrium Analysis with One Non-Market Good

The task of introducing non-separable externalities into a CGE model is more challenging than one might initially expect. Carbone and Smith (2008) describe the challenges in calibrating a model with a single non-market good and we base our discussion here on

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<sup>5</sup>While this literature seemed to recognize that the plausibility of separability restrictions in this context was an empirical issue, the literature in public economics continues to focus on its power as an analytical simplification rather than on its relevance for real problems. See Gauthier and Laroque (2010).

that study. Three factors contribute. First, the conventional practice calibrating constant elasticity of substitution (CES) or nested CES functions to describe preferences and production functions becomes significantly more difficult, because the externalities take the form of quasi-fixed goods in the preference structures.<sup>6</sup> This result arises because the arguments used to represent them must be treated as outside the control of individual agents. Once this change is made, the CES formulation no longer leads to convenient closed-form expressions for demand and supply.

Second, the available information to recover the parameters influencing how these services contribute to preferences (or production) is not what we encounter for private goods and services. As Ayres and Kneese noted, there are no market exchanges in these services. As a result, we do not have access to a price measuring the marginal willingness to pay for the last unit consumed of ecosystem services.

The literature on non-market valuation of environmental services must make one of two types of assumptions about preferences. With revealed preference strategies specific restrictions to preferences (i.e. weak complementarity) allow the information provided by observing records for private actions, such as trips to recreation sites or purchases of homes, to be used to measure trade-offs for the non-market services. Stated preference methods also make assumptions about preferences along with the presumption that stated choices authentically measure the actual choices an individual would make when faced with the same situation.

Beyond this, the results from these types of applied studies, measuring the economic values for environmental services, usually provide estimates of willingness to pay or Mar-

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<sup>6</sup>We could also introduce them as non-separable effects on production. The classic case of the laundry and the polluting steel plant is one example. Here we focus on feedbacks due to linkages in preferences. Analogous problems would arise in the case of production-side linkages. See Finnoff and Tschirhart (2003) for a fisheries example with production-side ecological feedback effects.

shallian consumer surplus for specific, *discrete*, changes in the services involved, not an estimate for the marginal willingness to pay or virtual price. In addition, these are usually measures for local situations such as a specific recreation site or housing market. Because the environmental services are not traded on markets, we should expect the marginal willingness to pay values to be quite different in different areas. Nonetheless, we need to include measures of these virtual prices at a scale that is consistent with the scale of the general equilibrium model. This issue is one aspect of the effects of scale that we raised earlier. We return to the challenges posed by the heterogeneity in virtual prices with a general equilibrium model that uses a representative agent format at the close of the paper in discussing the implications and next steps in this line of research.

Finally, non-separability implies that calibration must match both the social accounting matrix (SAM) representing the flows of private goods and services as final consumption, intermediate goods and factor inputs in the baseline year, *and* the flows of residuals arising from consumption and production. This alignment needs to also include the transfer functions linking residuals to the use and existence services as they are represented in preferences.<sup>7</sup> We develop a new method to calibrate these types of models which we describe in more detail below.

Ultimately, the answer to the Sandmo question about the empirical importance of these non-separabilities depends on the share of virtual income (i.e. private income plus the endowed environmental services valued at virtual prices in the benchmark year) accounted for by environmental services *and* the relationship between these services and private goods in preferences. As a point of reference, Carbone and Smith (2008) estimated the share

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<sup>7</sup>A parallel development would be required in a model that recognized how ecosystem services contribute to production. A ski resort is affected by snow, a beach resort by marine debris, water quality and congestion. To the extent that we model the services of these resorts in ways that include quality then these effects would be in production.

of virtual income associated with particulate-matter air pollution at 1.53% and found that non-separability between an air quality good and leisure demand led models that failed to incorporate these connections to either underestimate (in the case of complements) or overestimate (substitutes) the excess burden associated with a new 5% tax (in the presence of a pre-existing 40% tax on labor income) on either the energy or the transportation services sector. The errors ranged from 20% to 50% of the true excess burden of the taxes.

Carbone and Smith used elasticities of substitution between leisure and air quality that were multiples of two and one half the elasticity of substitution between other consumption goods in the preferences structure. We have no empirical basis for judging what elasticity values would be reasonable or unreasonable in this context, and we are unlikely to find answers in the existing literature. The revealed preference studies routinely assume, as a maintained condition, a specific substitution or complementarity restriction in order to estimate the trade-offs an individual would make to increase a specific non-market resource. This is the link that allows the choices of private goods to reveal the marginal values for changes in non-market goods that are assumed to be connected through preferences or technology to them. Stated preference studies focus on discrete changes in a specific resource and reveal little about the responses to small changes (and the responses in private goods associated with them) that are needed to estimate substitution relationships. Thus, we are left with an assessment that in this simple case, with one non-market resource and the relatively small share of income attributed to air quality, that the feedbacks could be important with “large enough” linkages between the non-market services and the marketed goods and services.

## 2.3 Krutilla and Feedbacks

Krutilla's paper is usually credited with defining existence or non-use values as relevant components of the economic gains realized from protecting or enhancing environmental services. By drawing a distinction between "on-site use" or use of environmental services with another private good his paper focused attention on how those services should enter preferences and whether the contributions observed through private goods' demands fully captured all of the reasons a person would be willing to trade off resources to protect a non-market resource as we noted. Hanemann's (1988) characterization of non-use or existence values is now widely accepted as the most general. He suggests the equivalent of a nested structure of effects (as described in equation (1)), with some influences to a consumer's well-being that arise in combination with private goods and some without. Thus, in his description of Krutilla's concepts we would observe the effects of non-market services with private goods' demands but these influences need not reflect everything.

Thus, combining Krutilla's arguments for re-specifying preferences with Ayres and Kneese's demonstration that a focus on general equilibrium was essential to the task of understanding externalities yields our primary conclusions; a transformation to general equilibrium analysis is required to fully acknowledge environmental feedbacks. Interactions outside markets are important within the ambient environment but so also is the structure in preferences (and production). This structure is what serves to define the full extent of non-market environmental feedbacks. Thus, to appreciate their potential importance we need multiple resources with different types of contributions to preferences (or production) relationships. We turn to that task in our model after describing the transformations to conventional CGE calibration to incorporate consistently these types of effects.

### 3 Calibrating Multiple Non-Market Resources

Typically, a subset of the parameters required to specify a numerical general equilibrium model are selected based on the literature and judgment, and the remainder are set to match a benchmark equilibrium.<sup>8</sup> As noted earlier, with homogenous-of-degree-one functions and market goods, this task is readily accomplished using Rutherford's (2002) calibrated share form of the constant elasticity of substitution (CES) function as in equation (6).

$$U = \left[ \sum_{i=1}^K \theta_i \left( \frac{d_i}{\bar{d}_i} \right)^\rho \right]^{1/\rho} \quad (6)$$

$$\sum_{i=1}^K \theta_i = 1$$

where  $\bar{d}_i$  is the benchmark level of consumption of good  $i$ , and  $\rho = 1 - 1/\sigma$ , where  $\sigma$  is the Allen elasticity of substitution. Under these circumstances  $\theta_i$  corresponds to the benchmark expenditure share for commodity  $i$  relative to the total for all  $K$  goods.<sup>9</sup>

Introducing non-market goods into this framework and treating them as quasi-fixed implies that preferences and production functions will no longer be homothetic and that the simple interpretation of the allocation terms ( $\theta_i$ ) as expenditure shares no longer holds (Perroni 1992, Carbone and Smith 2008). Carbone and Smith defined new shares in terms of virtual income using exogenously "set" virtual prices for air quality based on hedonic property value estimates of marginal willingness to pay. Here we propose a more general strategy. Let  $d$  designate a vector of goods that can be decomposed into two components,  $d_M$  and  $d_q$ , for market ( $M$ ) and quasi-fixed ( $q$ ) goods so  $U(d) = \bar{U}(d_M, d_q)$ .

<sup>8</sup>For discussion of this process see Mansur and Whalley (1984) and Rutherford (2002).

<sup>9</sup>If the function is nested, the same result holds and the shares correspond to the fraction of expenditures on goods (or factors) in a nest.

To write the budget constraint in general terms, assume production can be represented with an activity analysis framework, with  $A$  now describing a matrix with each element the net output of commodity  $i$  per unit of sector  $j$  (i.e. output minus input);  $y$  a vector of inputs available to each sector;  $E$  a matrix of initial endowments of the  $K$  goods to  $H$  households and  $D$  a matrix of demands for the  $K$  goods by the  $H$  households, with  $1$  a vector of ones.

When there is only one household, the general equilibrium conditions correspond to the first order conditions for a constrained optimization problem — maximizing utility subject to a budget constraint. The budget constraint is given in equation (7).

$$Ay - (DI - EI) \geq 0 \quad (7)$$

or

$$d \leq Ay + e$$

where  $d$  and  $e$  correspond to vectors of demands and initial endowments (i.e.  $d = DI$  and  $e = EI$  for the multiple household case).

Now for the problem distinguishing market and quasi-fixed goods, the budget constraint becomes equation (8).

$$\begin{bmatrix} d_M \\ d_q \end{bmatrix} = \begin{bmatrix} A_M \\ A_q \end{bmatrix} y + \begin{bmatrix} e_M \\ e_q \end{bmatrix} \quad (8)$$

We can separate these sets of constraints with the Lagrangian multipliers for the first group continuing to serve as market prices. In this setting the objective is to frame the problem so that it mimics Walras law (i.e. if  $z(p)$  is the representative consumer's vector of excess demands at price  $p$ , then the fact that income balances total expenditures

implies  $p^T z(p) = 0$ ). Equilibrium excess demand will exhibit complementary slackness with market prices. When we introduce non-market goods we need to augment income and structure prices so that the same condition continues to be satisfied for market and non-market goods. Dividing prices into market determined ( $p_M$ ) and virtual ( $p^q(p_M, d_q)$ ) for calibration, using Rutherford's calibrated-shares logic we simply set  $p^q(p_M, d_q)$  to an exogenously determined vector of constants,  $p^0$ , and augment endowments so that the designation of the share parameters in terms of virtual income reproduces the equilibrium. This logic relies on estimates of the marginal willingness to pay *at the benchmark* values of the vector  $d$ .

If we can develop a set of marginal willingness to pay estimates from the literature (and treat them as constants), then these can be easily incorporated in the Rutherford calibrated share framework as described above. If we observe the willingness to pay for a discrete change in some dimension of environmental quality, as is often the case in non-market valuation studies, then the calibration technique must derive the implied value for  $p^0$ . These values need to be consistent with market and non-market conditions in the benchmark equilibrium and to yield the correct area under the inverse demand curve for the non-market good. The logic associated with the process will, in principle, accommodate any form of non-market valuation information.<sup>10</sup> For example, structures commonly used in travel cost demand or averting behavior models could be accommodated. One needs only to define the relationship between the results available from the revealed preference model and the parameters of the CGE preference specification.<sup>11</sup>

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<sup>10</sup>For example, the early example developed by Espinosa and Smith (1995) did not recognize the feasibility of building in calibrating constraints into the optimization problem that defines the benchmark. Instead they assume air quality had a perfect substitute as an affine transformation of consumer services. Their strategy allowed calibration to a benchmark without the explicit definition of the willingness to pay expressions in terms of preferences. Perfect substitution in their case implies a simple function of expenditures on that private good should equal the benchmark willingness to pay.

<sup>11</sup>The logic parallels the arguments developed in Smith, Pattanayak and Van Houtven (2002) for using

## 4 A Stylized Model with Multiple Non-Market Goods

Our model is deliberately simple, allowing the two key elements influencing the nature and importance of the feedbacks between the non-market services and the demands for private market goods to be easily identified. These two features are: (a) the specific ways in which non-market services enter preference functions as non-separable influences on the trade-offs that agents would be prepared to make among marketed goods and services; and (b) the transformations that define the relationship between physical/biological responses of the model ecosystem in our application and the recognizable changes in the “services” that agents attribute to these activities or resources.

Our example uses an illustrative model of the U.S. economy proposed by Goulder and Williams (2003) in the context of evaluating the deadweight loss of energy taxes. It has five final consumption goods as well as leisure, four intermediate goods, and one input (labor). The model was designed to illustrate the performance of alternative measures of excess burden losses arising from adding different new taxes in a system with a pre-existing

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preference calibration to develop consistent, partial equilibrium benefit transfers. In another context it is the logic Bullock and Minot (2006) used to demonstrate weak complementarity could be used to numerically derive Hicksian welfare measures without requiring the Willig (1978) condition. However, one aspect of these parallels deserves further discussion. Non-market valuation estimates for the willingness to pay (WTP) for discrete increments in a non-market service are partial equilibrium measures that take prices and income as given. The benchmark for estimates of the WTP need not correspond to the prices and income for the market conditions represented by a given CGE model. As a result, adjustment to match those conditions is likely to be required. In most policy contexts this has been somewhat ad hoc, with adjustments using the consumer price indexes and/or arbitrary scaling based on real income growth. Ideally one would start the process by constructing a SAM for the benchmark associated with the timing (and the location) of the WTP estimate and then use that to estimate a starting point for the new calibration. The strategy used will depend on the assumptions made by the analyst about the interpretation of the representative agent's preferences — e.g. as a local approximation. This issue was discussed in formal terms for the partial equilibrium case by Smith et al. (2002). It was also raised indirectly in Eiserth and Shaw (1997). Our point is not that individuals recognize the general equilibrium implications of a change in a non-market good but that consistency implies WTP estimates be treated as derived from what has been described as a variation function (McConnell 1990). As a result, they will be functions of the prices and income associated with the individuals used to estimate them. Because these values need not correspond to the benchmark for the market data in an applied problem, consistency requires a consistent reference point for calibration.

tax on labor income. We add to it the United States Environmental Protection Agency (1996) estimates for emission rates in 1995 (the year of the market data used to calibrate the model) for sulfur dioxide and nitrogen oxides for each sector. Our objective is to link these emissions to acidic deposition rates and, in turn, to three interdependent ways acidic deposition is assumed to influence households. Details on the numerical model are presented in the appendices at the end of the paper.

Figure 1 provides a schematic description of the preferences we assume for the representative agent. Our primary channel through which reduced acid rain contributes to individual well-being is through its effect on outdoor recreational activities. We selected two types of recreational effects that have been documented in the literature (see Rowe, Lang, Chestnut, Latimer, Rae, Bernow and White (1995)). The first of these impacts arises in recreational fishing through the effect of acidity on fish stocks in the lakes in the Northeast. We use the experience in the Adirondacks to provide a tangible example of the impacts. The second interaction with recreational activities arises through the effects of acidic deposition on the quality and diversity of tree cover. These changes are assumed to influence the trade-offs people would make to undertake recreation that involves hiking to enjoy scenic vistas as part of their recreational experiences. We expect that both of these effects would be closely linked to consumption of market-based consumer services as well as to the allocation of leisure time. These linkages are reflected in the nesting structure of the representative agent's preferences in figure 1.

The other mechanism for an effect due to acidic deposition arises through what we described as the existence/habitat composite. These services make a weakly separable contribution to well being at the top level of the nesting structure. While our specification is somewhat arbitrary, the interconnection is consistent with the logical development we

described with non-market services making non-separable contributions to preferences.<sup>12</sup> It also is consistent with the general logic used to describe what might be treated as the “bundled” services of an ecosystem with the background descriptions given in contingent valuation scenarios (see Banzhaf, Burtraw, Evans and Krupnick (2006) as an example).<sup>13</sup> Specific types of use are not identified.

#### **4.1 Measures of Values for Non-Market Services**

Our specification of the links between sulfur and nitrogen emissions and the non-market services relies on simple algebraic relationships. For forest views we use the model in the United States Environmental Protection Agency (1999) Prospective Analysis describing how emissions affect deciviews of visibility to compute a unit value in 1995 dollars for emissions reduction in kg/hectare. The effects of acidic deposition on fish populations are based on a survey of 1,469 lakes during 1984 to 1987 reported in Driscoll, Lawrence, Bulger, Butler, Cronan, Eagar, Lambert, Likens, Stoddard and Weathers (2001). We obtained these data from the online database cited by the authors. For the records with complete data, we estimated a simple regression model relating the number of fish species in each lake relative to the maximum number of fish species in any of the lakes to a quadratic in the measured Ph level in each lake as well as controls for the size of the lake and the size of the watershed associated with each lake. The estimated equation is given

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<sup>12</sup>See Smith (2004) for a discussion of this formulation in comparison to others that have been used in decomposing use and non-use values.

<sup>13</sup>Banzhaf et al. (2006) describe a scenario in which a long term (10 year) program is proposed to reduce the effects of acidification for a specific set of ecosystem services. In the Banzhaf application the scenario describes the Adirondack Park as having a total of 3,000 lakes. 1,500 of these lakes are described as experiencing injuries due to acidic deposition. These “lakes of concern” have fish populations that are impacted. Forests and bird populations are experiencing some injuries. In the base case 90% of forests are described as “healthy” and 80% of bird populations at their historic level. The plan decreases the lakes of concern by 600 to 900 and makes small improvements in the population of the bird species and one tree species in the areas with the improved lakes. We treat this as a composite improvement, measured with a CES aggregate function, bundling the lakes (fish), birds, and trees into one arbitrary unit.

below.

$$\begin{aligned} \ln(\# \text{ fish species} / \text{max } \# \text{ fish species}) = \\ -6.91 + 1.47Ph - .097Ph^2 + .007 \text{ Surface Area} + .012 \times 10^{-4} \text{ Watershed Area} \\ n = 1,121 \\ R^2 = .367 \end{aligned} \quad (9)$$

Setting the surface area and watershed area at the mean values we derived a quadratic relationship between the relative number of species supported by a lake and acidic levels, as displayed in figure 2. It is important to acknowledge that this is a stylized description intended to illustrate the importance of baseline conditions for the response to efforts to control emission.

The last component of our analysis is the composite or habitat services that are included to represent effects of non-use services. Here we use the number of lakes improved in the Banzhaf et al. (2006) contingent valuation study of the benefits of reducing acidic deposition in the Adirondacks. Using the Kopp and Smith (1997) proposed CES index we derive the marginal willingness to pay for the habitat / non-use services, calibrated so the elasticity of substitution in the Kopp-Smith function is consistent with the estimates for the willingness to pay to improve 600 lakes. The scenario identifies a total of 3,000 lakes in the Adirondacks Park. 1,500 of these are described as being of concern due to acidic deposition. Thus, the improvement is for 600 of the 1500 lakes that are affected by the air pollution leading to acidic deposition (see Banzhaf et al. (2006)).

Table 1 summarizes the assumptions and data sources used for each non-market component of the model.<sup>14</sup> Linking the damages (per household) to a national model of the

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<sup>14</sup>The market components are taken from Goulder and Williams (2003), which is a model of the entire U.S. Hence, the input intensities in the model will reflect this assumption and to the extent that the local economy of the Adirondack region differs from national averages, this assumption will introduce inaccuracies.

U.S. economy (in 1995) we assume the problem is national in scope — at the level of importance represented by the measures available for the Adirondacks. All estimates for deposition and willingness to pay measures are transformed to 1995 dollars.

## 4.2 Design of Policy Scenarios

The policy scenarios are designed to examine the general equilibrium consequences of introducing a set of least-cost output taxes to achieve a 43% reduction in both  $SO_2$  and  $NO_x$  emissions, a reduction roughly consistent with estimates of the effect of the Clean Air Act amendments of 1990 over the period 1990-2010. The implied vector of tax rates for the sectors of the numerical model is: Primary Energy = 9.4%, Manufacturing = 0.4%, Transportation = 55.5%, Utilities = 42.5%.

These tax rates are derived in two steps. First, the model is calibrated to describe the 1995 level of market activity, pollution conditions (i.e. deposition rates), and non-market preferences for ecosystem services, based on estimates for the willingness to pay for reductions in pollution that reflect all three ecosystem contributions to individual well-being (i.e. recreational fishing, scenic vistas and recreational hiking, and composite species/habitat service). With preference parameters set at this level we consider the equilibrium prices for  $SO_2$  and  $NO_x$  permits that would yield at least a 43% reduction in emissions. The equivalent sectoral tax rates are what we label here as the least-cost output taxes. Because emissions are assumed to be a fixed fraction of output in each polluting sector of the economy, these taxes simply reflect the pollution intensity of these sectors implied by the calibration of the model. The equilibrium prices and quantities that result from the introduction of the output taxes (or, equivalently, pollution permits defined in units con-

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In principle, a SAM could be developed for the states contributing to the acidic deposition problem in Adirondack.

sistent with output) are calculated under the assumption that tax revenues are transferred in lump sum to consumers. Because the model involves feedback mechanisms, the tax rates to achieve the 43% reduction will depend on the preference specification linking the non-market services to the market goods. We calibrated taxes for the “central” case described below. The actual reduction in emissions will not be exactly 43% as the preference specification changes due to the effects of these changes on the both the extent and the impacts of feedbacks.

Implementing this policy of new taxes designed to reduce emissions results in changes in market prices, changes in the levels of fish, tree cover and scenic vistas, as well as to the composite species/habitat service. There are also changes in the virtual prices associated with these non-market services.

We have selected two aspects of our computations of the different general equilibrium solutions to illustrate the potential for feedback effects. The first considers how the degree of complementarity between the two use-based non-market services, market-based consumer services and leisure influence the benefits we attribute to the same policy changes. Three alternatives are evaluated: a “central” case with a baseline calibration of the elasticities in the model, a “high” complementarity case in which the degree of complementarity between the use-based services and their complementary market goods is twice as strong as in the central case, and a “low” complementarity case where this complementarity is half as strong as in the central case.

For each of the general equilibrium benefit computations, the actual general equilibrium response to policy is held constant. What is varied is the definition of the benefit measure used to reflect how important general equilibrium effects are. To accomplish this objective, we vary how the market and non-market environment are related the benefits of a change in the level of *one individual amenity*. The way the levels of market prices and

other environmental amenities influence our benefit measures illustrates the importance of treating the valuation problem in a general equilibrium framework.

To define the experiment more precisely, let  $e(p, q, u)$  designate the Hicksian expenditure function with  $p$  the vector of market prices,  $q$  the vector of quasi-fixed (from the individual's perspective) non-market services, and  $u$  the level of well-being. Equations (10) through (13) define the alternative measures. The total willingness to pay for a discrete change in one non-market service is simply the change in the expenditure level required to maintain utility level  $u^0$ . We adopt the notation splitting out  $q_i$  and  $q_{j \neq i}$  to distinguish our focus on the change in one non-market service versus the simultaneous changes in other subsets of non-market services that actually take place in a general equilibrium response to the tax policy.

At one end of the spectrum, the change in  $q_i$  could be measured before the other arguments in the expenditure function change (equation (10)). At the other end of the spectrum, all other changes could be assumed to have taken place at the outset (equation (13)). Our strategy for understanding how the general equilibrium effects change the value of the improvement in one non-market service is to compute a range of such measures as a decomposing the influence of the different effects of the general equilibrium change on the value of such an improvement. Specifically, we compare:

- The effect of a change in  $q_i$  alone:

$$WTP^{q_i} = e(p^0, q_{j \neq i}^0, q_i^1, u^0) - e(p^0, q^0, u^0) \quad (10)$$

- The effect of the general equilibrium level of non-market services:

$$WTP^q = e(p^0, q^1, u^0) - e(p^0, q_{j \neq i}^1, q_i^0, u^0) \quad (11)$$

- The effect of the general equilibrium level of prices:

$$WTP^P = e(p^1, q_{j \neq i}^0, q_i^1, u^0) - e(p^1, q^0, u^0) \quad (12)$$

- The effect of the levels of the general equilibrium quantities and prices:

$$WTP^{GE} = e(p^1, q^1, u^0) - e(p^1, q_{j \neq i}^1, q_i^0, u^0) \quad (13)$$

One might argue that the value of simultaneous changes in the levels of multiple amenities could be measured using a summation of standard, partial equilibrium values. Our analysis demonstrates that even the WTP measures for *individual* amenities are interrelated in a way that makes them non-separable from other non-market changes and market changes. Therefore, these measurements must be made jointly using a general equilibrium approach like the one described in this paper.

The comparisons developed in equations (10-13) parallel the distinctions between consumer surplus for a price change measured along a partial versus a general equilibrium demand function (see Just, Hueth and Schmitz (2004), pp. 327-330). The general equilibrium demand function for a particular good measures the consumer surplus due to an intervention — say a new commodity tax on that good — by evaluating that good's demand at the general equilibrium prices for all goods (i.e. reflecting the general equilibrium effects of the new tax in these markets). In our case, we consider separately the evaluation of a change in a single  $q_i$  evaluated at general equilibrium values for all other  $q$ 's, all general equilibrium prices for marketed goods or at general equilibrium values for both. The distinctions highlight the importance of the interconnections associated with feedbacks.

There is a separate issue that also relates to feedback effects between the non-market

components of a general equilibrium model and the markets. The easiest way to describe it is to recognize that in a general equilibrium setting a policy causes many changes simultaneously. Thus, while our least-cost output taxes might have been intended to improve the abundance of fish by reducing acidic deposition, reductions in emissions also affect the tree cover and the services we described as being associated with non-use or existence motives. In addition, the relative prices of the goods and services change. All of these effects are associated with the policy. This description of the general equilibrium consequences has been the traditional focus describing the difference between partial equilibrium and general equilibrium measures of the willingness to pay for a policy, considering *all* of its effects. Such a general equilibrium measure would be defined by equation (14).

$$WTP_{Total\ GE} = e(p^1, q^1, u^0) - e(p^0, q^0, u^0) \quad (14)$$

In this context, efforts to distinguish primary versus ancillary benefits of the policy would separate the effects of the changes in  $q_i$  versus the changes in the other  $q$ 's in different ways.

Our focus here is on how the treatment of the feedback effects influences the willingness to pay for a change in a single service. To illustrate this in a general equilibrium setting, we must define the way it would be accomplished in order to generate the general equilibrium effects. Our model abstracts from pollution abatement procedures and simplifies the transmission mechanism from emissions to effects. As a result, there are no options to adjust control responses and the policy is exceptionally costly. It would never “pass” a benefit-cost review. That is not our point.<sup>15</sup> Rather, our objective is to highlight how

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<sup>15</sup>The conventional general equilibrium willingness to pay for the taxes as a policy that changes both the vector of non-market services and the relative prices of market goods is negative, as expected. The specification of the degree of complementarity in the case also has an effect on the size of the loss. This impact is small. The larger story is the one we have highlighted that parallels the distinction between partial

preference linkages change the impact of the general equilibrium point of evaluation for the willingness to pay measures used to evaluate a single change in an environmental service.

We illustrate this by performing a sensitivity analysis with respect to all of the elasticities that control the relationships between the market and non-market goods — both for the use values and for the composite/habitat existence value included in the model. As we noted earlier, we do not know the nature of the substitution or complementary relationships between the non-market services and market goods. Revealed preference estimation methods treat this as a maintained assumption. Our calibration strategy assumes some degree of complementarity between the use-based non-market goods, leisure and key complementary market services. For existence value, however, any degree of substitution with the other components of preferences is potentially consistent with the idea of non-use value as long as the good is weakly separable.

In this part of the analysis, we focus on the virtual prices of the non-market goods as a way to evaluate the important relationships to look for. Large changes in virtual prices for the same set of taxes with changes in the preference structure signal important impacts on the relationships between non-market and market goods.

equilibrium and general equilibrium demand functions (and supply when there is not constant returns to scale).

Degree of Complementarity	$WTP_{Total\ GE}$	% difference from Central case
High	-2540.7	1.3
Central	-2508.6	—
Low	-2503.7	-0.2

NOTES: WTP measured in 100-millions of 1995 dollars.

### 4.3 Scenario Calibration

Two basic types of information are required for calibration of a conventional CGE model — expenditure levels for the benchmark equilibrium of the economy and prior information on the first-order responsiveness of the model, typically in the form of price or substitution elasticities. With these data and assumptions about the representative agent's preference function and all production technologies, the calibrated-shares logic calibrates the free parameters to replicate equilibrium output levels at the benchmark prices.

The inclusion of non-market commodities into this framework requires an extension of this logic — assigning (or computing based on the available non-market valuation measures) virtual prices consistent with the benchmark levels of  $SO_2$  and  $NO_x$ . The description underlying these virtual prices must be consistent with a description of the non-market services affected by the pollutants. It must also incorporate the connections between these services and the non-market activities people undertake. Thus, the definitions of the role of non-market services in preference function, as well as the role assumed for pollution in constructing the services that enter these virtual prices, contribute to the nature of the interactions between choices and responses outside markets that affect non-market services. If there is information on the marginal willingness to pay for the non-market services affected by pollution (and we are prepared to assume that these values are relevant to the levels of services implied by the benchmark equilibrium), then these estimates can be used to construct the virtual prices for the benchmark solution. If one has estimates of willingness to pay for discrete changes in non-market services, then one must calibrate to the benchmark virtual price that implies the correct total willingness to pay. This is the situation we illustrate with the current model.

We calibrate to match Hicksian and Marshallian labor supply elasticities because the

leisure-labor choice is likely to be one important determinant of the feedback effects in the model. This task is complicated by the fact that the use-based non-market services are non-separable arguments in the agent's preference function, hence the labor supply response depends on the non-market services level changes implied by a change in the market wage. Because the emissions that determine those service levels are generated throughout the economy, closed-form solutions for these elasticity responses are not available. Numerical techniques are required to solve the implied system of nonlinear equations — one equation for each elasticity value to be matched in the calibration of the model. This process along with solution for the virtual prices of the non-market services associated with the pollutants will be jointly determined. Thus, our numerical calibration strategy requires the simultaneous solution of:<sup>16</sup>

- Zero-profit, market-clearance and budget balance conditions to define the general equilibrium response of non-market service levels to a wage change and the resulting labor supply change.
- Conditions which define the parameters used to control the elasticity relationships we wish to calibrate.
- Conditions which define the willingness-to-pay relationship which determine the benchmark virtual prices for non-market goods.
- Conditions which define the parameters used to ensure that the benchmark equilibrium in the model replicates output and price levels in the calibration data.

The algebraic form of the nested CES preference specification corresponding to figure 1 for the representative agent is given in equation (15).

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<sup>16</sup>The GAMS computer code responsible for performing the model calibration and computing the counterfactual scenarios described in our results are available upon request.

$$U = \left[ \theta^h \left( \theta^u \left( \sum_{i=1}^n \theta_i^C \left( \frac{C_i}{C_{0i}} \right)^\psi \right)^{\xi/\psi} + (1 - \theta^u) \left( \theta^{r^l} \left( \frac{l}{l_0} \right)^\kappa \right. \right. \right. \\ \left. \left. \left. + (1 - \theta^{r^l}) \left( \theta_f^r \left( \frac{f}{f_0} \right)^\varrho + \theta_t^r \left( \frac{t}{t_0} \right)^\varrho + \theta_{CSV}^r \left( \frac{C_{CSV}}{C_{CSV_0}} \right)^\varrho \right)^{\kappa/\varrho} \right)^{\xi/\kappa} \right)^{\rho/\xi} + (1 - \theta^h) \left( \frac{h}{h_0} \right)^\rho \right]^{1/\rho} \quad (15)$$

where the “ $\theta$ ” terms are defined as value shares of benchmark expenditures in the parenthesized bundles of commodities that they modify.<sup>17</sup> This expression is given in Rutherford’s calibrated share form as described earlier. The exponent parameters ( $\rho, \xi, \kappa, \varrho, \psi$ ) define the elasticities of substitution between the various nests within the function.

$\xi$  and the value share of leisure,  $\theta^{r^l}$ , are chosen to match the specific Hicksian and Marshallian labor supply elasticity estimates supplied as prior information (0.25 and 0.05 respectively).  $\theta^h$ ,  $\theta_f^r$  and  $\theta_t^r$  are the value share parameters for the composite species/habitat, the fishing, and the scenic vista services, respectively. They are chosen to match our data on the willingness to pay for changes in the levels of these non-market services in the Adirondack study area (see table 1).

$\rho$ ,  $\kappa$  and  $\varrho$  are the parameters that determine the substitution relationships between leisure demand ( $l$ ), non-market services ( $f, t, h$ ), and consumer services ( $C_{CSV_0}$ ). In the policy scenarios, we vary the values these parameters take on *relative to the calibrated value of  $\xi$*  in order to achieve specific patterns of substitution between the market and non-market components of the preferences structure. This exercise is the strategy we use to vary the substitution and complementarity between market and non-market goods that determine the relative strength and character of the feedback effects in the economy.

<sup>17</sup>The top level terms ( $\theta^h$  and  $(1 - \theta^h)$ ) define shares of the total expenditures out of virtual income (market income plus the benchmark value of the non-market services and leisure, whereas the super-scripted instances within the various nests of the function are defined relative to the total expenditures within the nest.

We choose  $\rho$ ,  $\kappa$  and  $\varrho$  take on values that give the associated Allen elasticity parameters  $(\sigma_h, \sigma_{rl}, \sigma_r)$  specific relationships to the value of  $\sigma_u$ , the substitution elasticity that controls the labor supply elasticity.  $\rho = 1 - 1/\sigma_h$ ,  $\kappa = 1 - 1/\sigma_{rl}$ ,  $\varrho = 1 - 1/\sigma_r$ . In our central case,  $\sigma_h = \sigma_u$  and  $\sigma_{rl} = \sigma_r = \sigma_u/4$ . The effect of this specification is to assure that the cross-elasticities between the arguments within the nests governed by these parameters are one-fourth as substitutable with each other as any one of them is with the commodities in the bundle of consumption goods described in the bottom line of equation (15). The rationale for this calibration is that the use-based non-market services (fish and tree values) should exhibit strong relative complementarity with leisure time and the market-based consumer services that are required to enjoy visits to the Adirondacks.<sup>18</sup> A typical value for  $\sigma_u$  implied by matching the labor supply elasticities that we calibrate to is around 2.<sup>19</sup> This makes the value for  $\sigma_h = 2$  and  $\sigma_{rl} = \sigma_r = 0.5$ . In the low complementarity case,  $\sigma_{rl} = \sigma_r = 1$  and in the high complementarity case  $\sigma_{rl} = \sigma_r = 0.25$ . In the sensitivity analysis, we look at all combinations of  $\sigma_h$ ,  $\sigma_{rl}$  and  $\sigma_r$  that are equal to the values they take on in the central as well as twice and half these values.

To assure compatibility each variation in the model corresponds to a new calibration to benchmark conditions — altering the restrictions imposed as part of calibration in the substitution elasticities. Thus each calibrated version of the model reproduces the same willingness to pay measures for the non-market services *and* the same efficient output tax rates. The slopes of the virtual price function for each non-market service are different. Figure 3 illustrates the point for one non-market service. *A* and *B* can be interpreted as

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<sup>18</sup>We define commodities as complements based on the cross-price elasticities that would be implied by these substitution elasticities using the virtual prices. Smaller values for the  $\sigma$  terms imply smaller cross-price elasticities.

<sup>19</sup>The exact value of  $\sigma_u$  that matches our labor supply estimates will depend on the values of the other elasticity parameters in our preference structure. The range of values over all of calibrations we consider in the sensitivity analysis are between 1.75 and 2.7.

reflecting two alternative restrictions linking the substitution elasticities that might involve this non-market service. Changes in the elasticity together with the restriction to reproduce our benchmark values for willingness to pay and the implied restrictions linking the non-market services to market goods must alter the slopes and positions of the willingness to pay functions. Calibration assures that the total willingness to pay function for a fixed change in that non-market service will be reproduced under benchmark conditions. The functions are assumed in this case to be set to reproduce the WTP for the change from  $A^0$  to  $A^1$ . Thus the triangle represented by  $K$  must be equal to  $L$  so the areas under the two curves will be the same.

## 5 Results

Table 2 describes the effects of our policy scenario, a 43% reduction in  $SO_2$  and  $NO_x$  pollution, on the prices and quantities represented in the model. The different market and non-market activities represented in the model are described on the rows of the table. The three horizontal sections of the table, labeled High, Central and Low describe results under the different assumptions about the degree of complementarity between the use-based non-market services in the model and leisure and market-based consumer services. For each of these scenarios, we report the percentage change in the price (or virtual price) of the activity and the percentage change in the quantity supplied from benchmark levels.

Naturally, the largest effects of the pollution taxes are on market prices are in those sectors that are most pollution intensive in the benchmark data — transportation, utilities and primary energy production. All of these sectors experience large increases in cost and corresponding reductions in quantities produced and consumed after the taxes are implemented. Prices in other market sectors are relatively unaffected.

The virtual prices of the three non-market services go down significantly — between 18 and 75 percent depending on the service and the complementarity scenario we are considering. The marginal willingness to pay for these services goes down as the amounts provided by the ecosystem go up under the policy scenario. The extent of the reduction of the virtual prices depends on the degree of complementarity between the market and non-market goods in the preference structure. As the use-based services (fish and tree) become less complementary to leisure and consumer services, their values are less affected by the policy change. We can see by comparing the price changes for these goods in the High, Central and Low complementarity scenarios described in the table.

Demand for consumer services and leisure both increase between 9 and 15 percent as a result of the pollution taxes. This is due to the fact that these activities are not pollution intensive and therefore become cheaper relative to market activities like transportation and energy. It is also due to the fact that the complementarity with the use-based non-market services increases demand for these goods as the ecosystem improves under the new policy.

Notice that even the virtual price of the good we associate with the existence of non-use services is affected by the policy change and varies across the complementarity scenarios. While the effect is not as strong as for the use-based values, the table illustrates how the services attributed to existence values cannot be regarded as unaffected by changes to the other parts of the economy because they enter in a weakly separable form in preferences. Connections throughout the natural system as well as market-based feedbacks in other goods and services contribute to these changes.

To consider in more specific terms the connections between the different market and non-market goods interact, we now evaluate how the measures of total willingness to pay for the improvement in one individual non-market service (the fish service) delivered by the policy is affected by the other changes to the general equilibrium system. This is the

$q_i$  in our definitions of WTP in section 4.2. Table 3 reports on this topic. The different welfare measures described in section 4.2 are listed in the rows of the table. The column labeled “Before” describes the WTP calculation that an analyst would make if the other changes to the general equilibrium system were ignored in setting the baseline point for evaluating the change in  $q_i$ . The column labeled “After” describes the WTP calculation that incorporates some or all of the general equilibrium changes in setting the baselines for evaluation. The column labeled % Diff is the percentage difference between the Before and After column values. The WTP measures are in 100-millions of 1995 US dollars. The three vertical sections of the table, labeled “High”, “Central” and “Low” describe results under the difference assumptions about the degree of complementarity between the use-based non-market services and leisure and market-based consumer services, as in Table 2.

The improvement in the use-based fish services implied by the policy change are valued at between 560 and 890 million dollars depending on the complementarity scenario and the specific welfare measure used to evaluate the policy. With the exception of one case, the value of the fish services improvement is more valuable when some or all of the other general equilibrium adjustments are taken into account. The effect of introducing the other improvements in the ecosystem values (tree and existence services) in the calculation does not appear to have a large effect on the value of the improvement in the fish services. This is indicated in the table by the difference the values in the Before and After columns for the  $WTP^q$  measure. In the High complementarity scenario, where this effect is most strongly felt, it only results in a 2.7% difference in the willingness to pay for fish services.

Introducing the price changes in the market economy induced by the policy intervention to the baseline used of evaluating the change in fish services (indicated in the  $WTP^p$  row of the table) has substantially larger effects however. In the Central case, failing take these

influences into account would underestimate the value of the improvement in fish services by approximately 25%. In the High complementarity case, this error more than doubles (53%) and in the Low complementarity case it is approximately one half (12.5%). These changes are similar in magnitude to the changes in the values of the elasticity parameters in the nest of use-based services that we have assumed across these scenarios.

There is a strong intuition for these results. The higher the degree of complementarity between use-based services and leisure and the consumer services good, the more dependent is the value of an improvement in fish or tree services on matching increases in these market goods. As we noted earlier, a major effect of the policy intervention is to cause consumers to substitute out of pollution-intensive consumption and into activities like leisure and services. Thus, the price changes due to the policy add value to the increases in the ecosystem services by encouraging demand for complementary market goods.

The results described in table 4 explore the consequences of the different possible forms that non-separability of the non-market services might take in the preference structure for the equilibrium outcomes and the values placed by the consumer on these different services. The first three columns of the table indicate the value that each of the substitution elasticity parameters takes on in each scenario relative to the value assumed in the central cases. Recall that  $\sigma_h$  controls the degree to which the existence/habitat services is substitutable with other all other forms of consumption.  $\sigma_{rl}$  controls the substitution between leisure and the bundle of use-based ecosystem services and the consumer services good, and  $\sigma_r$  controls the substitution within that bundle. The three horizontal sections of the table, labeled Fish, Tree and Existence/Habitat refer to the three non-market services in the model. For each non-market service, we report the percentage change in the virtual price and quantity supplied from benchmark levels that is implied by the policy intervention.

Two conclusions emerge from the analysis of these alternative model specifications.

First, the equilibrium quantities of the different ecosystem services are less affected by the changes to the preference structure than the equilibrium virtual prices of the services. Nevertheless, the quantities do vary across the scenarios described here by as much as ten percentage points. This is a reflection of the feedback effects between the non-market goods and the market effects of the tax policy. Most of the “action”, however, is the changes in the virtual prices. The elasticities that control the use-based nest in preferences ( $\sigma_r$  and  $\sigma_{rI}$ ) have natural effects on the magnitude of the virtual price decreases for the use-based services. For example, the percentage drop in the virtual price on fish services changes is upwards of 80% when  $\sigma_r$  is half of the value it takes on in the central case and around 30% when it is twice the central value. This is, again, due to the fact that the value is more closely aligned to the use of consumer services when this elasticity value is small.

However, there are also more indirect effects.  $\sigma_h$  (the existence value elasticity) affects the virtual prices of the other services by more than ten percentage points over the range of values we consider. Thus, even in a model where the non-market services represent a somewhat small share of virtual income (the existence value and the tree value represents approximately 0.4% of virtual income each and the fish value is approximately 0.03% in our calibration), the presence of multiple services linked through the ecosystem and through their relationships to market goods can have a marked effect on the value of any one improvement in an ecosystem service. These effects simply reflect the pattern of equilibrium adjustments across the economy due to non-market and market feedback effects.

## 6 Implications

The early papers by Ayres and Kneese (1969) and Krutilla (1967) provided the conceptual basis for re-considering how economic assessments of environmental policy are undertaken. Ayres and Kneese argued that environmental externalities were not “exceptional and minor” but pervasive. Partial equilibrium strategies would be incomplete because they failed to account for the linkages between sectors through the non-market consequences of residuals management. Their focus was primarily on the supply side of general equilibrium models. Krutilla’s arguments can be used to suggest that the services attributed to modifications in the natural landscape, including the decisions about how to dispose of the residuals prominent in the Ayres and Kneese framework, entered preferences in several distinct ways. In his framework, these different contributions were associated with use and non-use motives for protecting ecosystems. The subsequent literature on non-market valuation has focused primarily on the challenges in measuring the use and non-use trade-offs. There is another challenge that follows from his framework. It arises once we recognize that, in a general equilibrium setting, non-market feedbacks change when we acknowledge existence values as a component of preferences.

The implications of these early papers have not been fully appreciated. Modern treatments of applied welfare economics (see Just et al. (2004) for example) focus attention on the market interactions that distinguish partial equilibrium and general equilibrium measures of consumer surplus (and deadweight loss). They fail to recognize the important feedbacks from the non-market consequences of policy. Sometimes policy is intended to improve some aspect of environmental quality. In other situations the objective is something else such as improving transportation or energy infrastructure and there are indirect effects on environmental services. In both cases there are feedbacks that can influence the

prices and quantities of market related goods and services in a general equilibrium. Ayres and Kneese conjectured correctly in our view that "... the partial equilibrium approach is probably not convergent to the general equilibrium solution..." (p. 296).

We have demonstrated in a simple case with multiple environmental services that they were correct. Even in a situation where the share of virtual income (i.e. the economic value of market and non-market services assessed at equilibrium prices and virtual prices) is small the errors from ignoring them can be large. We have also illustrated the sensitivity of these feedbacks to the structure of the substitution or complementarity relationships between market goods and non-market services.

Unfortunately we know little about the nature of these linkages. Efforts to measure the trade-offs people would make to increase non-market services (or to enhance their quality) have routinely assumed a preference linkage such as weak complementarity or perfect substitution to derive estimates (see Ebert (1998) and Herriges, Kling and Phaneuf (2004) for examples of these restrictions). To complete the work Ayres and Kneese and Krutilla, stated-preference research needs to be re-directed to measuring the nature of these connections. Our analysis has proposed a basis for how this task might be accomplished. The changes in virtual prices for non-market services signaled important feedbacks in our general equilibrium model.

As we noted earlier, a key element in most CGE models is the use of a representative agent to characterize all consumers. While it is possible to allow for more agents to reflect distributional effects, the degree of heterogeneity in the prices different consumers face is minimal due to the law of one price. With non-market goods, the virtual prices facing different groups would be different. This effect could be accommodated by having different agents, but the differences would arise from their hypothesized spatial location. It is also possible to reconsider aggregation relationships that might influence the specification for a

single representative agent's preferences from those facing different prices (see Bergstrom and Cornes (1981)). In either case, these changes would likely enhance concerns about the complementarity/substitution relationships we have focused on in this analysis.

A first step in this research would be efforts to develop tests for the spatial and temporal scales people perceive as the extent of the market for use and non-use related services. Such tests could be considered in a framework that is comparable to the scope test. A scope test asks how total willingness to pay changes with a change in the size of the change in a non-market good or service. The analysis we propose would consider how the marginal willingness to pay changes with modifications in the availability or quantity of related market and non-market goods and services over different spatial and temporal scales.

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# Figures and Tables

Figure 1: Nesting in Household Consumption

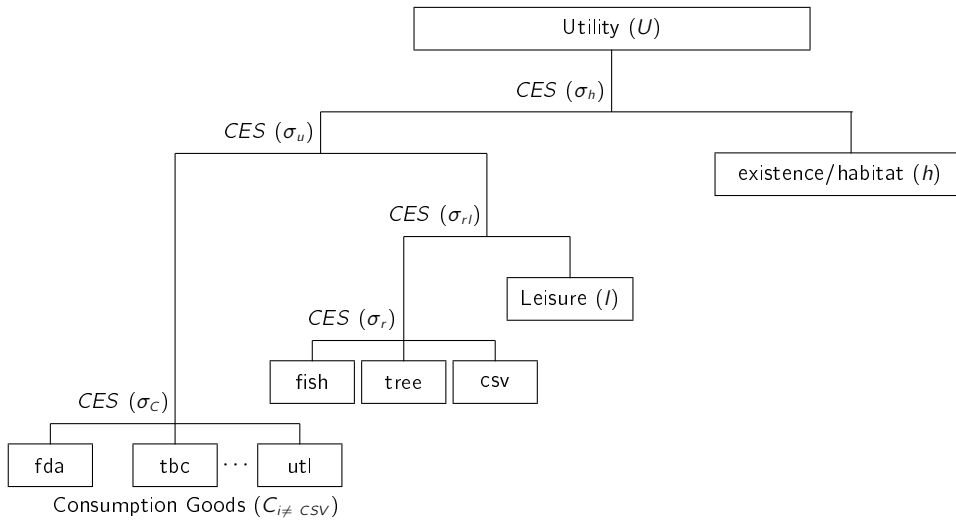


Figure 2: Relative Number of Species Supported by a Lake and Ph Levels

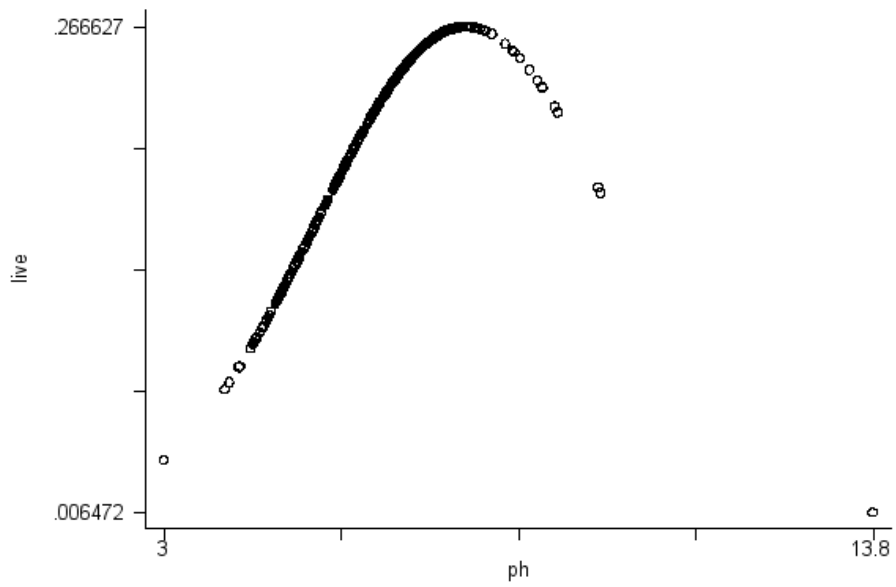


Figure 3: Effects of Substitution on Calibrated Virtual Price Functions

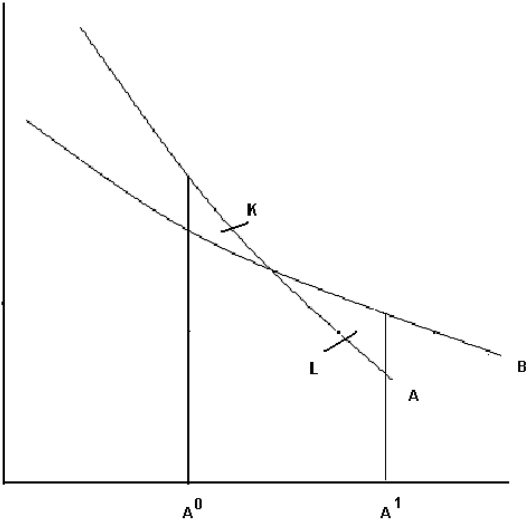


Table 1: Non-Market Components of the Acidic Deposition Model

Model Component	Transformation/Adjustment	Source
<i>Emission Rates</i>		
<i>SO<sub>2</sub>, NO<sub>x</sub></i>	Reported in thousands of short tons per year for full consumption; industrial processes, transportation and (where relevant) agricultural and forestry and natural sources; sectors aggregated to conform to Goulder and Williams (2003)	United States Environmental Protection Agency (1996)
<i>Deposition Rates</i>		
<i>SO<sub>2</sub>, NO<sub>x</sub></i>	Reported in kg/ha in Prospective Analysis; used 1990 base scenario to estimate the conversion from tons of emissions to kg/hectare/ton; for <i>SO<sub>2</sub></i> deposition rate is 22 kg/ha; for composite of <i>SO<sub>2</sub></i> and <i>NO<sub>x</sub></i> it is assumed to be 23 kg/ha	United States Environmental Protection Agency (1999)
<i>Willingness to Pay Measures</i>		
Willingness to Pay per Household per Year	\$1.33 for a 50% reduction per kg/ha in <i>SO<sub>2</sub></i> deposition rate; based on random utility recreation model computed for season for the quality improvement's impact on catch rates (1995 dollars)	Englin, Cameron, Mendelsohn, Parsons and Shankle (1991) is reported in New York State Environmental Cost study (Rowe et al. 1995) p.526
Willingness to Pay per Household for Forestry Views	\$2.56 per household for a 5% reduction in kg/ha that leads to improved forestry views; based on analysis of visibility and integral vistas from acidification for Adirondacks (1995 dollars)	New York State Environmental Cost study (Rowe et al. 1995) p.478
Willingness to Pay for Program Leading to Base Improvement	Redefine the increment based on Kopp and Smith (1997) characterization of index of stock of resources: $L$ = total stock of lakes $I$ = lakes of concern $(L^p - I^p)^{1/p}$ = index of effective lakes Changes in $I$ give rise to the effects of the plan (1995 dollars) WTP = \$48.04 for 50.8% increment	Banzhaf et al. (2006)

Table 2: % Changes in Equilibrium Prices and Quantities for 43% reduction in  $SO_2$  and  $NO_x$  by Level of Use-Based Complementarity

	<i>High</i> ( $\sigma_{rl}, \sigma_r = \sigma_u/8$ )		<i>Central</i> ( $\sigma_{rl}, \sigma_r = \sigma_u/4$ )		<i>Low</i> ( $\sigma_{rl}, \sigma_r = \sigma_u/2$ )	
	% $\Delta P$	% $\Delta Q$	% $\Delta P$	% $\Delta Q$	% $\Delta P$	% $\Delta Q$
Energy	24.8	-23.6	24.8	-22.7	24.8	-21.3
Services	0.8	-1.9	0.8	-1.5	0.8	-1.0
Agriculture	2.6	-3.4	2.6	-2.7	2.6	-1.6
Manufacturing	2.1	-4.8	2.1	-3.7	2.1	-2.1
Food and Alcohol	1.4	-5.4	1.4	-3.9	1.4	-1.4
Consumer Manufactures	1.7	-5.7	1.7	-4.2	1.7	-1.7
Transportation	145.2	-55.4	145.2	-54.6	145.2	-53.5
Utilities	91.7	-45.0	91.7	-44.1	91.7	-42.6
Consumer Services	0.9	14.2	0.9	12.5	0.9	9.2
Leisure	0.0	14.5	0.0	13.1	0.0	10.1
Fish Services	-74.5	74.9	-52.9	73.5	-38.7	71.2
Tree Services	-77.9	82.8	-55.9	80.1	-40.5	75.9
Existence/Habitat Services	-17.6	82.8	-18.7	80.1	-22.9	75.9

NOTES: The different market and nonmarket activities represented in the model are described on the rows of the table. The three horizontal sections of the table, labeled High, Central and Low describe results under the different assumptions about the degree of complementarity between the use-based nonmarket services in the model and leisure and market-based consumer services. For each of these scenarios, we report the percentage change in the price (or virtual price) of the activity and the percentage change in the quantity supplied from benchmark levels.

Table 3: Decomposition of Willingness to Pay Measures for Improvements in Fish Services by GE Adjustment Type

	Before	After	% Diff
<i>High</i>			
$WTP^{GE}$	5.6	8.9	58.7
$WTP^P$	5.6	8.6	53.1
$WTP^q$	5.6	5.8	2.7
$WTP^{q_i}$	5.6	5.6	—
<i>Central</i>			
$WTP^{GE}$	7.0	8.8	25.9
$WTP^P$	7.0	8.7	25.2
$WTP^q$	7.0	7.0	0.5
$WTP^{q_i}$	7.0	7.0	—
<i>Low</i>			
$WTP^{GE}$	7.6	8.6	12.2
$WTP^P$	7.6	8.6	12.5
$WTP^q$	7.6	7.6	-0.2
$WTP^{q_i}$	7.6	7.6	—

NOTES: **Before:** WTP for improvement in fish services before other GE adjustments have taken place (100-millions of 1995 dollars). **After:** WTP for improvement in fish services after other GE adjustments indicated in the first row of the table have taken place (100-millions of 1995 dollars). **% Diff:** Percentage difference between the Before and After column values. The three vertical sections of the table, labeled High, Central and Low describe results under the difference assumptions about the degree of complementarity between the use-based nonmarket services in the model and leisure and market-based consumer services.

Table 4: Elasticity Sensitivity Analysis: % Changes in Virtual Prices and Quantities of Nonmarket Services

Elasticity Scenario			<i>Fish</i>		<i>Tree</i>		<i>Existence/Habitat</i>	
$\sigma_h$	$\sigma_r$	$\sigma_{rl}$	% $\Delta$ P	% $\Delta$ Q	% $\Delta$ P	% $\Delta$ Q	% $\Delta$ P	% $\Delta$ Q
1/2	1/2	1/2	-69.3	74.5	-73.2	81.8	-35.9	81.9
1	1/2	1/2	-74.5	74.9	-77.9	82.8	-17.6	82.8
2	1/2	1/2	-82.7	75.8	-85.1	84.7	-6.7	84.6
1/2	1	1/2	-41.1	74.6	-44.7	82.1	-33.6	82.2
1	1	1/2	-47.0	75.1	-50.5	83.0	-16.2	83.1
2	1	1/2	-57.3	75.8	-60.3	84.7	-5.9	84.6
1/2	2	1/2	-21.9	74.6	-24.3	82.0	-32.5	82.1
1	2	1/2	-26.2	75.0	-28.6	82.8	-15.5	82.9
2	2	1/2	-34.3	75.7	-36.5	84.4	-5.5	84.3
1/2	1/2	1	-75.0	73.2	-78.1	79.4	-39.3	79.5
1	1/2	1	-79.4	73.6	-82.0	80.1	-19.8	80.1
2	1/2	1	-86.2	74.2	-88.1	81.5	-7.9	81.4
1/2	1	1	-47.6	73.2	-50.8	79.4	-37.5	79.4
1	1	1	-52.9	73.5	-55.9	80.1	-18.7	80.1
2	1	1	-62.2	74.2	-64.8	81.3	-7.3	81.3
1/2	2	1	-26.6	73.1	-28.8	79.1	-36.5	79.2
1	2	1	-30.7	73.4	-32.8	79.8	-18.0	79.8
2	2	1	-38.3	73.9	-40.4	80.9	-6.9	80.9
1/2	1/2	2	-82.8	71.5	-84.8	76.3	-45.0	76.3
1	1/2	2	-86.1	71.7	-87.7	76.7	-23.8	76.7
2	1/2	2	-91.0	72.1	-92.1	77.5	-10.3	77.4
1/2	1	2	-58.2	71.3	-60.6	75.9	-44.3	75.9
1	1	2	-62.5	71.5	-64.8	76.3	-23.3	76.3
2	1	2	-70.1	71.9	-72.0	77.1	-10.0	77.1
1/2	2	2	-35.1	71.1	-36.9	75.5	-43.8	75.5
1	2	2	-38.7	71.3	-40.5	75.9	-22.9	75.9
2	2	2	-45.5	71.7	-47.2	76.7	-9.7	76.6

NOTES: The first three columns of the table indicate the value that each of the substitution elasticity parameters takes on in each scenario relative to the value assumed in the central cases. The three horizontal sections of the table, labeled Fish, Tree and Existence/Habitat refer to the three nonmarket services in the model. For each nonmarket service, we report the percentage change in the virtual price and quantity supplied from benchmark levels.

## A Elements of the Numerical Model

Table 5 lists the dimensions of the economic model. The model describes a general equilibrium in sectors of the economy and primary factors.

Table 5: Elements of the Model

---

	<i>Primary Factors</i>
lab	Labor
	<i>Intermediate Sectors</i>
ene	Energy
svc	Services
agr	Agriculture
mnf	Manufactures
	<i>Final Consumption Sectors</i>
fda	Food and Alcohol
csv	Consumer Services
cmn	Consumer Manufactures
trn	Transportation
utl	Utilities

---

Benchmark data on quantities, prices, and elasticities provide the calibration point for the production and utility functions that describe the economy.

Key assumptions and notation:

- The model is identical to that used in Goulder and Williams [2003] except in the form of the utility function and the absence of a pre-existing labor income tax. Whenever possible we maintain the same calibration as Goulder and Williams [2003].
- All goods are produced via constant elasticity of substitution (CES) production functions. This implies constant returns to scale technology in all sectors.
- The representative agent's welfare is produced through the consumption of consumer goods, leisure, and environmental amenities, subject to time endowment and income constraints. The utility function is a nested CES function.

Table 6: Intermediate Production Benchmark Values

	energy	services	agriculture	manufactures
energy	253,800.3	35,748.4	12,135.2	83,751.8
services	55,608.3	1,182,177.2	48,378.1	753,981.8
agriculture	174.6	109,776.9	353,617.4	32,591.6
manufactures	108,723.6	537,487.8	58,516.9	2,017,510.8
labor	79,221.2	2,239,303.1	55,472.4	1,143,765.5
total	497,528.0	4,104,493.4	528,120.0	4,031,601.6

source – Reproduced from Table B2 in Goulder and Williams [2003].

note – All figures in millions of US 1995 \$.

Table 7: Final Consumption Production Benchmark Values

	food & alcohol	consumer services	consumer manufactures	transportation	utilities
energy	297.6	34.6	5,571.4	50,320.6	55,868.1
services	480,375.7	835,116.3	571,872.7	92,237.5	84,745.9
agriculture	24,721.9	105.5	7,131.1	0.5	0.5
manufactures	315,431.3	75,867.5	917,510.0	0.5	553.2
total	820,826.4	911,123.9	1,502,085.1	142,559.1	141,167.7

source – Reproduced from Table B3 in Goulder and Williams [2003].

note – All figures in millions of US 1995 \$.

Table 8: Model Notation and Parameter Values

		<i>Sets</i>	
$C$	Final Consumption Goods		{fda, csv, cmn, trn, utl}
$I$	Intermediate Goods		{ene, svc, agr, mnf}
		<i>Parameters</i>	
$T$	Aggregate time endowment		$\sim \eta_{lab} = 0.05, \eta_{lab}^h = 0.25$
$\sigma_j$	Substitution between inputs in intermediate and final sectors		$\sim \epsilon_{ene} = 0.9$
$\sigma_u$	Substitution between leisure-nonmarket bundle and market goods		$\sim \eta_{lab} = 0.05, \eta_{lab}^h = 0.25$
$\sigma_c$	Substitution between consumer goods in consumption nest		0.85
$\sigma_h$	Substitution between existence/habitat service and all other consumption		$= \frac{1}{2}\sigma_u, \sigma_u, 2\sigma_u$
$\sigma_{rl}$	Substitution between leisure and use-based nonmarket service bundle		$= \frac{1}{8}\sigma_u, \frac{1}{4}\sigma_u, \frac{1}{2}\sigma_u$
$\sigma_r$	Substitution between use-based nonmarket goods		$= \frac{1}{8}\sigma_u, \frac{1}{4}\sigma_u, \frac{1}{2}\sigma_u$

$\sim$  reads "calibrated to imply".

$\eta_{lab}$  and  $\eta_{lab}^h$  denote the uncompensated and compensated labor supply elasticities, respectively.

$\epsilon_{ene}$  denotes the own-price demand elasticity of energy.

# B Production Structures

Figure 4: Intermediate Goods

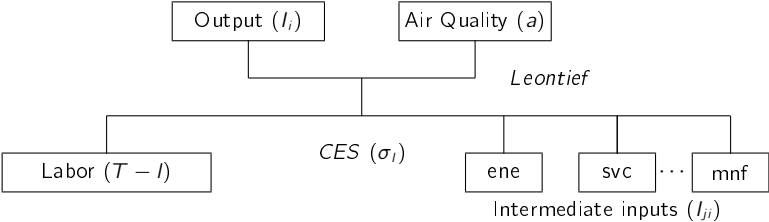


Figure 5: Final Goods

