Valuing Nature in a General Equilibrium

Jared C. Carbone and V. Kerry Smith

1. Introduction

While applied general equilibrium (or CGE) analysis is now well accepted as a method for evaluating the economy-wide effects of new environmental regulations, most policy analyses assume the important general equilibrium effects these rules generate can be limited to the market-based activities that enter the benefit-cost equation. That is, they model the market-based costs that these policies generate as the product of complex patterns of relative price adjustments throughout the economy. Meanwhile, the values of the non-market benefits of improvements in environmental quality are treated as if they are small enough or exceptional enough that they are independent of these adjustments. Some authors model the value of environmental quality improvements as a simple function of pollution levels (see Nordhaus [1994] for example). Some do not model damages explicitly. Instead, they implicitly assume that the changes in pollution levels are constant across their policy experiments and that this alone assures that the economic value of these changes is constant as well (see Hazilla and Kopp [1990] for example).

Both approaches are inconsistent with the idea that demand for environmental quality responds to relative price changes (and changes in other dimensions of the non-market services, environmental and other, available outside markets) the way other goods in economic models do. Both strategies are also inconsistent with the way that environmental economists conceive of these goods in the models used to recover empirical estimates of the tradeoffs people make to obtain them.

In this paper, we propose a new, general approach for including environmental benefits in CGE analyses of environmental regulations and use illustrative policy simulations to identify scenarios in which a general equilibrium treatment of benefits will substantially alter the conclusions of benefit-cost assessments. We argue that a full treatment of environmental benefits in general equilibrium analyses must acknowledge a number of important sources of interactions that are not admitted by models used in previous studies.

These inconsistencies with the historical treatment of non-market values are not simply logical inconsistencies. A moment of reflection reveals that people routinely combine market goods and services and their time to make use of environmental services. They spend on medical services to offset the adverse health effects of air pollution. The enjoyment of outdoor recreation requires significant expenditures of resources in the form of leisure time and the contracted services of hotels, restaurants and transportation.[1] If one accepts this idea, then the value of the health and amenities delivered by the environment to individuals must depend on the prices of these related goods and, conversely, the demand for these related goods must depend on the state of the environment. This is the logic that is the basis for revealed preference estimates of non-market benefits. These estimates underlie almost all benefit-cost analyses of existing environmental regulations. Yet analysts regularly employ them without acknowledging of the behavioral relationships from which they arise. The open question that remains is whether or not these relationships are empirically important to general equilibrium policy experiments.

As an acknowledgement of the idea that the market economy and the environment might interact in important ways, academic evaluations of the changes in air quality in the US and Europe have begun to conduct analyses that alter the assumption that environmental benefits do not interact with the general economy over the past half-decade [Matus et al 2008, Nam et al 2010, US EPA 2011]. A prominent example can also be found in the EPA's Second Prospective Analysis, completed as part of a continuing evaluation of the 1990 Clean Air Act Amendments (CAAA) in March 2011. To our knowledge, it is the first benefit-cost analysis of a set of rules to include a general equilibrium treatment of both the costs and the benefits. These studies have advanced the literature by including connections between the environment and human health in their models, but they do not resolve the issues that are the focus of our analysis. Fundamentally, the new models are no less problematic than the past literature in the sense that they do not model demand for environmental quality as an expression of economic tradeoffs, as a choice. As we will show, this is not just a conceptual issue; it also limits the scope for finding quantitatively important economy-environment interactions in policy experiments.

The generic issue extends well beyond the specific treatment of benefits used in the EPA's Second Prospective Analysis. What is at stake is establishment of a set of accepted

[1] U.S. expenditures on outdoor recreation were approximately $645 billion last year. In comparison, expenditures on pharmaceuticals totaled $331 billion and spending on motor vehicles and parts totaled $340 billion [NPR, 2012].

practices for quantifying the net benefits of any regulation that produces measurable changes in the levels of environmental services and is large enough to generate important economy-wide impacts. Almost by definition, it is the policies of national (as the case of the CAAA) or global (as in the case of global warming policies) significance that best fit this description. We argue that the treatment of environmental benefits in existing general equilibrium analyses deserves serious scrutiny and, in many cases, revision. We construct an illustrative CGE model of the effects of air pollution on ecosystem services and health to highlight the main concepts in the paper. Central to the analysis is the idea that these services connect with the demand and supply system for market goods through different channels that illustrate a few generic design principles for models of environmental quality improvements. First, policies that change pollution levels are assumed to affect multiple environmental services concurrently but through distinctive technical relationships. Thus, in our example, emissions of sulfur and nitrogen oxides contribute to acidic deposition that affects forests and the health of fisheries and have a separate influence of hospital admissions. These relationships need to be specified in ways that are consistent with the ecology and health sciences that define the physical impacts as well as measures of the tradeoffs people make to avoid them. As a consequence, values of different sources of benefits interact as components of a larger package of changes to the economic system.

Second, use-based environmental activities – those routinely associated with the revealed preference methods of non-market valuation – interact with each other and with market goods in contributing to consumers' well-being. In our illustrative model, we find that these complementary relationships can significantly alter the values associated with improvements in environmental services. The intuition behind this result is that the policy intervention required to affect the environmental change leads to changes in the prices of complementary goods which can either raise or lower the value of environmental services depending on the pattern of adjustment.

Third, and finally, non-use or existence services must also be accounted for in consumer preferences. By definition, these services have no observable choices involving other market goods that allow us to infer their value – they represent the ultimately separable good in some sense. It would be tempting, in light of this, to conclude that changes in the services labeled to reflect existence motives do not impact the rest of the economic system. However, we show that even this conclusion is incorrect; they exert an important influence on the values of other goods through the effect on the marginal utility of income.

Despite extensive research in non-market valuation over the past 50 years, an important obstacle to developing the types of models we consider here is that often we do not have an empirical basis for specifying the relative strength of the aggregate substitution or complementarity relationships required to describe the interactions between the economy and the environment. Thus empirical research in this area should be a high priority moving forward. However, this lack of empirical foundation does not obviate the need for researchers to explore the consequences of altering the empirically-unfounded assumptions currently used in CGE analysis. In our illustrative model, we use sensitivity analysis, performing over 300 consistent calibrations of the basic model, maintaining the linkages identified above and varying potentially important parameters. We then show how to use internal meta-analysis [Banzhaf and Smith, 2007] to identify the modeling judgments that were important to the conclusions and show where future improvements in the empirical basis for these assumptions would be most valuable.

The remainder of the paper proceeds as follows. Section 2 discusses how the early literatures in public and environmental economics contributed to the exclusion of linkages between environmental services and the market economy in benefit-cost analyses of environmental regulations. Section 3 outlines the features of our illustrative model, the conceptual logic behind the inclusion and calibration of the non-market effects in the model, and defines the welfare concepts we use to demonstrate how non-market general equilibrium feedbacks influence benefit measurement. Section 4 describes our policy experiments and findings. Section 5 discusses their implications.

2. Introducing Non-Market Resources Into a General Equilibrium Analysis

2.1 Context

A couple of historical developments in the literatures on optimal taxation and non-market valuation seem particularly important in shaping the subsequent treatment of measures for the tradeoffs people make for increments in environmental services in modern benefit-cost analyses. We briefly review these influences here.

When general equilibrium treatments of externalities are discussed in public economics, the analysis can typically be traced back to Sandmo's [1975] seminal work. One of his results seems to have been especially important to the way researchers working in the public finance tradition modeled the damages from externalities in the literature that followed. In his model, a central planner faces the task of taxing activities throughout the economy. A subset of these activities generates an externality. The planner must optimally internalize the externality subject to a revenue-raising constraint. In this setting, he finds that the optimal tax rates on the activities that are not directly responsible for the externality are independent of the social damages it produces, regardless of the patterns of substitution these goods exhibit with the external effect. Thus, the tax rates on these goods need not be adjusted in any way to account for interactions or feedback effects between the externality and these goods.

Sandmo's result was surprising and not at all obvious from the existing work on second-best taxation at the time. It was also influential because it left the basic logic of Pigouvian taxation of externalities intact and let the authors of subsequent experiments abstract from the complexities of these interactions and focus on other determinants of optimal tax structures. This was the background against which the literature on second-best environmental taxation developed years later. The result was that models with quite sophisticated descriptions of how general equilibrium interactions between market goods combine to determine the deadweight loss of regulation made their way into environmental policy analysis over the past twenty years. No comparable transformation took place in the practices of benefit transfer for policy analysis.

Nevertheless, Sandmo was careful to qualify his own result. He pointed out that it did not imply that the marginal social damages of externalities (or the marginal benefits of environmental quality improvements in our framework) were independent of the income and relative-price effects that result from the policy regime.[2] Thus there was no reason to expect that the value of environmental benefits would be unaffected by the feedback effects on these outcomes.

More specifically, we can draw an analogy to a general equilibrium demand function routinely used in applied welfare economics.[3] These functions are used to illustrate the proper role of general equilibrium effects for evaluating a change that influences a single market. It is

[2] See Sandmo [1975] pp. 92-93.
[3] See Just, Hueth, and Schmitz [2004] pp. 327-330 for definition.

important to evaluate this change at the values realized for the prices of all other goods and services *after* taking account of the general equilibrium effects of the intervention in the one market. In the presence of feedback effects on other non-market services, their final levels should be included. Of course, these effects do not matter if the non-market services make separable contributions to preferences and hence would not enter the demand function.

However, an assumption of separability would contradict the literature on the measurement of the damage from pollution using revealed preference methods. This research on measurement issues emphasizes how non-separabilities between market goods and non-market services can be used to estimate the tradeoffs a person would make to avoid external damages. Nonetheless, the logic of these valuation exercises is incomplete as well. It ignores the possibility that the value of these damages might be connected in some important way to the determination of relative prices throughout the economy by taking a partial equilibrium modeling approach. Of course, as a practical matter the importance of this effect depends on the size of the policy change giving rise to the differences in pollution that are used to recover the measures for damages.

Thus both perspectives are inherently partial equilibrium for different reasons. Public economics assumes separability in damages because non-separability does not influence the design of tax structures in Sandmo's framework. Non-market valuation studies focus on specific types of non-separability between damages and key market goods without acknowledging the broader implications of these connections for damages if environmental regulations have economy-wide impacts.

There have been attempts to model the costs and benefits of regulations using an integrated framework. These integrated assessment models have primarily sought to include some impacts of global warming that are thought to have relatively straightforward effects on the market economy such as changes in agricultural productivity (see, for example, Nordhaus [1994]). Similarly, the models used in both the MIT Joint Program on the Science and Policy of Climate Change (Matus et.al. [2008]) and the EPA's Second Prospective Analysis attempt to include some of the possible labor supply effects due to deaths as well as morbidity effects avoided due to conventional air pollutants. However, none of these approaches represent the sources for the tradeoffs that people make in order to obtain environmental services in a way that is consistent with the revealed preference logic associated with the framework that underlies modern non-market valuation methods. Moreover, there is not general agreement among researchers on what environmental benefits are important to include in such studies and how to go about doing it. As a result, a systematic discussion of how the varying treatments of these linkages across studies impact key model outcomes has not taken place.

2.2 Introducing Non-Market Goods and Feedbacks

To formalize 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* contributes to the individual's utility in at least two ways. This is represented analytically by introducing *q* through arguments in the preference function:

$$U = V\big(c(Q(q), x, l), h(q)\big) \tag{1}$$

q enters here as a sub-function $c(Q(q), x, l)$ where services associated with the environment 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 nature's value.[4]

Two aspects of any analysis of the role of environmental services in economic activity become clear when use and non-use values are viewed in this way. First, the value of some aspects of nature 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 imply 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.

---

[4] Hanemann [1988] first proposed a variation in this definition. Originally, non-use value was defined by including an additively separable term to preferences, where $U = V\big(c(Q, x, l)\big) + h(q)$ (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.

Second, the two components of the environment's 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.[5] When the two sets of services are derived from the same environmental system, such as an ecosystem, then changes in their levels are physically related to each other through the basic physical/biological functions of that ecosystem.[6] An important consequence of this characteristic is that, in general, policy interventions will affect the levels of all of these services that are sources for benefits. As a result, the value of the benefits due to an increment in any specific source cannot be evaluated without considering how it depends on the changes to other sources.

In a general equilibrium, these relationships influence how the non-market consequences of production and consumption choices feedback 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 influences 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 feedback to determine the equilibrium level of pollution and services delivered by the environment.[7]

§

We have outlined the conceptual logic describing the different channels through which environmental services interact with the economy. The second task is to develop a strategy for calibrating these relationships to produce a quantitative representation of the model for CGE analysis. Two challenges immediately arise. First, the conventional practice of calibrating

---

[5] The exception to this statement is the special case in which the services that are hypothesized to underlie non-use values are assumed to have perfect substitutes with a composite of all other private consumption. This is what would be implied by an specification of preferences that has these services making an additively separable contribution.

[6] This last feature of economic values – that they may be connected through technical relationships – parallels the logic set out by Ayres and Kneese [1969]. That is, in their framework the physical properties of materials and energy balances make 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 important to the performance of the joint economic/environmental system.

[7] Non-market feedback effects can arise from a number of sources. For example, congestion at a recreation site is due to the number of users at a location in relation to an exogenously specified capacity (see Timmins and Murdoch [2007] or Phaneuf et al [2009]). Open space amenities are due to the proportion of open space in a community including both potential and undeveloped land (see Walsh [2007]). In our example, feedbacks are due both to the different ways environmental services contribute to individual well-being and the physical interactions between pollutants and these various services. In addition, they lead to both substitution effects (as in these examples) and income effects.

constant elasticity of substitution (CES) or nested CES functions to describe preferences and production functions becomes significantly more difficult because the externalities must take the form of quasi-fixed goods in the preference structures.[8] This arises from the fact that the arguments used to represent them must be treated as *endogenous to the equilibrium in the model yet 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 which can be used to match model parameters to empirical estimates of the key elasticities in the model. For example, calibrating the labor supply elasticities requires modeling the effects of wage changes on the levels of the externalities in the model. With no closed-form solutions for these relationships, numerical methods are required.

Second, non-separability also 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, as well as the flows of pollution arising from consumption and production. This process must also include a description of the transfer functions that link pollution to the use and non-use services in the model.[9] We develop a new method to calibrate these types of models which we describe in more detail below.

3. An Illustrative Model with Multiple Non-Market Goods

Our model is designed to illustrate as simply as possible the three elements influencing the non-market services and the interactions between the non-market services and the demands for private market goods. It is not designed to be a comprehensive analysis of a specific regulation. The three elements we focus on are: (a) the specific ways in which non-market services enter preference functions as non-separable influences on the tradeoffs that agents would be prepared to make among marketed goods and services; (b) the transformations that define the relationship between physical/biological responses of the model ecosystem in our

[8] 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.

[9] 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.

application and the recognizable changes in the "services" that agents attribute to these activities or resources; and (c) the description of the health effects of air pollution. Elements (a) and (b) were the focus of the discussion in Section 2. We have chosen to study acidic deposition in our example policies because its complex ecosystem effects highlight the issues outlined in that discussion with respect to the measurement of benefits from multiple interacting sources. We include health effects in the model because they are often singled out in studies of air pollution as important sources of benefits attributed to air pollution regulations. Indeed, they are the only source of benefits in recent general equilibrium analyses reported as part of the EPA's Second Prospective Analysis (U.S. EPA [2011]) and in the recent studies using the EPPA-HE model (Matus et al. [2008], Nam et al. [2010]). Moreover, the treatment of measures of health effects provides a mechanism to illustrate how the assumptions used to link non-market effects to variables in a model that have implications for market choices influences their contribution to the general equilibrium feedback effects.

Our example builds on the illustrative model of the U.S. economy developed by Goulder and Williams [2003] for evaluating the deadweight loss of energy taxes. It has five final consumption goods as well as leisure, four intermediate goods, and one basic factor of production (labor). (The sector definitions and the benchmark data are described in Tables 5-7 in the appendix to the paper.) The model was designed to illustrate the performance of alternative measures of deadweight loss arising from adding different new taxes in a system with a pre-existing tax on labor income. For our purposes, the main virtues of the model are that it is simple and (prior to our modification) representative of the public-finance inspired CGE models that are commonly employed to study the efficiency costs of environmental regulations. 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 as well as the transmission functions that translate emissions into environmental services which we discuss in detail below.

The first issue that arises in our implementation stems from the challenges in developing a national level representation of environmental services. The Goulder-Williams model and almost all CGE models of U.S. environmental regulations use national-level accounts to depict the national economy. The acidic-deposition effects that are the subject of our experiments are a regional phenomenon affecting the Northeastern and Southeastern portions of the U.S. To reflect these effects at a comparable scale we would need national level measures of the affected ecosystem services. That is, we would like to characterize the forestry habitat, fishery effects, and so forth in relation to national measures of these services so this description is comparable to the market goods and services. As Smith [2012] discusses, there has been no effort to consider what these indexes would be for any environmental services. Indeed, even in the case of air pollution the measures reported by EPA are usually broad averages across monitoring stations rather than estimates of what people experience. Developing consistent indexes that attempt to authentically depict these services at a national level is beyond the scope of this paper. Instead, our analysis should be viewed as offering another indication of why attention to these types of issues would be important to policy analyses undertaken within a general equilibrium perspective. Here we assume that the aggregate measures of the tradeoffs all U.S. households would make for these services provide the basis for extrapolation. That is, we treat the effects as if they were present in each region of the U.S. based on the aggregate willingness to pay estimate.

Our objective is to link sulfur dioxide and nitrogen oxide emissions to acidic deposition rates and health effects. The first of these influences leads to three interdependent ways that acidic deposition is assumed to influence households. Figure 1 provides a schematic description of the representative agent's preferences in our model. The primary channel through which reduced acid rain contributes to individual well-being is through its effect on outdoor recreational activities. We select two types of recreational effects that have been documented in 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. The second interaction with recreational activities arises through the effects of acidic deposition on the quality and diversity of tree cover. These effects fall under the category of the ecosystem services that enter $Q(q)$ from equation (1) in the discussion from Section 2. 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 refer to in the model as the existence/habitat composite good. These services make a weakly separable contribution to well-being at the top level of the nesting structure and would enter $h(q)$

in equation (1). This formulation is consistent with the general logic used to describe the "bundled" services of an ecosystem that Banzhaf, Burtraw, Evans and Krupnick [2006] used in their contingent valuation scenarios.[10] Their results are used in our model calibration.

Finally, as we noted, the health effects are deliberately specified to mimic the logic used in the CGE analysis developed for the EPPA-HE model as well as the Second Prospective Report. The EPA strategy converts the health effects (both morbidity and mortality) into changes in the labor endowment available to the economy and includes estimates for reduced medical expenditures with reduced pollution. The EPPA-HE model includes the morbidity effects through a health production function that is specified to be Leontief in labor and medical services for each of the non-fatal health endpoints associated with the six types of air pollution represented in the model. Changes in pollution alter the fixed coefficients in this relationship proportionally, so more inputs are needed to deliver the same output. Health production is also Leontief with a bundle of all other consumption goods in the representative agent's utility function. Thus the output from this production function is an average substitute for all consumptions goods. Its unit price changes proportionately with pollution. The composite of these assumptions converts pollution (as a perfect complement to labor and medical services) to a cost increase. Mortality effects are treated as reducing the labor endowment. This induces another type of relative price change that is accommodated easily in the baseline normalization given homotheticity.[11]

Because the inputs to health production in the EPPA-HE model all contribute in fixed proportion to well-being in this framework, consumers do not "choose" the level of environmental services they consume per se; they are subjected to the equilibrium levels of pollutants and incur costs in proportion to changes in these levels but there is no role for evaluating a tradeoff between one's health and levels of other consumption. Similarly, because

---

[10] 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.

[11] The EPPA model does allow for income effects over time by allowing the share parameters and substitution elasticity among goods to vary over time as a function of GDP per capita. See Paltsev et. al. [2005] for details.

mortality effects are modeled as a scaling factor on the labor endowment in both the EPA and EPPA-HE studies, there is no choice made by consumers in responding to these effects and no pattern of substitution between these effects and other goods in the model. Thus, changes in mortality and morbidity exposure result only in income effects. This is a key difference between the framework we are proposing here and past studies.

We treat health effects as reducing the labor endowment to illustrate how strategic assumptions in the model's specification can minimize feedback effects. Our approach is comparable to the EPA specification and parallels the EPPA-HE treatment of mortality effects. The health benefits generated by our policy simulations are then used as a benchmark against which to judge the importance of the other non-market effects. Our analysis considers only the health effects on employment based on morbidity impacts. NO_x and SO_2 are assumed to lead to increased hospital admissions for all respiratory effects. We proportionately reduce the labor endowment using these incremental admissions rates with changes in each pollutant. We use the concentration response functions reported for each pollutant in the First Prospective Analysis.[12] The details of the specification are described in Table 1.

3.1 Linking Pollution to Non-Market Service Levels

The links between sulfur and nitrogen emissions and the non-market ecosystem services rely 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 reduced 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]. Data from the online database cited by the authors were assembled for this analysis. For the records with complete data, a simple regression model was estimated 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 resulting equation is given as (2) below.

[12] Concentration response functions were not reported for the morbidity effects of SO_2 and NO_x in the Second Prospective Report.

$$\ln(\neq \textit{fish species} / \max \neq \textit{fish species}) =$$
$$-6.91 + 1.47Ph - 0.97Ph^2 + .007\,\textit{Surface Area} + .012x10^{-4}\,\textit{Watershed Area} \tag{2}$$
$$n = 1{,}121$$
$$R^2 = .367$$

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. This stylized description simply illustrates the importance of baseline conditions for the response to efforts to control emission.

The last component of the ecological services relates to the assumed habitat services to represent 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 services, calibrated so that 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.[13] All estimates for deposition and willingness to pay measures are transformed to 1995 dollars.

3.2 Welfare Measures

A central objective of our analysis is to characterize how the various modifications to the economy induced with our counterfactual policy simulations – the changes to relative prices and in the levels of environmental services – contribute to the measures of environmental benefits that our model predicts. In the analysis that follows, we illustrate these effects with a

[13] 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.

decomposition of these influences for a single environmental service. The service we use in our illustration is our measure of the fish populations that is assumed to enhance recreational fishing. In the decomposition, our welfare measures for the improvement in fish populations differ in the extent to which they account for the general equilibrium effects of the counterfactual policy changes that produced this improvement. That is, they hold some aspects of the economic environment at their benchmark levels while allowing others to reflect their equilibrium levels in the counterfactual policy in a format that decomposes the factors contributing to general equilibrium demand changes. This allows us to describe how the different price and amenity effects contribute to the overall influence of general equilibrium effects on a single source of environmental benefits. It is worth emphasizing that our measures do not capture general equilibrium measure of the total benefits from reducing these pollutants, – they describe the importance of the general equilibrium adjustments for a single component of the benefits from pollution reductions. As such, the analysis describes how poorly an estimate of this value would perform if it ignored general equilibrium effects.

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 (3) through (6) define the alternative measures. The total willingness to pay (WTP) 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 separate the quality measure intended to represent fishing services, q_i , and the remaining environmental services designated as $q_{j \neq i}$.

At one end of the spectrum, the change in q_i induced by the counterfactual policy could be measured assuming that no other arguments in the expenditure function change from their pre-policy levels. This welfare measure is defined in equation (3). At the other end of the spectrum, all other arguments could be assumed to reflect their post-policy equilibrium levels. This full general equilibrium welfare measure of the change in q_i is described in equation (6)). Equations (4) and (5) describe welfare measures of fishery service improvements based on intermediate sets of assumptions in which some of the background arguments (levels of the other environmental amenities in (4) and market prices in (5)) change to reflect their equilibrium levels and others do not.[14] As we noted above, our strategy for evaluating the general equilibrium effects through the comparisons in equations (3-6) parallels the distinctions between consumer surplus measures for a price change using partial versus a general equilibrium demand function.[15]

- The effect of a change in q_i alone:

$$WTP^{q_i} = e\left(p^0, q^0_{j\neq i}, q^1_i, u^0\right) - e\left(p^0, q^0, u^0\right) \quad (3)$$

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

$$WTP^{q} = e\left(p^0, q^1, u^0\right) - e\left(p^0, q^1_{j\neq i}, q^0_i, u^0\right) \quad (4)$$

- The effect of the general equilibrium level of prices:

$$WTP^{p} = e\left(p^1, q^0_{j\neq i}, q^1_i, u^0\right) - e\left(p^1, q^0, u^0\right) \quad (5)$$

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

$$WTP^{GE} = e\left(p^1, q^1, u^0\right) - e\left(p^1, q^1_{j\neq i}, q^0_i, u^0\right) \quad (6)$$

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 this is not the case. Even the WTP measures for individual amenities are interrelated.

It is worth emphasizing at this point that our main objective is to consider how the treatment of the general equilibrium effects influences the willingness to pay for a change in individual services – not to produce comprehensive measures of the net benefits of environmental regulations.[16] To illustrate these effects, we must construct policy scenarios that

[14] None of these measures reflect *directly* the health effects of reduced air pollution. Health effects reduce labor time endowments and do not separately contribute to preferences. As a result, they are influencing relative prices through their effects on wage rates.

[15] 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).

[16] There is a separate issue that also relates to feedback effects between the non-market components of a general equilibrium model and the markets. 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

seek to reproduce the effects of actual policy interventions. Nevertheless, we have abstracted from a number of important considerations that will affect the total net benefits of the regulations in unrealistic ways because they are not the focus of the analysis. For example, our model abstracts from pollution abatement technologies that exist and are routinely employed by polluters to control the effects of acidic deposition. The transmission mechanisms that describe the relationship between emissions to environmental effects are also stylized. Our purpose is simply to highlight how preference linkages change the impact of the general equilibrium evaluation point for willingness to pay measures associated with a change in a single environmental service.

3.3 Calibration Logic

Two basic types of information are required for calibrating a conventional CGE model – expenditure levels for the benchmark equilibrium of the economy and information on the price responsiveness of the model, typically in the form of price or substitution elasticities. With these data and assumptions about the functional forms that describe representative-agent preferences and production technologies, the calibration procedure assigns the free parameters to replicate equilibrium output levels at the benchmark prices and external estimates of the price responsiveness of key activities in the model [Mansur and Whalley, 1984].

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 definition of the role of non-market services in preference functions, 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.

The algebraic form of the nested CES preference specification corresponding to Figure 1 for the representative agent is given in equation (7).

---

general equilibrium measures of the willingness to pay for a policy, considering all of its effects. Such a general equilibrium measure would be defined as: $WTP_{Total\,GE} = e\left(p^1, q^1, u^0\right) - e\left(p^0, q^0, u^0\right)$.

$$U=\left[\theta^{h}\left(\theta^{u}\left(\sum_{i=1}^{n}\theta_{i}^{C}\left(\frac{C_{i}}{C_{0i}}\right)^{\psi}\right)^{\xi/\psi}+\left(1-\theta^{u}\right)\left(\theta^{rl}\left(\frac{l}{l_{0}}\right)^{\kappa}+\left(1-\theta^{rl}\right)\right.\right.\right.$$

$$\left.\left.\left.\left(\theta_{f}^{r}\left(\frac{f}{f_{0}}\right)^{\vartheta}+\theta_{t}^{r}\left(\frac{t}{t_{0}}\right)^{\vartheta}+\theta_{csv}^{r}\left(\frac{C_{csv}}{C_{csv_{0}}}\right)^{\vartheta}\right)^{\kappa/\vartheta}\right)^{\xi/\kappa}\right)^{\rho/\xi}+\left(1-\theta^{h}\right)\left(\frac{h}{h_{0}}\right)^{\rho}\right]^{1/\rho} \quad (7)$$

Where the "θ" terms are defined as value shares of benchmark expenditures within each of the parenthesized bundles of commodities that they modify based on Rutherford's [2002] calibrated-shares formulation of the nested CES function. Benchmark levels of the different consumption goods in the function are indicated using the "0" subscript. The exponent parameters ($\rho, \xi, \kappa, \vartheta, \psi$) determine the elasticities of substitution between the arguments within and across the various nesting structures. C_i indicates the level of consumption of market good *i*, where *i* indexes the set of final consumption goods described in Table 5 except for consumer services (CSV). These services enter the preference structure differently from other market goods in order to establish specific substitution patterns between these activities, leisure and the non-market services in the model.

To accommodate the non-market goods that enter the preference function, the value shares are defined in terms of *full income*. Full income is defined as market income (from wages in our model) plus the benchmark value of the non-market services and leisure, where non-market services are valued at the benchmark values of marginal willingness to pay for these services implied by our calibration procedure (i.e. their virtual prices) and leisure is valued at the benchmark wage rate.

ρ, κ and ϑ are the parameters that determine the substitution relationships between leisure demand (*l*), non-market services related to fisheries (*f*), tree cover (*t*) and existence/habitat (*h*), and consumer services (C_{csv}). In the policy scenarios, we vary the values these parameters take on relative to the calibrated value of ξ 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 determine the relative strength and character of the feedback effects in the economy.

We choose ρ, κ and ϑ to take on values that give the associated Allen-Uzawa elasticity parameters ($\sigma_h, \sigma_{rl}, \sigma_r$) specific relationships to the value of σ_u, the substitution elasticity that controls the labor supply elasticity. ($\rho = 1 - 1/\sigma_h, \kappa = 1 - 1/\sigma_{rl}, \vartheta = 1 - 1/\sigma_r$, $\xi = 1 - 1/\sigma_u$.) 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 top line of equation (7). 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.[17]

ξ and the value share of leisure, θ^{rl}, in equation (7) are chosen to match the specific Hicksian and Marshallian labor supply elasticity estimates supplied as prior information (0.25 and 0.05 respectively). Including the non-separable environmental and health services in the model complicates this task because a change to the wage rate will, in general, result in changes in the levels of pollutants and their associated non-market services in the model. These effects feed back to affect the elasticity of labor supply. Thus one requires a realization of the pollution response generated by the wage experiment to calibrate the level of these elasticities.

θ^h, θ^r_f and θ^r_t in (7) 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. We use estimates of WTP for discrete changes in these services described in external studies (see Table 1) along with the definition of WTP (see equation (6)) to match the WTP predictions generated by the model in experiments where the supply of each non-market service is exogenously increased – one at a time – to reflect the change described in each of the external studies. This process implies levels of marginal willingness to pay for each of these services at the benchmark levels of these services described by the EPA pollution data and our assumed

[17] 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 σ terms imply smaller cross-price elasticities.

transmission functions. We use these implied values as the virtual prices for non-market services to define θ^h, θ_f^r and θ_t^r.

The calibration tasks discussed above are related to each other. That is, the calibration of the value share parameters depends on the value of full income, which depends on the value of non-market time and services to which the model is calibrated. The calibration of the substitution elasticities in the preference function depends on the realization of the labor supply elasticity calibration procedure. Finally, both the labor supply calibration and the calibration of the WTP for non-market services depend on the general equilibrium system. We use numerical techniques to simultaneously solve a system of nonlinear equations characterized by the calibration rules outlined above and the equilibrium conditions that define the general equilibrium model. Thus, our numerical calibration strategy requires the simultaneous solution of:[18]

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

As discussed, we judge the importance of the non-market effects by varying the assumptions regarding the substitution patterns between the market and non-market goods in the preference structure in a type of sensitivity analysis. To assure comparability, 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

[18] The GAMS computer code responsible for performing the model calibration and computing the counterfactual scenarios described in our results are available upon request.

same output tax rates that are used to affect the pollution changes in our policy scenarios. The slopes of the virtual price (or inverse demand) function for each non-market service will vary across these calibrations. Figure 3 illustrates the point for one non-market service. *A* and *B* can be interpreted as 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. Intuitively, when a given non-market service is more complementary with other goods (based on one of our substitution elasticity assumptions) its inverse demand curve will be more inelastic.

4. Counterfactual Policy Experiments

4.1 Policy Scenarios

Our analysis considers three percentage reductions (10%, 20% and 40%) in NO_x and SO_2 from the benchmark level of emissions. We affect these changes in the simulation model by endogenously calculating values of the minimum-cost set of output taxes required to generate the desired reductions in emission levels.[19] The 40% reduction scenario corresponds approximately to the size of the reduction attributed to the Clean Air Act Amendments.

Each of the scenarios is used with modeling variations to evaluate the effects of substitution and complementarity. As we noted, σ_h controls how easy it is to substitute existence/habitat services for other consumption. σ_r is the substitution elasticity for the use-based environmental services associated with recreation linked to consumer service goods and σ_{rl} is the substitution elasticity between this recreation nest of market and non-market goods with leisure time. Each of these elasticities is varied from a "Reference" level (based on the

[19] Recall that there is no abatement technology included in the model and we assume that pollution levels are proportional to output in each polluting sector. Thus output taxes scaled to the pollution intensity of output in each sector represents a minimum-cost abatement policy.

assumptions described in Section 3.3) to "Low" (1/2 times the reference) and "High" (2 times the reference). Low implies relative complementarity and high implies substitution for the affected market and non-market goods in preferences.

Finally, we consider three different scalings for the health effects in the model. In addition to the reference case which corresponds to the actual values of the concentration response functions described in Table 1 we scale the magnitude of the effects by three multipliers: (a) zero to correspond to the case of no health effects; (b) thirty-two which is selected so the effects of NO_x and SO_2 match the levels in EPA's Second Prospective Report for a 40% reduction of pollution, namely 0.21% of benchmark GDP and (c) a little over three times that large using a multiplier of 100.

This design implies 324 cases (4x3x3x3x3) and a need to summarize the findings compactly. We present two sets of selective results for price and quantity changes and for the benefit measures defined in equations (3) through (6) and rely on the internal meta-analysis strategy proposed by Banzhaf and Smith [2007]. That is, we use regression analysis to estimate response surfaces for the percentage differential in the benefit measure due to general equilibrium effects.

4.2 Results

Table 2 provides an illustrative description of our findings on the counterfactual price and quantity changes produced by the model. We selected the largest reduction (40%) in NO_x and SO_2 pollution and compare the effects of zero health impacts, the health effects implied by the Second Prospective Report, and the highest level of the health impacts. The different market and non-market activities represented in the model are described in the rows of the table. We selected the reference calibration for the assumptions concerning the degree of complementarity between the use-based services, environmental services, and leisure, together with market based consumer services. For each scenario we report the percentage change in the price (or virtual price) and the percentage change in quantity from the benchmark levels.

Naturally, the largest effects of the pollution taxes are on market prices and 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. Note that there is no change in the price for the health effects because the wage rate is the numeraire and the EPA strategy has the health effects reducing the representative agent's time endowment. At the level corresponding to the impact of *all* pollutants in the Second Prospective Report (0.21 percent of benchmark GDP), the largest reduction in air pollution has about 0.10 percent increase in effective health services measured in these labor time units.

Comparing the effects of zero and the highest health multipliers—the first and last set of columns in Table 2, we see the introduction of health effects in this way has no perceptible influence on the percentage changes in relative prices of marketed goods affected by the pollution reduction. There is no effect on the changes in virtual prices and quantities of the non-market services. By contrast, a change in the substitution elasticity for non-use services (σ_h), which is also separable from the use-related non-market services, does influence the changes in their virtual prices and quantities. For the results shown in the table, this elasticity is held at its reference level. If we increase it to the high level, the reduction in the virtual price of fishing services is 50.0% compared to 59.3%.

All the other changes in prices and quantities of market goods align with expectations and are insensitive to the inclusion or exclusion of health services regardless of the calibration of the substitution/complementarity relationships. These calibrations do alter the percentage change in leisure selected.

§

The main objective for our analysis is to evaluate how alternative specifications would influence our conclusions on the importance of general equilibrium effects for measures of the benefits of the policy when it is evaluated only by the recreational fishing impacts. These results are reported in Tables 3 and 4.

To consider in more specific terms the connections between how the different market and non-market goods interact, we now evaluate how the measures of total willingness to pay for the improvement in the fish services delivered by the policy reducing air pollution is affected by the other changes to the general equilibrium system. Before turning to the results, it is important to re-emphasize that, while the model accounts for a full set of general equilibrium effects in the policy simulations, our different welfare measures include only selected parts of these effects in their definitions as a method of decomposition.

The fishing service is the q_i in our definitions of WTP from Section 3.2 Table 3 reports these results. The different welfare measures are listed in the rows of the table. The rows include the equation number where each measure is defined. A column labeled "WTP No GE" describes the WTP calculation that would be made if the other changes to the general equilibrium system, aside from fish services, were ignored in setting the baseline point for evaluating the change in q_i. The column labeled "WTP with GE" describes the WTP calculation that incorporates some or all of the general equilibrium changes in setting the baselines for evaluation based on the definition of the welfare measure listed on the row of the table. The column labeled "% Diff" is the percentage difference between the no general equilibrium and general equilibrium column values. The WTP measures are in 100-millions of 1995 U.S. dollars. The three vertical sections of the table, labeled "High", "Reference" 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 panels in the table illustrate the effects of the reference maximum levels for the health effect for these alternative general equilibrium measures. As with the price effects described in Table 2, the differentials in the welfare measures are not impacted by the treatment of these health effects. These two sets of results, along with the sensitivity analysis summarized in Table 4 confirm our conclusion. The EPA strategy assures the general equilibrium effects of air pollution will be minimal.

The improvement in the use-based fish services using the reference level of the health effects implied by the policy change are valued at between 703 and 1089 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 improved 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 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 no general equilibrium and general equilibrium columns for the WTP^q measure. In the High complementarity scenario, with the reference level of health effects, where the influence is most strongly felt, it only results in a 3.4% 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 in evaluating the change in fish services (indicated in the WTP^p row of the table) has substantially larger effects however. In the Reference case, failing to take these influences into account would underestimate the value of the improvement in fish services by approximately 23.5%. In the High complementarity case, this error more than doubles (48.5%) and in the Low complementarity case it is approximately one half (11.8%).

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 in Table 3 vary a limited number of the structural features describing how the relationship between non-market services, marketed goods, and leisure influence measures of the benefits due to a reduction in NO_x and SO_2 emissions. The available empirical research on the nature of these substitution and complementarity relationships is limited. As a result, it is reasonable to ask whether our conclusions in these cases are specific to the assumptions being used to characterize these preference relationships. To address this question we re-calibrated the model 324 times for different assumptions about preferences, the role of health effects, and the size of the pollution reduction. In each case we derive least-cost taxes to achieve the specified pollution reduction *given* the features of the preferences and health effects. Thus, the specific natures of the taxes are different in each case. The policies are comparable when they are defined in terms of a proportionate reduction in air pollution.

Table 4 uses the internal meta-analysis logic to summarize these findings. The dependent variable for each of the regression models is the percentage differential between no general equilibrium and general equilibrium baseline conditions for each of the four benefit measures defined in equations (3) through (6). The estimates confirm some of our overall conclusions—(a) health effects do not matter to these differentials regardless of the preference specification; and (b) the size of pollution reduction influences the differentials for all of the measures.

When we consider the substitution and complementarity relationships in the preference specification, the findings are more nuanced. For example, the substitution elasticity for non-use services with the nest for use related non-market services, leisure and consumer services (σ_h) is only influential when it implies greater substitution and then it reduces the effect of using the general equilibrium prices for baseline. High values of σ_r, implying greater substitution among use-related services, reduce discrepancies due to counting general equilibrium effects in all cases aside from the one that considers only fishing services. In this case, substitution increases the discrepancy. Complementarity in these goods consistently increases the discrepancy for all measures of benefits. Finally, the record is mixed considering leisure and the use-related nest. Here only WTP^Q is affected by partial versus general equilibrium baselines and the role of substitution and complementarity is opposite. In the complementarity case, the discrepancy is larger while it is smaller with substitution between leisure and this nest. Our bottom line conclusion is simple and direct—general equilibrium effects matter. They can be large even with relatively small pollution effects and they depend on the nature of the non-separability in preferences.

5. Implications

Modern treatments of applied welfare economics focus attention on the market interactions that distinguish partial equilibrium and general equilibrium measures of consumer surplus (and deadweight loss). A recent EPA study took an important first step in developing a general equilibrium model to assess the net benefits of large scale rules that alter air pollutants. Their analysis could be interpreted to imply the general equilibrium interactions generated by these changes to the modeling framework are small. . We have demonstrated that this conclusion results from the approach they used to introduce non-market services into the model. Their strategy boils down to treating pollution reductions as very modest income effects, in a set of preference specifications that maintains unitary income elasticities of demand for all goods and services. The effects are approximately equal then across all goods and largely neutral to all the other influences of air pollution.

The current approaches to policy analysis whether in public economics for the design of policy instruments or in environmental economics for benefit-cost analysis fail to recognize the important feedbacks from the non-market consequences of policy interventions. In the case of environmental policies, the action is intended to improve some aspect of environmental services. In other situations, the objective is some other aspect of public services – such as improving transportation or energy infrastructure – where there may be important indirect effects on environmental services. In either case, feedbacks such as the ones described in this paper can influence the prices and quantities of market related goods and services in a general equilibrium.

When the field of environmental economics was still in its infancy, Ayres and Kneese [1969] conjectured that "…the partial equilibrium approach is probably not convergent to the general equilibrium solution…" (p. 296) when externalities are pervasive in the economy. We have demonstrated in a simple case with multiple environmental services that they were correct. Even in a situation where the economic value of non-market services is small as a fraction of the aggregate value of the economic system, the errors from ignoring them can be large.

While we have outlined a strategy for including environmental benefits in general equilibrium models that covers many policy-relevant applications, much work remains for future research. We highlighted a number of practical considerations – such as detailed descriptions of abatement costs, pollution transmission functions, and regional data aggregation that match the environmental policy area – which we have abstracted away from in our example model and which a researcher conducting a detailed policy analysis of a regulation would need to consider. Equally important, the national accounts already reflect the effects of spatially delineated environmental services. The housing expenditures in consumption imperfectly reflect spatial differences in amenities on the rents and imputed rents (for owner occupied housing)included in this measure for housing. While there are a number of flaws in these measures, they do allow for regional differences in housing markets (see Prescott [1997]). Similarly, we should expect some portion of the consumption expenditures for averting activities, vacations, health, and other goods and services around the country result from differences in environmental services at these locations. A detailed model would reflect how these measures would change as pollution affects the services linked to them. This is a tall order but it is inherent in a serious reform to any effort to model the joint interaction of the economy and the environment. Another important conceptual challenge arises from the need to adapt the logic of a CGE model to include a major source of benefits in existing partial equilibrium analyses of many regulations – the benefits from life extension captured by calculations of the value of a statistical life. Incorporating these values is conceptually different from the ecosystem and health effects treated in our analysis. It requires integrating a description of the risk tradeoffs individuals are willing to make into the general equilibrium model of market and non-market choices. These are formidable problems. Our analysis has suggested even in the simplest case –with a very narrow measure for the effects of feedbacks they can be important. Most of these additions seem likely to add to the importance of non-market feedbacks. In our opinion this is how models valuing nature in a general equilibrium are essential to serious definitions of the contributions of economics to the wider debate about sustainability science.

References

Ayres, Robert U. and Allen V. Kneese, "Production, Consumption and Externalities," *American Economic Review,* June 1969, 59.

Banzhaf, H. Spencer, Dallas Burtraw, David Evans, and Alan Krupnick, "Valuation of Natural Resource Improvements in the Adirondacks," *Land Economics*, 2006, 82, 445-464.

Banzhaf, H. Spencer and V. Kerry Smith, "Meta-analysis in Model Implementation: Choice Sets and the Valuation of Air Quality Improvements." *Journal of Applied Econometrics*, 2007, 22(6): 1013-31.

Carbone, Jared C. and V. Kerry Smith, "Evaluating Policy Interventions with General Equilibrium Externalities," *Journal of Public Economics*, 2008, 92, 1254-1274.

Driscoll, C. T., G. B. Lawrence, A. J. Bulger, T. J. Butler, C. S. Cronan, C. Eagar, K. F. Lambert, G. E. Likens, J. L. Stoddard, and K. C. Weathers, "Acidic Deposition in the Northeastern United States: Sources and Inputs, Ecosystem Effects and Management Strategies," *Bioscience*, March 2001, 51, 180-198.

Englin, J.E., T.A. Cameron, R.E. Mendelsohn, G.A. Parsons, and S.A. Shankle, "Valuation of Damages to Recreational Trout Fishing in the Upper Northeast Due to Acidic Deposition," Technical Report, National Acidic Precipitation Assessment Program, Pacific Northwest Laboratory March 1991.

Finnoff, David and John Tschirhart, "Harvesting in an eight-species ecosystem," *Journal of Environmental Economics and Management*, 2003, 45, 589-611.

Goulder, Lawrence H. and Roberton C. Williams III , "The Substantial Bias from Ignoring General Equilibrium Effects in Estimating Excess Burden, and a Practical Solution," *Journal of Political Economy*, 2003, 111 (4), 898-927.

Hanemann, Michael, “Three Approaches to Defining "Existence" or "Non-Use" Value under Certainty,” Unpublished paper, Department of Agricultural and Resource Economics, University of California, Berkeley 1988.

Hazilla, Michael and Raymond J. Kopp, “ Social Costs of Environmenatl Quality regulations: A General Equilibrium Analysis,” *Journal of Political Economy*, 1990,98, (4), 853-873.

Just, Richard E., Darrell L. Hueth, and Andrew Schmitz, *The Welfare Economics of Public Policy: A Practical Approach to Project And Policy Evaluation*, Edward Elgar, 2004.

Kopp, R. J. and V. Kerry Smith, “Constructing Measures of Economic Value,” in R. J. Kopp, W. Pommerhne, and N. Schwarz, eds., *Determining the Value of Non-Marketed Goods, Economic, Psychological and Policy Relevant Aspects of Contingent Valuation*, Boston: Kluwer Nijhoff, 1997.

Mansur, Ahsan and John Whalley, “Numerical Specification of Applied General Equilibrium Models: Estimations, Calibrations, and Data,” in Herbert E. Scarf and John B. Shoven, eds., *Applied General Equilibrium Analysis*, Cambridge: Cambridge University Press, 1984.

Matus, Kira, Trent Yang, Sergey Paltsev, John Reilly and Kyung-Min Nam, 2008, “Toward Integrated Assessment of Environmental Change: Air Pollution Health Effects in the USA,” *Climatic Change*, Vol. 88(1): 59-92.

Nam, Kyung-Min, Noelle E. Selin, John M. Reilly and Sergey Paltsev, 2010, “Measuring Welfare Loss Caused by Air Pollution in Europe: A CGE Analysis,” *Energy Policy*, Vol. 38(9): 5057-5071.

National Public Radio, “Outdoor Recreation An ‘Overlooked Economic Giant’”, State Impact, June 11, 2012. (http://stateimpact.npr.org/idaho/2012/06/11/outdoor-recreation-an-overlooked-economic-giant/).

Nordhaus, William D., *Managing the Global Commons: The Economics of Climate Change.* Cambridge, Massachusetts: The MIT Press, 1994.

Paltsev, Sergey, John M. Reilly, Henry D. Jacoby, Richard S. Eckaus, James McFarland, Marcus Sarolim, Malcolm Asadoorian, and Mustafa Babiker, 2005, The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4 MIT Joint program on Science and Policy of Global Change, Report No. 125, August.

Phaneuf, Daniel J., Jared C. Carbone, and Joseph A. Herriges, "Non-Price Equilibria for Non-Marketed Goods," *Journal of Environmental Economics and Management*, 2009, 57, 45-64.

Prescott, Edward C., "On Defining Real Consumption," Review Federal Reserve Bank of St. Louis, 1997, Vol. 79 (May/June): 47-53.

Rowe, R.D., C.M. Lang, L.G. Chestnut, D.A. Latimer, D.A. Rae, S.M. Bernow, and D.E. White, "The New York Electricity Externality Study Volume I: Introduction and Methods," Technical Report, Empire State Electric Energy Research Corporation, New York 1995.

Rutherford, Thomas F., "Lecture Notes on Constant Elasticity Forms," unpublished paper, University of Colorado, Boulder November 2002.

Sandmo, A., "Optimal Taxation in the Presence of Externalities," *The Swedish Journal of Economics*, 1975, 77(1): 86-98.

Smith, V. Kerry, "Reflections: – In Search of Crosswalks between Macroeconomics and Environmental Economics," *Review of Environmental Economics and Policy*, 2012, in press.

Timmins, Christopher and Jennifer Murdock, *A Revealed Preference Approach to the Measurement of Congestion in Travel Cost Models*, Journal of Environmental Economics and Management, 2007, . 53 (2), 230—249.

United States Environmental Protection Agency, National Air Quality and Emissions Trends Report, 1995 1996. EPA 454/R-96-05.

United States Environmental Protection Agency, The Benefits and Costs of the Clean Air Act of 1990 to 2010, EPA Report to Congress November 1999.

U.S. Environmental Protection Agency, The Benefits and Costs of the Clean Air Act from 1990 to 2020," Final Report, Office of Air and Radiation, March 2011.

Figure 1: Nesting in Household Consumption

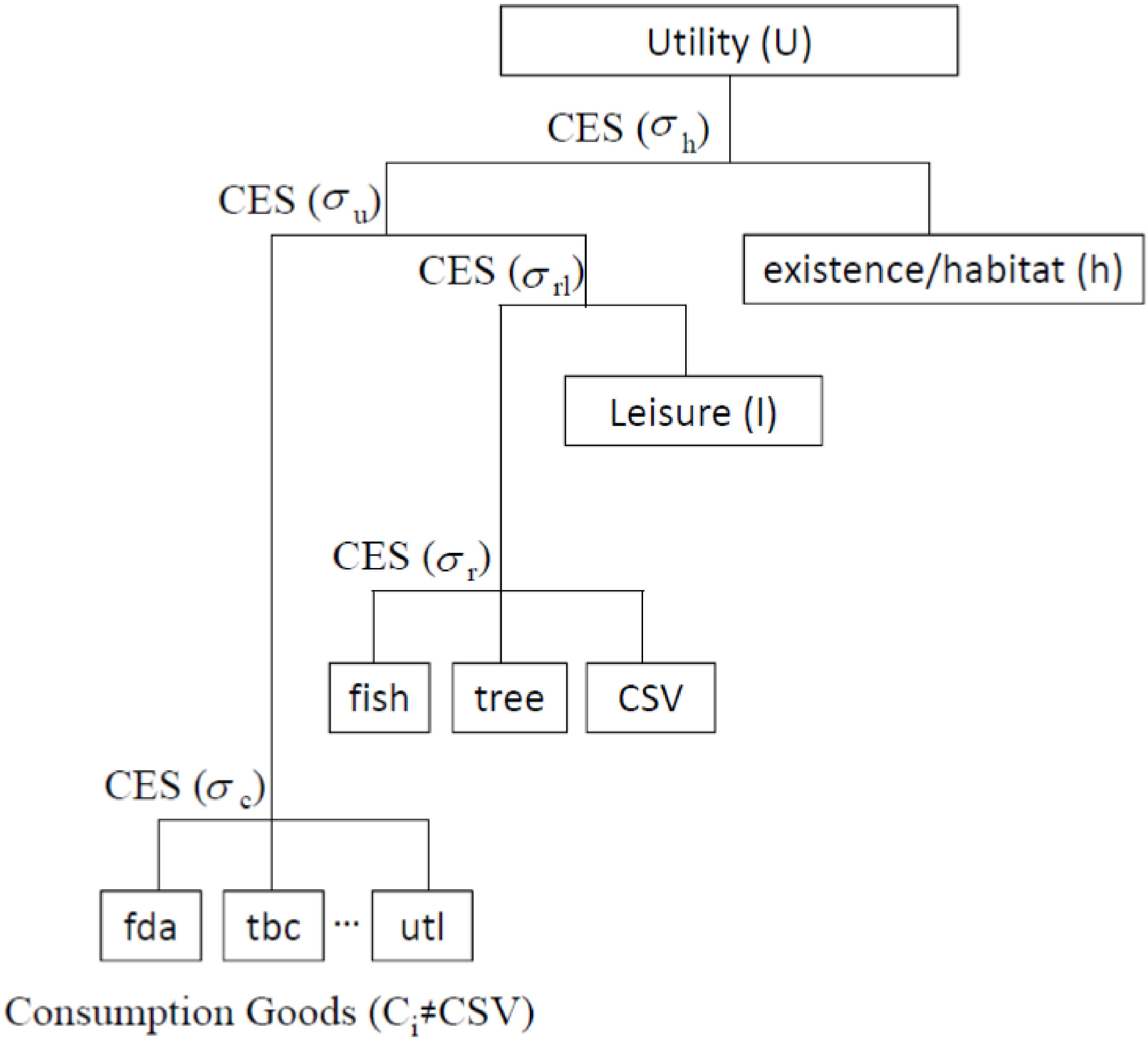

Figure 2: Relative Number of Species Supported by a Lake and Ph Levels

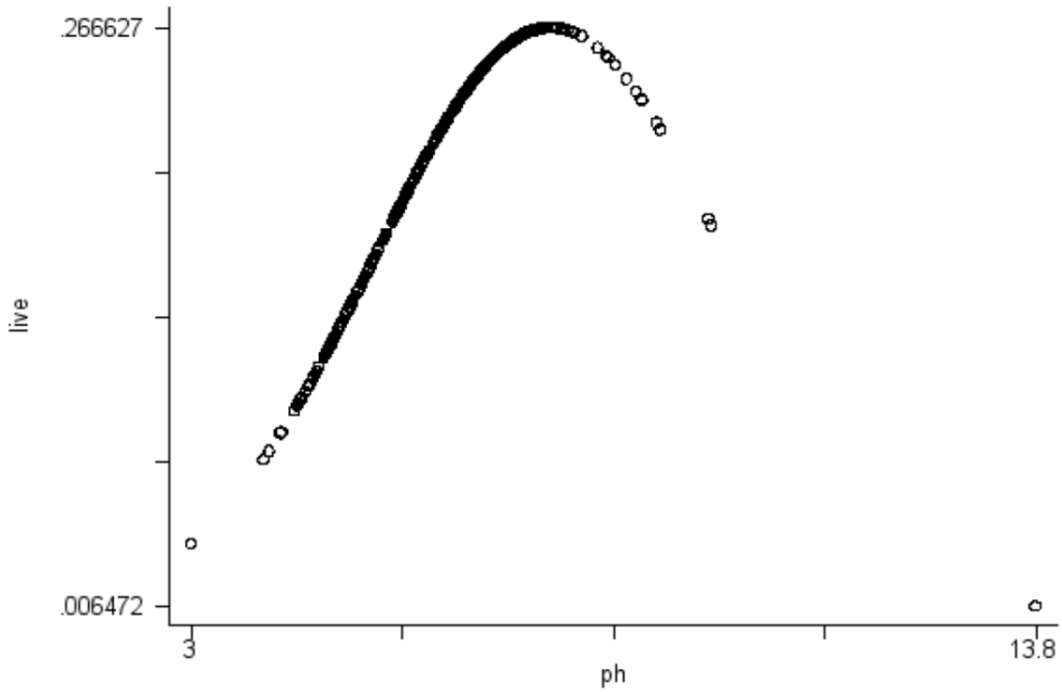

Figure 3: Effects of Substitution on Calibrated Virtual Price Functions

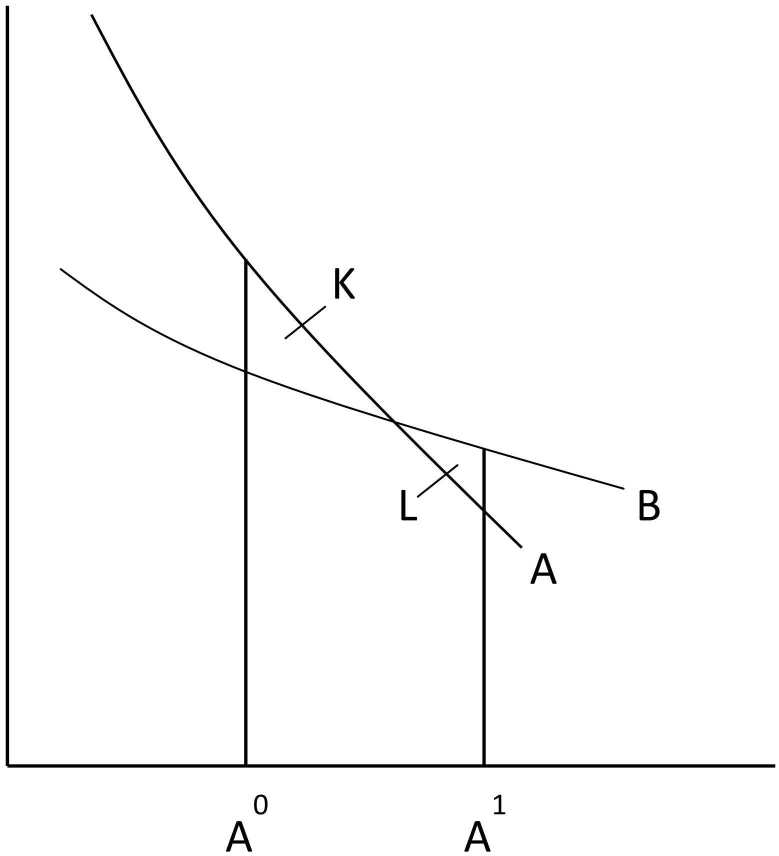

Table 1: Non-Market Components of the Acidic Deposition Model

Model Component	Transformation/Adjustment	Source
Emission Rates		
SO_2 and NO_x	Reported in thousands of short tons per year for full consumption; industrial processes, transportation and (where relevant) aggregated to conform to Goulder and Williams (2003)	United States Environmental Protection Agency (1996)
Deposition Rates		
SO_2 and NO_x	Reported in kg/ha in Prospective Analysis; used 1990 base scenario to estimate the conversion from tons of emissions to kg/hectare/ton; for SO_2 deposition rate is 22kg/ha; for composite of SO_2 and NO_x it is assumed to be 23 kg/ha	United States Environmental Protection Agency (1999)
Willingness to Pay Measures		
Willingness to Pay per Household per Year	$1.33 for a 50% reduction per kg/ha in SO2 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	New York State Environmental Cost Study (Rowe et al. 1995) p. 478

	vistas from acidification for Adirondacks (1995 dollars)	
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 $(L^{\rho} - I^{\rho})^{1/\rho}$ = 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)
Health Effects		
	The logic is based on a proportionate adjustment to the benchmark labor time endowment for the Goulder-Williams model. Thus if $\overline{L}$ = the benchmark endowment the endowment for scenario *j* is $L_j = \left(1 - (30/235) \cdot CR_j \cdot 365\right) \cdot \overline{L}$ $CR_j = \sum y_0 \cdot \left(\exp(\beta_i \cdot \Delta AP_{ij}) - 1\right)$ Where β_i = pollutant coefficient relevant for NO_x and SO_2 (.00378 and .00446 respectively) ΔAP_{ij} = change in ambient concentration of pollutant *i* for scenario *j* y_0=daily hospital admission rate per	United States Environmental Protection Agency (1999) Tables D-16 for NO_x and D-19 for SO_2

person in benchmark

30=assumed days lost per hospital admission

235=assumed work days per year

365=days in year

Table 2: Changes in Equilibrium Prices and Quantities for 40% reduction in NO_x and SO_2 With/Without Health Effects

	No Health Effect		Health to Match Prospective		Max Health Effect	
	%ΔP	%ΔQ	%ΔP	%ΔQ	%ΔP	%ΔQ
Energy	24.3	-21.6	24.3	-21.5	24.3	-21.3
Services	0.9	-1.4	0.9	-1.2	0.9	-0.9
Agriculture	2.8	-2.6	2.8	-2.4	2.8	-2.1
Manufacturing	2.6	-3.6	2.6	-3.5	2.6	-3.2
Food and Alcohol	1.6	-3.7	1.6	-3.6	1.6	-3.2
Consumer Manufactures	2.0	-4.0	2.0	-3.9	2.0	-3.6
Transportation	85.1	-42.2	85.1	-42.1	85.1	-41.9
Utilities	123.8	-50.8	123.8	-50.7	123.8	-50.6
Consumer Services	1.0	11.8	1.0	11.9	1.0	12.3
Leisure		12.4		12.6		12.9
Fish Services	-50.2	66.0	-50.0	65.8	-49.5	65.5
Forestry View Services	-50.6	66.7	-50.3	66.4	-49.7	65.9
Non-Use/Habitat Services	-16.4	66.7	-16.3	66.4	-16.0	65.9
Health Effects	-	-		0.1		0.5

NOTES: The different market and non-market activities represented in the model are described on the rows of the table. 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. These results are all for the reference case specification for substitution that $\sigma_{rl} = \sigma_r = \sigma_u / 4$; with $\sigma_h =$ and σ_u calibrated to match the Marshallian and Hicksian labor supply elasticities.

Table 3: Decomposition of Willingness to Pay Measures for Improvements in Fish Services by General Equilibrium Adjustment Type with Reference and Maximum Health Effects

	Reference Health Effects			Max Health Effects		
	WTP No GE	WTP with GE	% Diff	WTP No GE	WTP with GE	% Diff
		High			High	
WTP^{GE} (eq (6))	927.5	1034.1	11.5	923.9	1030.1	11.5
WTP^{P} (eq (5))	927.6	1037.1	11.8	924.0	1033.1	11.8
WTP^{Q} (eq (4))	927.6	925.1	-0.3	924.0	921.5	-0.3
WTP^{qi} (eq (3))	927.6	927.6	0.0	924.0	924.0	0.0
		Reference			Reference	
WTP^{GE} (eq (6))	857.8	1066.3	24.3	855.1	1062.8	24.3
WTP^{P} (eq (5))	857.8	1059.6	23.5	855.1	1056.2	23.5
WTP^{Q} (eq (4))	857.8	863.2	0.6	855.1	860.4	0.6
WTP^{qi} (eq (3))	857.8	857.8	0.0	855.1	855.1	0.0
		Low			Low	
WTP^{GE} (eq (6))	702.7	1089.2	55.0	701.3	1086.9	55.0
WTP^{P} (eq (5))	702.7	1043.5	48.5	701.3	1041.4	48.5
WTP^{Q} (eq (4))	702.6	726.3	3.4	701.2	724.8	3.4
WTP^{qi} (eq (3))	702.7	702.6	0.0	701.3	701.2	0.0

Table 4: Factors Affecting Properties of General Equilibrium Effects on Benefit Measures

Features of Sensitivity Analysis	WTP^{GE} (eq (6))	WTP^{P} (eq (5))	WTP^{Q} (eq (4))	WTP^{qi} (eq (3))
Multiplier for the Health Effect	-.0001	-.0000	-.0001	-.0000
	(-0.01)	(-0.01)	(-0.05)	(-0.39)
Percentage Reduction in NO_x and SO_2	.807	.697	.039	.0001
	(28.17)	(33.85)	(8.66)	(4.71)
Fixed Effects				
σ_r = low	17.466	11.249	3.425	.005
	(19.96)	(17.89)	(24.99)	(7.80)
σ_r = high	-7.059	-6.008	-.822	.003
	(-8.07)	(-9.55)	(-6.00)	(5.73)
σ_h = low	-.451	-.710	-.001	-.001
	(-0.52)	(-1.13)	(-0.01)	(-1.64)
σ_h = high	-1.350	-1.640	.012	.001
	(-1.54)	(-2.61)	(0.09)	(1.35)
σ_{rl} = low	-.546	.258	-.514	-.000
	(-0.62)	(0.41)	(-3.75)	(-0.68)
σ_{rl} = high	1.190	-4.97	1.114	-.000
	(1.36)	(-0.79)	(8.12)	(-0.63)
Intercept	-4.925	-2.632	-.543	-.007
	(-4.13)	(-3.07)	(-2.90)	(-8.91)
R^2	0.838	0.860	0.805	0.236

NOTES: Each column reports the regression estimates for the percentage difference between the willingness to pay estimates for the change in fish services due to the air pollution change measured without taking general equilibrium adjustments and with these adjustments as defined by the equations below the label for each column. The numbers in parenthesis below each coefficient correspond to the t-ratios for tests of the null hypothesis of no association. The percentage differentials are not random variables. These models are developed as part of a strategy for summarizing a large number of scenarios. The t-tests are reported as gauges of the factors that were influential. The multiplier for the health effect is the numerical scaling of the results of the concentration response functions (values=0 (no health effects, 1 (reference level), 32 (matches Prospective Report estimates for 40% reduction) and 100). The percentage reduction corresponds to the reduction from baseline 10, 20 and 40 percent. The remaining terms are fixed effects for the alternative levels of the three substitution elasticities. The reference case is the omitted category in each case.

Appendix 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

	Primary Factors
lab	Labor
	Intermediate Sectors
ene	Energy
svc	Services
agr	Agriculture
mnf	Manufactures
	Final Consumption Sectors
fda	Food and Alcohol
csv	Consumer Services
cmn	Consumer Manufactures
trn	Transportation
util	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- Reported from Table B3 in Goulder and Williams [2003].
note- All figures in millions of US 1995 $.

Table 8: Model Notation and Parameter Values

	Sets	
C	Final Consumption Goods	{fda,csv,cmn,trn,utl}
I	Intermediate Goods	{ene,svc,agr,mnf}
	Parameters	
T	Aggregate time endowment	$\sim \eta_{lab} = 0.05, \eta^h_{lab} = 0.25$
σ_j	Substitution between inputs in intermediate and final sectors	$\sim \in_{ene} = 0.9$
σ_u	Substitution between leisure-nonmarket bundle and market goods	$\sim \eta_{lab} = 0.05, \eta^h_{lab} = 0.25$
σ_C	Substitution between consumer goods in consumption nest	0.85
σ_h	Substitution between existence/habitat service and all other consumption	$= \frac{1}{2}\sigma_u, \sigma_u, 2\sigma_u$
σ_{rl}	Substitution between leisure and use-based nonmarket service bundle	$= \frac{1}{8}\sigma_u, \frac{1}{4}\sigma_u, \frac{1}{2}\sigma_u$
σ_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".

η_{lab} and η^h_{lab} denote the uncompensated and compensated labor supply elasticities, respectively.

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

Appendix B: Production Structures

Figure 4: Intermediate Goods

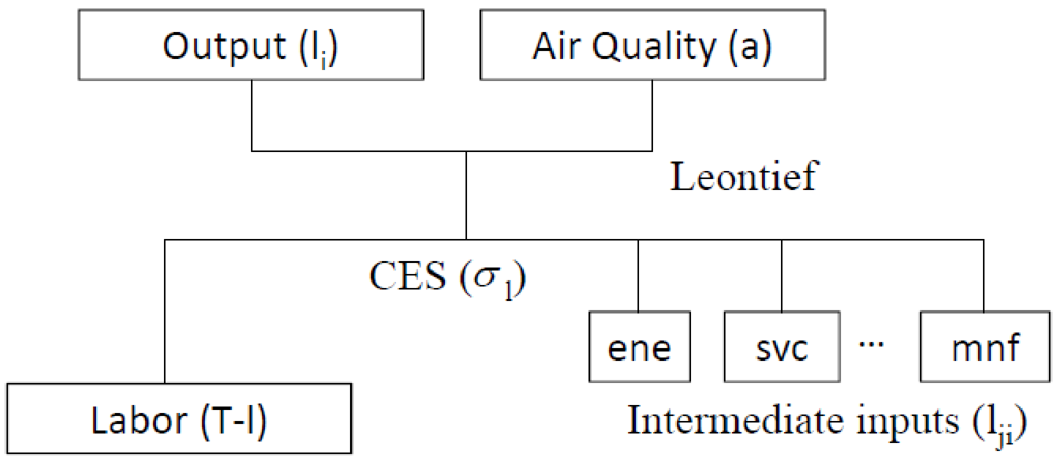

Figure 5: Final Goods