Economy-Wide Modeling, Environmental Macroeconomics, and Benefit-Cost Analysis

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ABSTRACT *This paper develops a new method for evaluating benefit estimates prepared for major environmental rules and addresses three criticisms of existing practices: (1) using benefit estimates from the literature without adjusting for the conceptual differences underlying their meaning, (2) ignoring feedback effects of policy, and (3) failing to recognize the potential for economy-wide effects of large policies. Our approach adapts a general equilibrium framework characteristic of macroeconomic models and focuses on the effects of introducing nonmarket environmental services into the aggregate or "stand-in" preference function. Two recent policies illustrate how it can be used to assess economy-wide effects.* (JEL D61, H41)

1. Introduction

Benefit-cost analyses (BCAs) are based on a practical logic that facilitates judgments about whether a proposed policy is likely to yield sufficient benefits to offset its costs. These analyses generally assume the changes under study are small in relationship to the overall economy. Moreover, the time and resource constraints conditioning how they can be prepared usually require relying on existing research. This observation is especially relevant for BCAs used as part of assessing the merits of environmental regulations. These analyses generally rely on estimates derived from benefit transfers for resources similar to those affected by a rule.

Cost estimates are often provided as part of the design of a regulation. The legislative mandates underlying many environmental rules often specify that the regulated community use a prescribed technological approach or demonstrate any proposed alternative approach is equivalent. As a result, responding to these types of mandates requires a cost analysis to judge the best technologies that are economically achievable.

The purpose of our paper is to demonstrate how a simple general equilibrium model can serve a *screening role* in judging when the economy-wide effects of regulations are important enough to require a change in the partial equilibrium assumptions of conventional benefit-cost methods. Sunstein's (2018) new book, *The Cost-Benefit Revolution,* uses an analogy to describe why policies often have unintended consequences that have implications for BCA. He suggests the world, or in our case the economic system, is like a spider's web—pull on one part and there may be unexpected responses someplace else in the system.[1] This characterization offers an apt description of the motivation for our research objective: we need a simple gauge for judging when the general equilibrium effects of a regulation should be recognized for BCA. In Sunstein's terms we want to "fill in the web" with models that are simple enough to understand and manipulate. To meet this goal, we use the formal structure underlying neoclassical welfare economics, along with the strategy of Prescott (2003) style macro models.[2]

[1] See Sunstein (2018, 213).

[2] That is, a simple theoretical model is used to identify and organize the important influences to the phenomenon being explained. The roles for factors related to preferences (substitution and income effects), technology (production and productivity assumptions), and institutions (tax, transfer, and, in our case, regulatory) are specified, but the details

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We add to this framework the contribution of environmental services as nonseparable elements in the representative agent's preferences. Environmental services are affected by pollution emissions, and these emissions arise from the production of market goods. So our "web" provides explicit feedbacks between environmental services and the consumption of these market goods and services. It also is sufficiently general to allow choices among different private goods and services that would alter emissions and the impacts on environmental services.

Our approach is illustrated using a typical macro-style, general equilibrium model. With this model we require four types of information to calibrate its parameters: (1) an estimate of the ratio of the monetary value for a change in those nonmarket environmental services affected by a proposed rule relative to the expenditures on marketed goods and services[3]; (2) measures of the emissions, as well as the change in environmental services corresponding to the value share that is associated with the change; (3) the specification of a preference function describing how market and nonmarket goods and services contribute to the well-being of a representative household; and (4) measures for the equilibrium shares of time allocated to the production of marketed goods and services and to household production.[4]

Our paper is organized into six sections after this introduction. Section 2 uses a second-order approximation for the willingness-to-pay (WTP) function to describe the important features associated with the selection of a functional form to describe preference for a representative household. We compute the coefficients for the second-order terms in this approximation for each solution of our models. They are used to evaluate the importance of our selection of a preference specification and of a policy to illustrate our approach. These tasks are accomplished by considering whether changes in environmental services, or a market price for a good directly linked to these services, is the most important influence to the WTP. Decisions about the preference function and about the importance we assign to environmental services in the overall economy influence our assessment of the importance of general equilibrium effects for the benefit measurement strategies typically used in BCA. Section 3 discusses the past literature and its treatment of the distinction between partial and general equilibrium measures to provide some context for our proposed methodology. The fourth section outlines the details of our extension to Rogerson's (2008) general equilibrium model, including the three different specifications we considered for the representative household's preference function. We also discuss how each specification performed in calibrating the model parameters. Our index for the importance of general equilibrium effects is the ratio of the shadow value for environmental services evaluated for the economy *before* a proposed policy compared to the shadow value *with* the policy. Partial equilibrium BCA assumes each policy under study is not large enough to have economy-wide effects, so our index would be one in that case. We expect that policies with large economy-wide effects will generally cause the ratio to be greater than one. Section 5 discusses the results from calibrating the model to fit the data and measures of the coefficients of the second-order approximation for WTP to judge how the relative importance of price and environmental quality changes. After that background, in the last section we describe two policy examples to illustrate how our index for the importance of general equilibrium effects would work, and summarize the results for each. This discussion closes with some consideration of the research implications that arise from our proposed strategy.

are deliberately simpler than one might find in conventional computable general equilibrium models.

[3] Both components are defined for a case where these monetary values can be developed and measured at an aggregate level.

[4] The share of leisure is then derived implicitly as the residual, given a fixed total time constraint.

2. Intuition for Our Proposal and the Effects of Preference Specifications on WTP

Background

When we step back from the details of general equilibrium models designed for either micro or macro policy applications, some general features help to distinguish their structures. As a rule, the micro-oriented versions tend to build up components of each production sector individually and allow for several types of households (distinguished by income levels or demographic characteristics). They usually assume that constant elasticity of substitution (CES) functions adequately describe both production and preferences. This format allows for rich sectoral detail that matches available social accounting matrices. The goal is usually to provide a model that can be used for a number of applications and adequately represent most aspects of the economy being studied.[5]

By contrast, those designed in the macro tradition tend to be focused around reconciling outcomes that seem to match Sunstein's unintended consequences story. Often the analysis begins with a puzzle or a small number of empirically observed outcomes that the model is intended to address. As a result, these general equilibrium models are less detailed and adopt specifications for preferences and production that allow analysts to "control" some of the specific features of the model influencing general equilibrium outcomes. The focus is then on the relative importance of the remaining factors and how each contributes to the equilibrium outcomes under *different* exogenous changes to the economy, such as different tax rates or patterns of technological change. Production is often described using linear technologies so that relative prices of marketed goods are determined by the specified fixed coefficients. These input requirements are usually assumed to change at exogenously determined rates to reflect productivity advance (for examples, see Rogerson [2008] and Durate and Restuccia [2010]). The goal is to evaluate the importance of distortions (introduced through the budget constraint) or the features of preferences (such as the inclusion of nonmarket household-produced services) as influences to the general equilibrium outcomes and potential sources for explaining the observed outcomes within one or more existing economies.

We adopt the macro orientation here and extend Rogerson's model. To appreciate the implications of this approach, we need to distinguish the ways that general equilibrium effects can influence a BCA. The first is through relative prices. When a new regulation increases costs, the affected sectors' prices rise, and the effects of these cost increases then spread to other industries that may not have been considered as directly impacted by the rule.[6] The resulting general equilibrium effects on relative prices can then depend on both the costs and the adjustments through substitutions made in other sectors. In our model, relative prices are determined by the technology, so the cost increases associated with the regulation will be the only added source (beyond assumed exogenous productivity increase) for a change in them and they are confined to the sectors assumed to be directly impacted. This specification is one example of the ways the model formulation "controls" how the general equilibrium effects unfold. Consumer adjustment cannot affect relative prices.

The second way general equilibrium effects can influence the results of a BCA in our model is through the roles assigned to nonmarket services. In our examples, they provide the reasons for the new regulations. Conventional practice in developing benefit measures for policy analyses maintains that the proposed changes in these services will be realized based on the pace of implementation of the new rules. As a result, if the rule is intended to improve air quality by some amount (i.e., reducing the ambient concentration of specific pollutants), the benefit measures estimate the amount consumers would be willing to pay for that improvement as if it were guaranteed.[7] The changes in air quality are often engineering estimates that are combined with atmospheric modeling to project how ambient conditions will be different. In the partial equilibrium estimates they do not take account of how cost-induced changes in relative prices would change the mix of goods and services or how changes in

[5] Rutherford's (1999) package, MPS-GE, within GAMS is one set of software often used in these types of applications.

[6] Recognition of these effects for gauging the costs of regulations was the important contribution of Hazilla and Kopp's (1990) analysis.

[7] See Schlee and Smith (2019) for the derivation of a measure of the importance of uncertainty in the outcomes of rules.

environmental quality might also affect those consumption patterns. In general equilibrium, both sets of adjustments can influence emissions and the realized change in environmental quality. In our model, as we noted, the relative price change is controlled to match the assumed productivity advance and the added cost estimates for each new rule. Nonetheless, adjustments in the composition of goods and services to those changes and to changes in air quality will alter emissions and the "final" general equilibrium–realized change in air quality.

One way to understand the relative importance of these multiple effects for BCAs is to use the properties of a representative agent's WTP function, as it is influenced by changes in the relative prices of market goods and by changes in measures of environmental quality. To appreciate the implications of selecting a functional form for preferences, we evaluate the numerical importance of these prices and quality effects for different preference specifications. We use a second-order approximation of the WTP function to isolate indexes of the importance of changes in quasi-fixed environmental services versus relative prices. These indexes allow us to describe how a preference specification affects our assessment of the relative importance of general equilibrium considerations for BCAs.

Decomposing WTP

We develop our decomposition of the WTP function in stages. First, we consider a second-order expansion of this function in terms of the variable that is used to represent the effects of environmental services, while prices and income are held constant. Then, in the next stage of our development we add a further expansion, allowing the price of the good responsible for pollution emissions, as well as environmental services, to change.

Let $V(q,p,m)$ be a general representation for the indirect utility function that we use to describe the preferences for what Prescott has labeled the "stand-in" household in macro models.[8] This function is the dual representation of choices implicitly made by a budget-constrained, utility maximizing agent, with p designating the prices of private goods and m the exogenous income. For this derivation, we assume one private good along with the numeraire used to define income.[9] The amount of environmental services is designated by q and is fixed from the agent's perspective. The indirect utility function is assumed concave in q.

In stage 1, the WTP (W) associated with a change in q from q_0 to $q(t)$ is defined in equation [1].

$$V(q(t), p, m - W(t)) = V(q_0, p, m). \qquad [1]$$

WTP is specified as a function of t, an index for the magnitude of the policy change. More specifically, the outcome of policy can be described in terms of the baseline level of environmental quality (q_0) and the size of the change in policy (t) as follows: $q(t) = q_0 + \alpha t$, with $\alpha = q_1 - q_0$. Substituting for $q(t)$ using this relationship in equation [1], we can differentiate [1] with respect to t as in equation [2] and use the result to develop a direct interpretation for the strategies of many benefit transfer applications when $t = 1$ as in [2a]. We see the first-order approximation would estimate the WTP for a policy improving environmental quality using the shadow value for q and the change in quality associated with that policy. We use b to designate the shadow value. The partial derivatives of the WTP function are evaluated at the baseline situation or with $t = 1$ in [2a]; based on the definition in equation [1], $W(0) = 0$.

$$V_q \alpha - V_m W' = 0, \qquad [2]$$

$$W(1) \approx W(0) + W'(0) = W'(0) = \frac{V_q}{V_m}(q_1 - q_0)$$
$$= b(q_1 - q_0). \qquad [2a]$$

[8] The concept of a stand-in preference function focuses on selecting a specification for preferences of an aggregate agent that is capable of reproducing the empirical "facts" or the data describing baseline aggregate conditions used to calibrate the model.

[9] Our computational model will have market and household-produced services as well as the manufactured good. Leisure is also a rival and exclusive "commodity" from the representative agent's perspective. As a result there are consumer reallocations that can affect the amount of emissions produced in general equilibrium.

Differentiating equation [2] again with respect to t yields [3]. Our second-order expansion for $W(t)$ has the general form given in [4].

$$V_{qq}\alpha^2 - V_{qm}\alpha W' - V_{mq}W'\alpha + V_{mm}(W')^2 - V_m W'' = 0, \quad [3]$$

$$W(t) \approx W(0) + W'(0)t + \frac{1}{2}W''(0)t^2. \quad [4]$$

Solving [3] for W'' with substitutions from equation [2a], we have equation [5].

$$W''(0) = \frac{V_{qq}}{V_m}\alpha^2 - 2\frac{V_{mq}}{V_m}\frac{V_q}{V_m}\alpha^2 + \frac{V_{mm}}{V_m}(\frac{V_q}{V_m})^2\alpha^2. \quad [5]$$

Substituting [2a] and [5] into [4], we have [6].

$$W(1) \approx \frac{V_q}{V_m}\alpha + \frac{1}{2}\left[\frac{V_{qq}}{V_m}\alpha^2 - 2\frac{V_{mq}}{V_m}\frac{V_q}{V_m}\alpha^2 + \frac{V_{mm}}{V_m}\left(\frac{V_q}{V_m}\right)^2\alpha^2\right]. \quad [6]$$

To interpret this expression for the second-order approximation of WTP, we use the properties of the marginal WTP or shadow value (b) for a change in environmental services, q. We start with an explanation of the properties of this shadow value using our general description of preferences. Equation [7] repeats the definition (used in equation [2a]) for the shadow value for a small change in q in terms of $V(\cdot)$.

$$b = \frac{V_q}{V_m}. \quad [7]$$

The partial derivatives of b with respect to q, m, and p are given in equations [8a] through [8c].

$$b_q = \frac{V_{qq}}{V_m} - b\frac{V_{mq}}{V_m}. \quad [8a]$$

$$b_m = \frac{V_{qm}}{V_m} - b\frac{V_{mm}}{V_m}. \quad [8b]$$

$$b_p = \frac{V_{qp}}{V_m} - b\frac{V_{mp}}{V_m}. \quad [8c]$$

General equilibrium adjustments can cause b to change because the arguments of $V(\cdot)$ have new values that are determined by the equilibrium with the policy, inducing the change in q. Our model specifies the relative price changes "outside the equilibrium adjustment." That is, they are determined by the analyst's assumptions about the cost of the proposed rule and about the pace of productivity advance. If we used a different specification for production technologies, these relative prices would also be determined by the general equilibrium adjustments. In our case, it is only q and m that are affected by general equilibrium adjustment. They change as the representative household responds to the regulation's effect on relative prices and on the rate of emissions, assuming compliance. As the household adjusts consumption and labor/leisure choices, income and environmental quality change. In this "story" there may be further adjustment. The model describes a static equilibrium, so all these responses are embedded in the expressions for how the equilibrium is solved. The marginal WTP for q is our "window" on the importance of these responses. As a result, we selected the ratio of the shadow value evaluated at the baseline equilibrium (or assuming partial equilibrium assumptions hold) to the value after the economy adjusts to the policy (or allowing for a general equilibrium perspective) as our index for the importance of general equilibrium effects on the practices used for BCA.

Most of the practical strategies for benefit analysis assume WTP can be approximated with a first-order approximation, as in equation [2a]. The performance of this strategy for benefit measurement in this example, where we assume prices are fixed, depends directly on how b changes in response to the change in q and on the effects of the associated adjustments in choice variables in response to the policy causing q to change. As we explained, both of these influences will depend on the preference specification, the size of the change in q, and the economic structure determining general equilibrium outcomes. We can see these connections using our second-order approximation in [6] after substituting with the expressions for marginal WTP from equations [8a] through [8c]. The result is given in equation [9].

$$W(1) \approx b(q_1 - q_0) + \frac{1}{2}(b_q - bb_m)(q_1 - q_0)^2, \qquad [9]$$

where b_q–bb_m is an index of the effects of a preference specification for the role of q and m on b.[10] These influences are captured by judging the importance of changes in b with the size of the changes in q and m. When this second-order term is small (in absolute magnitude), we expect the first-order expression, using estimates of b, will provide a reasonable approximation for WTP for changes in q from q_0 to q_1.

Consider, now, policies that involve both relative price and quality changes. This derivation corresponds to what we described as stage 2 of our outline for judging the effects of preference specifications on macro general equilibrium models. In stage 2 we assume that only one private good is directly affected by the policy, as well as the environmental quality, as the objective of the policy.[11]

The WTP is now for simultaneous changes in that good's price and in environmental quality.[12] As a result, our expansion considers the effects of both changes for the second-order approximation of WTP. We repeat the same logic used in stage 1. We define $p(t)=p_0+\beta t$ with $\beta=p_1$–p_0 and $q(t)=q_0+\alpha t$, with $\alpha=q_1-q_0$ and t our index of the magnitude of the policy as before. Following the same logic, we can derive an expression for WTP (designated now as $w(t)$) in equation [10] when both quality and price change.[13]

$$\begin{aligned} w(1) \approx\ & b(q_1 - q_0) - x(p_1 - p_0) \\ & + \frac{1}{2}(b_q - bb_m)(q_1 - q_0)^2 \\ & - \frac{1}{2}(x_p + xx_m)(p_1 - p_0)^2 \\ & + (b_p + xb_m)(q_1 - q_0)(p_1 - p_0). \qquad [10] \end{aligned}$$

Our private good is labeled as x. We evaluate the partial derivatives at $t=0$, again so we are considering the assessment from the baseline conditions, and the overall expression for WTP at $t=1$. As with our stage 1 analysis, the coefficients for the second-order terms describe how the features of a preference specification can influence the relative importance of price and environmental quality changes. $x(p_1-p_0)$ is now the first-order measure of the benefits due to a price change for this good (or costs if these effects are the only source for the price changes). In the context of conventional BCA the costs of meeting the regulation are included in computing the net benefits. This expression reveals another first-order effect that is sometimes not counted. The price increase for x leads to a consumer surplus loss approximated by $x(p_1-p_0)$. This omission implies traditional practices may overstate the benefits of the q_1-q_0 increase (with price increases) by ignoring this term.

Conventional practice assumes these price effects are small. Nonetheless, as our examples below illustrate, even with small price changes these effects can imply general equilibrium influences on WTP need to be considered. The coefficients of the second-order approximation provide a way to gauge how the preference specification influences the properties of the shadow value function and the demand function for the private good in influencing the general equilibrium effects of policy changes. By computing them for our baseline solution to the model (developed in Section 4 below) and for each of the example policies, we can compare the effects of a preference specification on the assessment of the importance of general equilibrium effects and describe whether they are due to quality change, price changes for directly related goods, or a composite of these effects.

3. Background and Past Literature

Kokoski and Smith (1987) and Hazilla and Kopp (1990) were the first, to our knowledge, to use computable general equilibrium (CGE) models to assess the importance of general equilibrium effects of environmental policies for BCAs. Both studies focused on measuring

[10] This term parallels Anderson's (1980) equivalent of a Slutsky equation for an inverse demand function.

[11] Our approach could readily be generalized to a case where more private goods and services are assumed to respond. This would be necessary with a neoclassical specification for the production technology.

[12] Recall the design of our model limits the relative price effects to these direct, cost-related impacts. An alternative description of the production technology would require further generalization to allow for multiple price changes.

[13] The derivation is given in Appendix A.

the costs and relative price effects arising from multimarket, general equilibrium responses. Later Espinosa and Smith (1995) and Espinosa (1996) extended this logic and introduced measures of the value of nonmarket resources into the preference specifications in an 11-region CGE model for the world economy—the Harrison, Rutherford, and Wooten (1989) model. The Espinosa-Smith extension to that model replaced the original Cobb-Douglas preference specification with a Stone-Geary form and allowed measures of air pollution to shift the subsistence parameters for the consumption goods related to health effects. This formulation treats these health-related private goods as perfect substitutes for environmental services. It does imply nonunitary income elasticities and allows environmental services to influence, indirectly, the marginal rates of substitution between other aggregated market goods and services that are not influenced directly through the subsistence parameters.

More recently, Mayeres and Van Regenorter (2008) argued that feedback effects between changes in environmental services and consumption choices were of second-order effects. However, their model must yield this conclusion because they assumed private goods and services provided perfect substitutes for environmental services. The first direct evaluation of the importance of substitution or complementarity between private goods and nonmarket services was provided by Carbone and Smith (2008). Their small CGE model extended work by Goulder and Williams (2003) and compared the effects of air quality entering household preferences in two ways: (1) combined with leisure versus (2) in a subfunction with marketed goods. Their focus was on partial equilibrium and general equilibrium measures of the excess burden of a new tax (given a preexisting tax on income). Their findings indicate that the importance of nonmarket services depended on the model's measure for the virtual expenditures on environmental quality as a fraction of GDP and the nature of the linkage between quality and private goods or leisure. Complementary relationships tended to lead to somewhat larger discrepancies between the partial equilibrium measure of excess burden and the full compensating variation measure of welfare loss of the tax because the former ignored environmental quality benefits. Unfortunately, their analysis does not offer direct guidance for conventional practices used in BCAs.

Perhaps the closest large-scale effort to address the question can be found in the Second Prospective Analysis prepared by the U.S. Environmental Protection Agency (EPA) (2011). One chapter of this report compares conventional partial equilibrium benefit measures with those developed with a large-scale CGE model. The EPA analysis uses a large, complex, multisector CGE model (EMPAX). Emissions of air pollutants are not part of the EMPAX model. As a result, there are no feedback effects of policy. The EPA's analysis of the 1990 Clean Air Act amendments (CAAA) introduces the effects of the amendments as differences in the labor endowment for the "with" rules (i.e., labor available because the policy reduces the number of deaths due to air pollution in expected value terms) compared to the "without" case (where the reductions in labor available take place), along with the difference in the medical expenditures in the two situations. The annual net benefit estimates comparing "with" and "without" CAAA policies using partial and general equilibrium measures for 2010 indicate that the partial equilibrium measures were 109 times larger than the general equilibrium measures. This difference is not simply a general equilibrium effect. The partial equilibrium analysis relies on the value of a statistical life (VSL) to monetize the reductions in mortality risks associated with air quality improvements. By contrast, the general equilibrium estimates treat the effects of air pollution reductions as equivalent to an increase in the labor endowment.[14]

[14] The partial and general equilibrium analyses are discussed as adopting alternative approaches to defining benefits with the CGE based on a human capital approach. The general equilibrium approach uses the additions to the time endowment due to avoided mortality and avoided such days, as well as reduced medical expenditures. The EPA's assessment (U.S. Environmental Protection Agency 2015a, 17–19) of the potential limitations also noted that mortality and morbidity effects for individuals outside the labor force were excluded. The partial equilibrium analysis treats the policy as reducing the risk of death. The benefit concept used is then a measure of the WTP to reduce risk, not a value for labor time. There have been few comparisons of the effects of doing general equilibrium analyses allowing for different

The other two approaches used to compare partial and general equilibrium estimates are associated with specific strategies for estimating the benefits of changes in environmental quality. The first of these involves sorting models that provide a structural counterpart to reduced-form hedonic modeling.[15] The second group adopts structural approaches to evaluate hedonic property value models.[16] Both examples are best treated as efforts to compare restricted and unrestricted welfare measures. Factor and product models are not represented, and thus income levels and prices are not jointly determined within the models.

4. Model

Our analysis extends Rogerson's (2008) model in three ways. First, we introduce nonmarket environmental service into the model so that these services affect the market equilibrium but are outside the household's private choice set. Second, we consider how different preference specifications for the representative household in the model influence our assessment of the general equilibrium effects of policy. Finally, we show how a macro general equilibrium model can be used to evaluate the "size" of policies based on their likely general equilibrium effects for benefit analysis.

To interpret the implications of our findings for policy, it is especially important that our calibrations of the model's free parameters exactly match the data moments used to represent the baseline condition of the economy. An inexact match would confound issues associated with the model's fit to the economy with the model's assessment of the importance of the general equilibrium responses to a proposed policy.

Outline of the Components

Environmental services are now introduced into Rogerson's (2008) model. They are treated *as being determined within the model,* but outside the representative agent's control. Rogerson's framework focuses on time allocation. As such it is well suited for judging the importance of nonmarket environmental services, because most revealed preference benefit methods maintain that time allocation decisions provide some of the most important pathways for environmental services to affect individual behavior.

Three different preference specifications, each a variation of the Brown and Heien (1972) S-branch utility function, are considered in our extensions. Rogerson's model has the top level of the nested preference specification as a Cobb-Douglas function in terms of consumption and leisure. Consumption is composed of one branch with market goods, including a subsistence level of the produced commodities, and a branch for services using a CES function that is composed of market and home-produced services.[17] Labor income is taxed at a proportional rate. These tax revenues finance a lump-sum transfer to the representative household. To assure our extension is as transparent as possible, we use the same notation as in Rogerson's paper for the elements in the model that do not change (Appendix D summarizes all the elements in the model).

Our first specification introduces environmental services into the subfunction for home-produced services ($F(S,N,q)$), so it maintains the Rogerson CES function for consumption as composed of two parts. The

ways to measure the values people place on environmental services. Smith and Carbone (2007) used a small CGE model originally developed by Goulder and Williams (2003) to compare alternative calibrations of air quality changes. Using a VSL-based measure for the value as compared to one based on hedonic property values implies larger partial equilibrium and general equilibrium benefit measures. Their focus was on measures of excess burden of taxes that affect the generation of pollution emissions and are not directly comparable to the general question we pose. Nonetheless, comparing their partial and general equilibrium estimates, there is a much smaller difference with the VSL-based calibration than what is implied by the EPA study.

[15] See Kuminoff, Smith, and Timmins (2013) for an overview of these models.

[16] Kuminoff, Parmeter, and Pope (2010) provide an example of this approach.

[17] A common reason for using the Stone-Geary specification with a subsistence-level of consumption is to assure nonunitary income elasticities. However, with quasi-fixed goods, the nested CES becomes nonhomothetic, so this formulation would not be necessary when air quality is introduced (see Carbone and Smith 2008). We maintain this format for the goods branch in one of our preference specifications to allow comparison of the calibrated parameters with Rogerson's results.

first of these was marketed goods and the second was a subfunction composed of marketed services plus home-produced services. As equation [11] indicates, we add q to this subfunction.

$$C = (\alpha_G (G - \bar{G})^{\varepsilon} + (1 - \alpha_G) F(S, N, q)^{\varepsilon})^{\frac{1}{\varepsilon}}, \qquad [11]$$

where C = consumption, G = market goods, S = market services, N = home-produced services, and $\sigma_{(G-\bar{G})F} = 1/(1-\varepsilon)$.[18]

The subsistence parameter for marketed goods, $\bar{G}$, assures the income elasticities are not unitary. Our first modification is given in equation [12].[19] We use a nested CES to describe home production.

$$F(S,N,q) = (\alpha_S S^{\eta} + (1-\alpha_S)[\alpha_N N^{\varphi} + (1-\alpha_N) q^{\varphi}]^{\eta/\varphi})^{1/\eta}. \qquad [12]$$

We use air quality for the environmental service in our empirical analysis because both of our policy examples deal with regulations restricting emissions of air pollutants. When we used this modification to calibrate the model it did *not* provide an exact match to the time-share targets providing the basis for that process. As a result, we report the parameter values implied by this calibration but do not use them in illustrating how our index of general equilibrium effects would work for our two policy examples. Our two alternative preference specifications yield calibrated parameters whose predicted time moments exactly fit the data moments for our baseline years. This exact fit to the data allows us to focus on how the properties of the preference specification and the nature of the policy affect judgements about the importance of general equilibrium outcomes.[20]

The second specification we considered also assumes environmental quality enters through the home production function and simply replaces the term describing the contribution of marketed services with one that includes a subsistence parameter for the services ($\bar{S}$), as in equation [12a] below.[21] This added parameter is enough to permit an exact match to the data moments.

$$F(S,N,q) = (\alpha_S (S + \bar{S})^{\eta} + (1-\alpha_S)[\alpha_N N^{\varphi} + (1-\alpha_N) q^{\varphi}]^{\eta/\varphi})^{1/\eta}. \qquad [12a]$$

As we noted, environmental services are treated as quasi-fixed in the first-order conditions describing the agent's choice of G, S, and N. Thus, the level of q influences the marginal rate of substitution between market and household-produced services, as well as that for all other choices, but is not a choice variable.

Early research on averting behavior in response to air pollution focused on materials damage and increased cleaning expenses (see Harford 1984), which would be consistent with this specification (see chapter 4 by Freeman, Herriges, and Kling [2014] and Smith [1991]). Some other examples of these types of effects include using bottled water in response to water contamination (Smith and Desvousges 1986); spending time indoors during high-pollution alerts (Mansfield, Johnson, and Van Houtven 2006); and household landscaping decisions in mitigating the temperature effects of climate change (Klaiber, Abbott, and Smith 2017). It is also consistent with recent work on air pollution in the United States (Deschênes, Greenstone, and Shapiro 2017) and in China (see Zhang and Mu 2018).

The feedback effect is portrayed simply in equation [13].

$$q = \frac{1}{\mu \cdot G}. \qquad [13]$$

The parameter μ reflects both the emissions produced as a result of the selected amount of

[18] This equation is the elasticity for a CES function, treating $(G - \bar{G})$ as a composite substitute for F, also as a composite. In this case it holds the level of consumption constant. Our specification adds the subsistence parameter. Baumgärtner, Drupp, and Quaas (2017) derive an expression for this elasticity in the appendix to their paper.

[19] Rogerson's model excludes the term in q and has a CES subfunction in S and N.

[20] This approach is commonly used in judging the "fit" of these types of macro general equilibrium models before using them for a policy analysis. This type of near perfect match to moments is generally expected; see Rogerson (2008), Bridgman, Duernecker, and Herrendorf (2018), and Herrendorf, Rogerson, and Valentinyi (2013).

[21] The threshold or subsistence parameters play a key role in the magnitude of own- and cross-price effects (see Brown and Heien 1972, 742).

G and the atmospheric diffusion process for these emissions. Thus, environmental services are assumed to be the inverse of the ambient concentration of pollution. μ is the key parameter we use to introduce how policy affects environmental quality. That is, when policy sets requirements for specific pollution control technologies or introduces incentive-based programs, the effects are represented in our model as reductions in the emissions produced per unit of output. These effects modify one component of μ. The second component of this parameter is an aggregate representation of the diffusion of emissions.[22] Depending on how ambient quality is measured, this term converts the emissions implied by an output level into an index of air quality.

The third preference specification retains the subsistence parameter for services but moves the contribution of environmental quality from household services to the leisure component of the top-level utility function. This approach would be consistent with more recent analyses of the effects of air pollution on recreation (see Graff Zivin and Neidell [2009] and Ward and Beatty [2016] for examples involving air pollution, and Chan and Wichman [2018] for an example with temperature). q enters through the leisure term (L) in the top-level Cobb-Douglas function. The preference function in this case retains the Rogerson formulation for the C subfunction and is given by equation [14].[23] This specification provides a direct link between q and labor/leisure decisions. By including q with leisure in preferences, the effects of tax policies on decisions to use home production to provide more services or to take more leisure can be more directly affected by changes in environmental quality. That is, the exogenous level of q (from the agent's perspective) will affect the marginal rate of substitution between leisure and consumption goods. In our first two specifications the effects of q are primarily through home production whose output is not taxed. This distinction has been a key issue emphasized in the macro literature.[24]

$$U(C,L,q) = \alpha_C \log(C) + (1-\alpha_C)\log(\alpha_H L^{\varphi} + (1-\alpha_H)q^{\varphi})^{1/\varphi}). \qquad [14]$$

For convenience we use the same parameter labels to describe the substitution relationship between leisure and environmental quality (φ) as were used in equation [12a] to characterize the link between N and q, but the economic interpretation is different for these two alternative treatments of how q contributes to household well-being.

Market goods and services as well as home production are the result of fixed coefficient technologies based on labor allocated to each activity (H_i designating the labor time, with $i = G$, S, and N for each sector), as in equation [15]. Capital is absorbed into the A_i parameters. As we explain below, by including the exogenous productivity effects through the input requirement parameters and defining moments for calibration of the model's remaining parameters in different years (1950 and 2005), we are implicitly recognizing that productivity growth is in part due to the changing role of capital in each sector over time.

$$G = A_G H_G,\ \ S = A_S H_S,\ \ N = A_N H_N. \qquad [15]$$

These labor requirements describing the sectoral productivities (the A_i's) change over time, each at a different exogenous rate.[25] The wage is normalized to unity, so the equilib-

[22] See Baker et al. (2018) for a discussion of the important difference in the effects of the models used to depict this diffusion process for reduced-form partial equilibrium benefit measures.

[23] This specification parallels the one used by Carbone and Smith (2008) and allows us to evaluate some aspects of the variations on the EPA Second Prospective Analysis proposed by Marten and Newbold (2017).

[24] The tax effect here is different from the tax interaction effect associated with replacing an income tax with an effluent charge. In the analyses of these tax interactions, most of the analyses assumed environmental quality made a separable contribution to preferences and thus ignored the potential effects of environmental quality on labor/leisure choices. We can gauge the relative importance of this specification difference by comparing the computed marginal utility of income for each our preference specifications at the baseline solution. With q entering the household-production function, the model produces, as expected, a lower marginal utility of income: $V_m = 1.0958$ for the low q share and $V_m = 0.9426$ for the high q share. By contrast, when q enters preferences with leisure, the marginal utility of income is larger: $V_m = 1.1238$ for the low q share and $V_m = 0.9991$ for the high q share.

[25] We adopt Rogerson's assumptions about average growth rates in productivity for the goods and service sectors ($\gamma_G = 2.48$ and $\gamma_S = 1.44$, respectively) and use Duernecker

rium market prices for market goods are given in equation [16].

$$P_G = \frac{1}{A_G},\ P_S = \frac{1}{A_S}. \quad [16]$$

Leisure (L) is the residual from time allocated to market activity (for producing G and S) and home production (N), with total time normalized to unity, and is defined in equation [17].[26]

$$L = 1 - H_\mathrm{G} - H_\mathrm{S} - H_\mathrm{N}. \quad [17]$$

Calibration

Before discussing the specifics of the model's calibration, some background for the logic we use in calibrating the nonmarket component of the model may help in explaining how we use the benefit estimates from existing studies. Twenty years ago, in *Nature's Numbers,* the Panel on Integrated Environmental and Economic Accounting (Nordhaus and Kokkelenberg 1999) noted, "The nub of the difficulty in constructing a set of environmentally adjusted national accounts lies in estimating the consumption services of environmental assets" (p. 179). The report went on to describe the needs of what was labeled as the "damages borne approach." Over this period, there has been great progress using proxy measures for these consumption services, such as using the ambient concentrations of various pollutants for air quality services, biological oxygen demand and suspended solids for water quality services, and so forth. As a rule, these types of measures are linked to physical or constant dollar, monetary measures of the outputs whose production processes give rise to the pollution.[27] The engineering assumptions used to estimate emission rates per unit of the outputs involved are expressed in terms consistent with the economic model's measure of output. This process assures that the resulting predictions for emissions match what is observed. In large-scale partial equilibrium models, these emissions levels are associated with point and mobile sources. The point sources are located in a geographic framework that links emissions in one set of locations to ambient concentrations of those pollutants in other locations. The air diffusion models compared by Baker et al. (2018) are responsible for these predictions and are important to the overall policy evaluations.

Our model measures inputs and outputs as index numbers connected to a normalized measure of total time available to the economy. The wage rate is also normalized. As a result, the output measures for market goods (G), services (S), and home production of services (N) in the model do not have a direct physical (such as kilowatt hours for electricity) or monetary interpretation separate from labor time (i.e., constant dollars of value added). Our model also reduces the composite of emission rates and diffusion effects to a single equation as given in [13] above. To introduce nonmarket services into the model we must confront the effects of these normalizations in using the available estimates for the benefits from reducing air pollution.[28] We need to select a measure of the importance of environmental services to aggregate economic activity that can be expressed as a ratio consistent with the indexes used for our measures of outputs and inputs in the model. One way of accomplishing this task is to use measures of the marginal WTP for reducing air pollution, as it is defined in the model, along with an observed change in air quality completed by the baseline year, to construct a value share for air quality. In our case it is the monetary value of a change in air pollution relative to an estimate of the before-tax wage compensation.[29] We developed estimates for the ratio from the literature and link each one to an expression defined in terms of the parameters

and Herrendorf's (2018) estimate for the growth rate in productivity in home production ($\gamma_N = 0.10$).

[26] Rogerson does not define L, since it is implied by other allocations and the normalization used for total time.

[27] Muller (2016) discusses many of the consistency issues that must be addressed in using physical versus monetary measures for marketed goods and environmental services. Whatever the choice, there are adjustment factors that must be built into the data structure to assure consistency of the modeled outcomes with the empirical record used to estimate or calibrate a model.

[28] This issue is conceptually similar to the question motivating Herrendorf, Rogerson, and Valentinyi's (2013) analysis of value-added versus expenditure-based definitions for aggregate consumption.

[29] Carbone and Smith (2008, 2013) used a similar logic to calibrate the CGE models.

of our model. This equation is then used as one of the data moments that are part of the calibration for each of our specifications of household preferences. To develop the share estimates describing the "value" of reducing air pollution, we select values for the marginal WTP that span the range of estimates in the literature.[30]

With this background, we follow Rogerson's calibration strategy and select most of the model's parameters (α_C, α_G, α_S, α_N, ε, η, φ, $\overline{G}$, $\overline{S}$) to match the time moments based on the first-order conditions for optimal allocation of time.[31] With q added to the model, we include the moment for the value share for the damages reduced due to lower levels of air pollution over the years used in defining this moment, as we explained above. For the model that has one subsistence parameter ($\overline{G}$), we select the parameter determining substitution between market goods and services (ε), both market and home production, using calibration. When a second subsistence parameter ($\overline{S}$) is introduced for services, then we assume a value for ε that implies an elasticity of 0.45, and we determine the service subsistence parameter via calibration.[32] This selection for the elasticity uses a value comparable to Rogerson's calibration in his baseline case as well as to the target used by Duarte and Restuccia (2010).[33] However, in Rogerson's case the subfunction for household activities did not include $\overline{S}$.

As this discussion implies, when there are more parameters in the model to be calibrated than available data moments, some of the parameters are set to specific values based on the available empirical literature. We investigated the sensitivity of our results to these choices. As a rule, the parameters that are predefined from the literature are ones where there is consensus on their values. In addition, the ability to match the data moments exactly is another "cross-check" on these choices.

Two years, 1950 and 2005, were selected for calibrating our models.[34] Each year is treated as a competitive equilibrium. The representative agent cannot influence prices and takes environmental quality as given. The equilibrium process allows the choices of goods and services to alter the realized environmental quality. While the model is static and the representative agent's preferences do not change over time, productivity is specified to change over time for produced goods and services as well as home-produced services at fixed rates. We set the elasticity of substitution between market services and household-produced services ($\sigma_{SN} = 1/(1-\eta)$) equal to 1.82.[35] Equations [D14] through [D16] in Appendix D define the first-order conditions for the home-production subfunction specification with two subsistence parameters.[36] The equations for the leisure subfunction specification are also in Appendix D and correspond to equations [D11] through [D13].

Time allocations for each of the two years create six of the seven data moments. These conditions necessarily coordinate with selection of goods and services, given exogenous

[30] Our current research with Jared Carbone and Nicholas Muller uses Muller's AP2 model to estimate the benefits of reducing PM2.5 from 2011 levels to the lowest observed reading at the county level and finds that a reduction in monetized damages was about 15% of median income for the average U.S. household.

[31] These parameters correspond to the preference specification with q entering the production of household services. When q enters a subfunction with leisure, the parameter α_N is replaced by α_H.

[32] We did evaluate the sensitivity of our results to this assumption and found it did not affect our overall conclusions.

[33] Durate and Restuccia (2010) did not have home production and argued a parameter for subsistence level of services could serve as a proxy for home production (p. 139).

[34] Rogerson used 2003 as his end year. We selected 2005 because it is a closer match to some of the sources for measures of air quality and precedes the Great Recession. We used data from Duernecker and Herrendorf (2018) for the time allocation in 2005 and the estimated rate of productivity in home production. Rogerson selected this productivity rate via calibration and derived a negative value. Duernecker and Herrendorf estimated positive productivities for home production in 10 of the 12 developed economies considered in their analysis. Only Italy and Austria had negative values. In addition, we used data from the GGDC database (http://ggdc.webhosting.rug.nl/ggdc/SimpleAggregates.mvc/IndustrySelect) to calibrate the productivity growth rates in the goods and service sectors.

[35] When preferences include q in the home production function, σ_{SN} relates to the elasticity of substitution between service and the composite of home-produced services along with the effect of environmental quality. We have examined alternative values of η between 0.2 and 0.5, and our overall conclusions remain unchanged.

[36] Matlab code for using the model is available in Appendix C.

labor productivity and the income tax rates (τ) for each of these two years ($\tau = 0.17$ for 1950; $\tau = 0.30$ for 2005). We set the value for q in 1950 based on actual air pollution levels in that year and then select μ to assure the model's solution for q in 2005 corresponds to the air quality conditions observed in 2005. As a result, we treat emissions as fixed at the observed level in 1950. q is determined endogenously in 2005, recognizing the feedback effects between G and q as well as its impact on other trade-offs.[37] Our calibration includes the targets for the time shares for each of the two years and an estimate for the value share of the pretax wage compensation associated with a large change in environmental quality (q) in 2005, as defined in equation [18].

$$\frac{\frac{U_q(q-q_0)}{U_L/(1-\tau)}}{W(H_G+H_S)} = \text{Aggregate value of increment to } q \text{ from baseline of } q_0 \text{ relative to aggregate wage compensation } (W(H_G+H_S)), \quad [18]$$

where W is the wage rate.[38]

The budget constraint for the representative household is given by equation [19], with W normalized to unity.

$$P_G \cdot G + P_S \cdot S = (1-\tau)(H_G + H_S) + T, \quad [19]$$

where T = transfer of taxes to household. The numerator in equation [18] describes the marginal value for q (which we labeled as b in developing our second-order approximation for WTP). Now we define the shadow value in terms of the derivatives of the direct utility function defining preferences (i.e., $U_q(1-\tau)/U_L$), because this is the way our structural model is specified. Our conceptual development of the framework for evaluating the influence of each preference specification was general and did not include the income tax (τ). Our empirical analysis computing the indexes includes its distorting effects on the household's choices of work and leisure. The arguments of the direct utility function and its derivatives correspond to the solutions from each version of the models for these variables.

Once the preference parameters are determined from the calibration, the specific values used for this marginal rate of substitution depend on how we are using it to gauge general equilibrium effects. For example, in our index of general equilibrium effects, the partial equilibrium estimate for the marginal rate of substitution is computed using the values of the arguments corresponding to the baseline solution of the model for each q-share calibration. The denominator uses the value of the marginal rate of substitution computed based on the values for the choice variables corresponding to the solution of the model with each policy.

Table 1 describes the sources and assumptions for both low and high q-share estimates. For defining the moment used in the low q-share calibration, the marginal rate of substitution uses an estimate of the marginal WTP from the literature together with a measure of the change in air quality from 1950 to 2005. In each calibration of the model, the exact algebraic form of the expression for marginal WTP and the preference parameters involved will change with each of the alternative preference specifications.

The process of developing the value share estimate for environmental services combines two important issues that arise in using nonmarket valuation estimates in BCAs. The first of these involves selecting an estimate for the marginal WTP for the specific environmental service. The second is the definition of *the extent of the market* for the environmental public good (or the number of households who would value the change in q).[39]

[37] In the calibration, our strategy of targeting q or μ is equivalent to each other in a model that can match all the data moments perfectly. We calibrate the μ value in 2005 explicitly because we are defining μ as a product of two influences. One of these is the emissions rate that links G with emissions, and a second that translates emissions into Q. We introduce the effects of policy in our examples by modifying the first of these effects. By calibrating μ to match 2005 conditions we can solve for the diffusion effects and keep those constant for the policy simulations, consistent with what was implied from the 2005 conditions.

[38] The income used to define the q share for calibration reflects the taxed wage income plus the transfer of taxes (T) to the household (see equation [19]).

[39] Recognition of this second point is consistent with Wallenius and Prescott's (2011) argument that aggregate preference constructs must represent all the households in

Table 1
Values and Sources for the Construction of q-Share Measures for Calibration

Variable	Value	Year	Source
A. Analysis for Low q Share			
PM10	110.5 μg/m³	1950	Matus et al. (2008). David Mintz personal communication in 2003. Derived from average of second maximum of PM10. Applies 0.415 to average of second maximum. See U.S. Environmental Protection Agency (1996).
PM10	25.2 μg/m³	2005	
Proportionate change	0.772		
Marginal rate of substitution	$34.60	2005	Average from Smith and Huang (1995) adjusted to convert to PM10.
μ	93.5	2005	Ambient concentration of PM10 in 2005 divided by value of G, which is product productivity parameter A_G and H_G (=0.2693).
Share of aggregate wage compensation	0.0536		Wage compensation comes from the Labor Compensation (Compensation of Employees) series from the Groningen Growth and Development Centre Databases. We used the EU KLEMS Database, accessed through http://ggdc.webhosting.rug.nl/ggdc/SimpleAggregates.mvc/IndustrySelect.
B. Analysis for High q Share			
PM10	23.64 μg/m³	With Clean Air Act	U.S. Environmental Protection Agency (2011, box 4-1). Population-weighted average of PM2.5 for New York, Pittsburgh, Chicago, Los Angeles, scaled by 1/0.55.
PM10	52.94 μg/m³	Without Clean Air Act	U.S. Environmental Protection Agency (2011, box 4-1). Population-weighted average of PM2.5 for New York, Pittsburgh, Chicago, Los Angeles, scaled by 1/0.55.
Proportionate change	0.553		
Aggregate benefits	$1.3 trillion	2006 dollars for 2010	U.S. Environmental Protection Agency (2011, table 7.5).
Share of aggregate wage compensation	0.175		Wage compensation comes from the Labor Compensation (Compensation of Employees) series from the Groningen Growth and Development Centre Databases. We used the EU KLEMS Database, accessed through http://ggdc.webhosting.rug.nl/ggdc/SimpleAggregates.mvc/IndustrySelect.

Two different values for the q share of wage income are considered in our calibrations for each preference specification. These calibrations are based on measures of the benefits from controlling particulate matter (PM10—particulate matter 10 microns or smaller). The first uses measures for the average annual concentration of PM10 in 1950 and 2005, along with estimates from a meta-analysis of hedonic property model estimates (Smith and Huang 1995). The ambient concentration of particulate matter declined over this period by 77.2%. We selected the average of the past estimates in 2005 dollars as the largest plausible measure for the marginal WTP based on the hedonic property value research. This measure is about 50% larger than Chay and Greenstone's (2005) estimate.[40] It implies that the monetary value for this change in particulates would be about 5.4% of total wage compensation in 2005.[41]

The second measure for the q share is based on estimates adapted from the Second Prospective Analysis. This analysis compares "current" conditions with the 1990 Clean Air Act amendments relative to a counterfactual that is intended to represent the ambient conditions "without" regulations. Using the

the economy. We assumed 128.5 million households in the United States for 2005.

[40] The Chay-Greenstone estimate for the effect of particulate matter on housing is not easily interpreted as a marginal WTP. See Bishop et al. (2019) for a discussion of the issues.

[41] Using the Chay-Greenstone estimate would reduce the share to about 3.7%.

annual benefits for 2010 (measured in 2006 dollars) as a fraction of wage compensation in 2007 (the closest year with comparable measures for wage compensation from the GGDC database[42]), the benefits would be 17.5% of total wage compensation.[43] These benefits are due to *all* the changes in criteria air pollutants the analysis attributes to the Clean Air Act. Nonetheless, we use this estimate for an example that provides a potential upper bound for the value share, because reductions in particulates account for the majority reductions in mortality risk.[44]

Calibration is based on choosing the parameters for each specification to minimize a quadratic loss function (*OB*) defined in terms of the moments associated with the decentralized solution implied by the model for the time shares in 1950 and 2005 and for the value share (i.e., reduced air pollution damages relative to wage income) in 2005. The air pollution in the value share is not a choice variable but is implied by the choices of time allocation to maximize the agent's utility, given budget constraints. Feedbacks imply air quality will change as the decisions about private goods and services change and so will the marginal rates of substitution for private goods and services. Equation [20] defines the loss function using the low value of the -value share (0.0536).

$$OB = \sum_{t=1950,2005} \sum_{j=G,S,N} (H_j^t - \hat{H}_j^t)^2 + \left(\frac{\dfrac{\widehat{U_q(q-q_0)}}{U_L}}{\dfrac{1-\tau}{W(H_G+H_S)}} - 0.0536\right)^2, \qquad [20]$$

where $\hat{H}_j^t$ is the model prediction for the time share associated with the jth good or service at a given set of values for the parameters calibrated by the moment conditions.

5. Results

Our empirical results have three components. First, we discuss the calibration of three versions of the model, distinguished by the preference function used to describe the representative household's behavior. The second component computes the values for the terms in our second-order approximation for WTP, allowing for changes in both environmental quality and a change in the price of G, using each of these specifications with the baseline solutions for each version of the model. This set of results gauges how each specification would change the relative importance of environmental quality versus price effects for WTP. The third part uses the two sets of calibrated model parameters that provide "perfect fits" to the data moments to illustrate how our index of the importance of general equilibrium effects on benefit measures would work with two different policies. One was selected to be smaller in its effects, and the other involves a large set of regulatory changes impacting air quality. The findings for the two policies are discussed in the last section of the paper.

As we noted throughout the development of our model, price changes are set exogenously. For the baseline solution it is the pace of productivity advance that changes the relative price of G between 1950 and 2005. For the policy scenarios we use the parameters for the calibrated models and adjust the production coefficient for G to reflect both productivity advance and the costs of each policy (in percentage terms) as if they were imposed in 2005. We compute both the environmental quality and price terms in the second-order approximation because we are interested in the relative importance of price and quality change for the policy scenarios as well as the baseline solution with each preference specification. Our index of general equilibrium effects is evaluated using the equilibrium solutions for choice variables with each scenario (i.e., baseline and each policy), prefer-

[42] See http://ggdc.webhosting.rug.nl/ggdc/SimpleAggregates.mvc/IndustrySelect.

[43] This estimate may seem to be a back-of-the-envelope assessment. It is intended as an upper bound. If we were to use the EPA estimate for benefits in 2000, it would amount to 749 billion (in 2006 dollars). Relative to 2000 wage compensation (also measured in 2006 dollars) it would be 14.7%. We selected the larger estimate as our upper bound.

[44] Recently, Muller (2019) reported estimates of the value of changes in PM2.5 as a fraction of GDP from 1957 to 2016. In the post–World War II period he estimated the value of PM2.5 would have been about 30% of GDP. By the end of the period it was under 20%. So our largest monetary value share for a change in air pollution for the period 1950 to 2005 is broadly consistent with his results.

ence specification, and set of parameter values derived from each calibration as the q-value share is changed between the low and high values. These solutions will be affected by the composite of the price changes and the endogenously determined changes in environmental quality, as the agent's choices of market goods and services and home production change in response to both sets of influences.

As we noted earlier, to gauge general equilibrium responses we use the ratio of the partial equilibrium shadow value (or marginal rate of substitution $(U_q(1-\tau)/U_L)$) for q to the general equilibrium value.[45] We compare the marginal rate of substitution implied at the baseline equilibrium without a policy $(U_q^0(1-\tau)/U_L^0)$ to the model-induced marginal rate of substitution at the new equilibrium with each policy $(U_q^1(1-\tau)/U_L^1)$. We generally expect that the ratio of a baseline marginal rate of substitution to policy-induced marginal rate of substitution (with baseline value in the numerator) will be equal to or greater than one. With larger general equilibrium responses we expect the index to be larger. Of course, both the policy and the preference specification will influence how the index reflects the importance of general equilibrium responses.

Calibration Results

Table 2 presents the calibrated parameters for the three specifications for the preference function; each is paired with one of the two values for the q-value share (low and high). Our applications all involve changes in air quality attributed to reductions in the ambient concentration of PM10. Several aspects of the calibrated models presented in Table 2 are notable. First, the calibrated models with one subsistence parameter do *not* match the time share moments well (see the last seven rows in the table). The discrepancy in moments is larger for both the time share allocated to leisure and the time share associated with the production of market services. When the model is augmented to include a second subsistence parameter for market services, regardless of the placement of the environmental quality measure or the magnitude of its value share, the match between actual time shares and the model's predicted time shares is exact. For the preference specifications with a second subsistence parameter, we no longer select $\sigma_{(G-\bar{G})F}$ as part of the calibration. This parameter is preset at 0.45, as noted earlier. A negative value for $\bar{G}$ in Table 2 implies an additive effect in the top level of the preference nest, while a negative estimate for $\bar{S}$ implies a negative effect (see equations [11] and [12a]). It is also important to acknowledge in this context the subsistence parameters can have any sign. Their primary role here is to allow the price and income elasticities implied by each calibration to be consistent with the responses implied by the time shares and the values for the q share.

The calibrated values for the share parameters (α's) are generally stable for the marketed goods and services with the two subsistence parameter models regardless of the size of the q share used. As expected, the calibrated share parameters involving q (α_N for the case of q in household production and α_H when q enters preferences with leisure) display pronounced differences as the magnitude of the q-share changes. The two subsistence parameter models imply substitution elasticities for q in either home-produced services or in the leisure-time specifications that are larger than one. There is little direct empirical evidence on how environmental quality substitutes for household services. Smith (1991) adapted an argument originally developed by Mäler (1985) to demonstrate how perfect substitution of private goods and environmental quality could be used in nonmarket valuation. Our technology assumptions imply the link to household services is simply a scaled version of time. Thus, we do not learn about

[45] We use a different designation for the shadow value $U_q(1-\tau)/U_L$ and not b because Rogerson's model includes the income tax and transfer in the specification of the budget constraint. Our empirical estimates of the terms in contributing to the second approximation include the effect of taxes. The simple derivation in Section 2 did not. Changes in tax rates would affect the marginal value for environmental quality in general equilibrium. The values for these tax rates also affect our partial versus general equilibrium comparison.

Table 2
Model Calibrations with Alternative Preference Specifications and q Shares

	Household Production, One Subsistence Parameter		Household Production, Two Subsistence Parameters		Leisure Subfunction, Two Subsistence Parameters	
	Low Share	High Share	Low Share	High Share	Low Share	High Share
Calibrated Parameters						
α_C	0.5783	0.6069	0.6211	0.6741	0.5696	0.5065
α_G	0.9211	0.9990	0.0979	0.1196	0.0872	0.0872
α_S	0.3810	0.2472	0.4625	0.3076	0.5565	0.5565
α_H	—	—	—	—	0.8601	0.6735
α_N	0.4472	0.2166	0.7113	0.3727	—	—
σ_{Nq}	9.4569	4.1435	1.3569	1.4006	—	—
σ_{Lq}	—	—	—	—	1.1971	1.0515
σ_{GF}	0.0914	0.0920	—	—	—	—
$\overline{G}$	–0.0567	–0.0332	–0.0029	0.0061	–0.0039	–0.0039
$\overline{S}$	—	—	0.1846	0.2716	0.1341	0.1341
Model Moments						
Data moment						
1950 H_G 0.1150	0.1163	0.1209	0.1150	0.1150	0.1150	0.1150
1950 H_S 0.1350	0.1589	0.1551	0.1350	0.1350	0.1350	0.1350
1950 H_N 0.2500	0.2438	0.2639	0.2500	0.2500	0.2500	0.2500
2005 q share 0.0536/0.1747	0.0590	0.1711	0.0536	0.1747	0.0536	0.1747
2005 H_G 0.0700	0.0710	0.0731	0.0700	0.0700	0.0700	0.0700
2005 H_S 0.2320	0.2133	0.2114	0.2320	0.2320	0.2320	0.2320
2005 H_N 0.2040	0.2104	0.1929	0.2040	0.2040	0.2040	0.2040

the structural parameters from these empirical analyses and cannot directly cite estimates supporting our selections. The reduced-form estimates from averting behavior models cited earlier are consistent with our general logic.

In the case of the air quality–leisure substitution relationship, the available empirical evidence would suggest a complementary relationship, implying elasticities less than one (Ward and Beatty 2016). The evidence for judging the calibrated parameters based on existing independent estimates for these elasticities is limited. Most studies involve specific recreation activities and not the overall uses of leisure time that would be captured in a macro model. Finally, while our analysis does not directly calibrate parameters to match the value of PM10 in 2005, both of the two subsistence parameter models imply values for PM10 rounded to one significant digit that match the observed value in 2005. This close correspondence is established because the diffusion parameter, μ, was set to match our estimate of PM10 in 2005 using an estimate of the particulate emission rate from market goods (G).

Effects of the Preference Specification

The choice of the preference function involves a balancing of how well the model captures the time moments compared with its ability to represent the nonmarket role of environmental services by matching the value share used in calibration. Because we are using the model to evaluate the importance of general equilibrium effects of environmental policies, it is also important to gauge how the preference specification conditions the relative importance of environmental quality and price changes. This task is met with the coefficients of the second-order terms in our approximation for WTP. These coefficients provide a way to evaluate the relative contributions of the changes in environmental services and price changes that arise in computing the general equilibrium effects of a policy.

The first two columns of Table 3 provide the estimates for these terms using the two specifications that exactly match the time and value share moments. They are evaluated at the solution for baseline conditions in 2005.[46] These results suggest that the selection of a preference specification has its primary effects on the properties of the function describing the marginal WTP for q. Nonetheless, in a general equilibrium context we can expect spillover effects on market goods closely related to environmental services. In our case G is the exclusive source for the pollution emissions that are the basis for changes in environmental quality, q. The symbol x in Table 3 corresponds to market goods (G). Both the level of x using the calibrated values for the model parameters for the baseline solution (with each preference specification and value share) and the contribution of price changes to the second-order expansion are largely insensitive to the selection of a preference specification or to the size of the q share used in calibration. This result was expected because our specifications focus on changing how environmental quality contributes to well-being—either through the home production of services or through the use of leisure time. The top level of the preference function does not change the role assumed for G. It is a part of the consumption aggregate. The price effects of productivity changes or, in the case of G, productivity and the costs of new rules can be partially offset through substitution of market or home-produced services.

In the case of environmental quality changes, decisions about the form of the preference specification are not as important as the relative size of the q-share parameter. Comparing the coefficients for the quadratic term in the WTP approximation for changes in environmental quality (i.e., $(b_q - bb_m)$) computed for the preference specifications with q in home production versus q in the leisure subfunction, we see the effects of quality changes are similar in the two cases.

When we consider these same effects for the low-share and high-share calibrations, the differences are dramatic. The term for the second-order effect of q changes is four and one-half times larger in absolute magnitude with the high share calibration using the home-production specification. Environmental quality changes are over five times larger with the leisure subfunction specification. The differences in the cross-product effects of q and the price of G, comparing the low and high share cases, are also large but somewhat smaller under the leisure subfunction specification than under the home-production specification. We find each preference specification leads to about the same values for marginal WTP (b) regardless of the size of the q share used in calibration.

Finally, the overall contribution of the second-order terms will depend on the size of the quality and price changes. Our two examples compute these changes using simplified versions of each proposed policy analysis to compute a change in the term for the emission rate embedded in μ The final estimated value for q with each policy is a general equilibrium solution of the model. As we noted, the price change for G reflects the assumed productivity advance as well as the adjustment imposed on the 2005 value for the production coefficient to introduce the costs estimated to be associated with each policy. To see how these differences affect our measures of the importance of the preference specification and the general equilibrium effects, we now turn to the policy examples.

6. Policy Examples

Our examples involve two different policy analyses associated with air pollution that are distinguished by their implications for the magnitude of the change in emissions and costs. We introduce the costs of policies by altering the productivity parameters associated with the aggregate for market goods. Greater

[46] There are some important details in implementing this logic. Our definitions of the coefficients were in terms of a general indirect utility function. Our adaptation and extensions to the Rogerson model use direct utility functions. So to compute the partial derivatives associated with these indexes, we are using numerical approximations and evaluate them using the values of the arguments that correspond to the baseline solution for each preference specification and q-share value. This same process is repeated for the cases where these indexes are evaluated for each of the two policies.

Table 3

Coefficients of the Second-Order Willingness to Pay Approximation for Policy Examples

	Baseline Solution		Clean Power Plan		Second Prospective Analysis	
Computed Parameter	Low Share Calibration	High Share Calibration	Low Share Calibration	High Share Calibration	Low Share Calibration	High Share Calibration
Home Production Subfunction, Two Subsistence Parameters						
b	0.9356	3.7309	0.8942	3.5871	0.5200	2.2249
x	0.2693	0.2693	0.2646	0.2660	0.2559	0.2733
$b_q - bb_m$	–17.5154	–73.7371	–15.7629	–67.2846	–4.3647	–21.9025
$x_p + xx_m$	–0.4620	–0.4435	–0.4371	–0.4214	–0.3743	–0.3828
$b_p + xb_m$	0.0237	0.1337	0.0223	0.1271	0.0125	0.0824
Leisure Subfunction, Two Subsistence Parameters						
b	0.9356	3.7308	0.8876	3.5139	0.4626	1.6736
x	0.2693	0.2693	0.2641	0.2641	0.2493	0.2491
$b_q - bb_m$	–20.7342	–105.7920	–18.4854	–93.6200	–4.4743	–20.6572
$x_p + xx_m$	–0.4670	–0.4669	–0.4410	–0.4410	–0.3689	–0.3686
$b_p + xb_m$	0.2528	1.1467	0.2352	1.0592	0.1158	0.4757

Note: $w(1) \approx b(q_1 - q_0) - x(p_1 - p_0) + \frac{1}{2}(b_q - bb_m)(q_1 - q_0)^2 - \frac{1}{2}(x_p + xx_m)(p_1 - p_0)^2 + (b_p + xb_m)(q_1 - q_0)(p_1 - p_0).$

time requirements to produce the market goods imply increased costs. We convert the costs to a percentage change over an estimate of operating costs and use this percentage to adjust the production coefficient. The impact of each policy on environmental quality is introduced through the specification of the μ term that creates the link between market goods (G), emissions, and environmental quality.

The first example is the original version of the Clean Power Plan (CPP). While it does not appear likely to be implemented in the near future, what is relevant for our purposes is using it as an example for the set of adjustments required to adapt the information in a typical regulatory impact analysis (RIA) to evaluate the potential for economy-wide effects.

Some context for the CPP helps in understanding the adjustments we made in framing the estimates for analysis. In August 2015, the EPA released the final RIA for the plan (see U.S. Environmental Protection Agency 2015b). The analysis assumes that the compliance period begins seven years after the final rule is issued (in 2022). By 2030, the analysis estimates that there would be about an 18.5% reduction in CO_2 emissions from the estimated emissions without the plan. A variety of options were provided to states. The EPA analysis estimates the best system of emission reductions as performance rates for fossil-fueled electric generating units as well as for natural gas combined cycle units. Based on each state's power plants in 2012, a separate goal was developed for each state measured as a mass (tons of CO_2 derived translating performance rates with each state's mix of allowed electric generating capacity to a total level of CO_2 emissions reduced) or a rate (a weighted average of emission performance rates in terms of pounds of CO_2 emissions per net megawatt hours of electricity generated).[47]

To implement our strategy, this array of information must be distilled to yield two specific adjustments to our model. First, we need the implied reduction in the ancillary pollution in a form that matches our model. This task means SO_2, NO_x, and PM2.5 must be expressed as PM10 equivalents. Second, we need a simple estimate for the compliance cost of the rule. Thus, we are drastically reducing the complexity present in the full details of the rule. Since our objective is to provide an example, the results should not be considered an evaluation of the properties of the benefit estimates reported in the RIA. A

[47] Examples for how the rules could allow for trading systems or technology-based standards as part of the implementation process were described as part of the information describing options available to states for responding to the plan.

more detailed treatment of the distinctions between the separate air pollutants would be needed to develop this type of assessment. Of course, it is also important to acknowledge that any evaluation of economy-wide effects conducted on the time scale required for most RIAs would also need to simplify the details of a rule. When the modeling of the economy is kept as simple as possible, these assumptions largely amount to changes in the weighted averages of the impacts of different terms entering preferences, productivity coefficients, and diffusion parameters. As a result, they can be subjected to sensitivity analyses in straightforward ways.[48]

When full compliance is assumed to be reached, the RIA estimates the annualized cost increase to be 2.5% to 4% (see tables 3.8 and 3.9 in U.S. Environmental Protection Agency 2015b). These cost increases are for the electric generating sector, a small subset of the complete industrial sector in the economy. Compliance costs are estimated as increments to the total costs of generating power under baseline conditions (i.e., first row of table 3.9). These modeled costs include assumptions about the performance of energy efficiency programs in each state. The cost estimates also assume a compliance schedule with the effects of these demand-side energy efficiency programs on electricity demands treated as exogenous influences on the model's estimates of the effects of the proposed rules on compliance costs.[49] We cannot remove the effects of these types of assumptions on the incremental cost estimates or evaluate the sensitivity of results to changes in them. We use the estimated percentage increase over the base generating costs in 2030 for the mass- and rate-based programs and apply them as if the effects were realized in a single year for the manufacturing sector as a whole. Table B1 in Appendix B reports the results for an alternative treatment of the control costs. In this analysis we focus on impact in the electricity sector and adjust the effects for the industrial or manufacturing sector. Since electricity generation is a small component of the industrial sector, we used the fact that it was 4.5% of the nonservice output and reduced the cost increase to 0.15%. We retained the same reduction in air pollution.[50]

In our model all of the emissions arise from the industrial sector. For the example we present in the text we assume the full cost increments associated with the proposed regulations are imposed on this sector. This overstates the general equilibrium impacts of the rule. As we noted, electric generation is a small fraction of the overall industrial sector in the U.S. economy. As a result, we know at the outset that our primary analysis of the policy provides an upper bound on the general equilibrium effects. Nonetheless, interpreting the policy in this way, along with our brief comparison with an alternative implementation, serves to illustrate the decisions that need to be made when adapting the information in typical RIAs to fit a simple model. The process forces consideration of how the information is "connected" to the model and what those judgments imply for interpreting the model's results.

The discussion in the RIA primarily considers reductions in SO_2 and NO_x. In the EPA analysis the reductions in particulate matter were computed outside the integrated planning model used to estimate the other emission reductions. This difference is important for two reasons. First, most of the health benefits arise from reductions of particulate matter. The regulation's effects on PM2.5 are primarily indirect in that atmospheric concentrations of SO_2 and NO_x contribute to the formation of PM2.5. The RIA develops these measures using the Benefits Mapping and Analysis Program, Community Edition (BenMAP-CE) (see Abt Associates 2012). The analysis uses a benefit-per-ton emission reduction to develop the health benefits. This shorthand reduces the detailed atmospheric modeling that would be required for a full assessment to one that is based on unit values per ton of emissions of PM2.5 or its precursors SO_2 and NO_x. While the specific analysis in the RIA was done at a

[48] Indeed, meta-regression summaries of these types of sensitivity analyses could easily be developed.

[49] The EPA (U.S. Environmental Protection Agency 2015b) estimated that 90% of the costs of the state-specific programs are paid through electricity surcharges.

[50] We are grateful to an anonymous reviewer for suggesting this alternative interpretation of the CPP policy.

disaggregate level, only the overall estimates for ancillary benefits are provided in the supporting documents.[51]

When the annual benefits due to health effects in 2030 are converted to 2005 dollars, they range from \$12.1 to \$29.4 billion. To match them to our model we use a weighted average of Fann, Fulcher, and Hubbell's (2009) measures for the values of a ton reduction in the emissions of SO_2 and NO_x from electric generating units. These values arise from the effects of each pollutant on the associated levels of PM2.5. With these estimates, we can recover an estimate for the "equivalent" reduction in PM10. That is, this reduction in PM10 would yield the same benefits as that associated with reductions in SO_2 and NO_x, which are the source of the contributions to reduced particulate matter. Table B2 in Appendix B summarizes the elements for the inputs to our analysis of the CPP. We selected the 4% cost increase and a 2.5% reduction in PM10 to characterize the effects of the plan as if full compliance occurred in a single year—our last year 2005.

As we noted, the numerical values for the derivatives of *b* and *x*, computed using solutions for each of our amended versions of Rogerson's model, will vary as the equilibrium values for *G*, *S*, *N*, and *q* change.[52] The third and fourth columns of Table 3 compare the coefficients for our indexes of the effects of change in environmental quality and the price of *G* on WTP. They are summarized for each preference specification and *q*-share. In general, the overall magnitudes (in absolute value) of the coefficients for the second-order terms are smaller when compared with the values computed for the baseline solution. Nonetheless, the judgments about the importance of quality or price effects remain largely the same with the CPP example. Changes in quality make the largest (in absolute magnitude) contribution to WTP. Both preference specifications and *q*-share values are consistent with this conclusion.

To place these computed sources of influence on WTP in perspective, we also need to consider the model's implied changes in environmental quality and the price of *G*. The general equilibrium change $(q_1 - q_0)$ in *q* with the CPP is about 0.0027 and the price change $(p_1 - p_0)$ for *G* is 0.0100. The last part of our findings is a summary of how our proposed index would rate the economy-wide effects of our stylized version of the CPP. The first two columns of Table 4 provide our results. The first row of the table reports our overall index with each preference specification. As expected, the economy-wide or general equilibrium shadow value for *q* is less than the partial equilibrium value implied by the baseline calibration of each model. The results imply a 4% to 6% difference between the partial and general equilibrium marginal values, regardless of whether we introduced *q* as making a nonseparable contribution to the household service subfunction or to the subfunction involving leisure. Moreover, the value share for *q* does not have a large effect on these conclusions.

The first and most obvious explanation for these small effects with the CPP is that the cost increases are small and the substitution elasticities implied by each calibration provide signals that these cost effects would be muted through household adjustments. When *q* enters the household service subfunction, both calibrations imply about the same substitution elasticities, $\sigma_{Nq} = 1.4$. The elasticities implied for the case of *q* entering the leisure subfunction do differ somewhat with the size of the *q* share. With this specification (in the last two columns of Table 2), there is a smaller substitution elasticity implied with the larger *q* share and, not surprisingly, larger discrep-

[51] There is no information on the implied values for the estimated reductions in PM2.5 concentrations due to reduced levels of SO_2 and NO_x in the atmosphere. Our model is based on PM10 not PM2.5. An approximate link between PM2.5 and PM10 is used to adjust the results: PM2.5 = 0.55 × PM10. The distributions for PM10, measures of extreme values of PM10, and the distributions for PM2.5 change in different ways with each rule. This approximation does not adequately reflect these changes. It does reflect that any change in the modeling strategies used to gauge economy-wide effects will impose new data needs. The current partial equilibrium analysts for large rules develop this type of information for important subregions. When small general equilibrium models are used in these types of sensitive analyses, it would be possible to identify the associated data needs at an early stage in the RIA development process.

[52] Once the time allocations for these goods and services are determined, leisure is a residual implied by those allocations. The marginal value of leisure will affect the trade-offs contributing to each equilibrium solution.

Table 4
Decomposition of Indexes for General Equilibrium Effects

Policy	Clean Power Plan Low Share Calibration	Clean Power Plan High Share Calibration	Second Prospective Analysis Low Share Calibration	Second Prospective Analysis High Share Calibration
Home Production Subfunction, Two Subsistence Parameters				
Total general equilibrium index	1.0463	1.0401	1.7991	1.6768
Turn off price changes	1.0444	1.0385	1.7847	1.6648
Turn off q changes	1.0018	1.0015	1.0078	1.0065
Leisure Subfunction, Two Subsistence Parameters				
Total general equilibrium index	1.0540	1.0617	2.0224	2.2293
Turn off price changes	1.0542	1.0620	2.0239	2.2312
Turn off q changes	0.9998	0.9998	0.9993	0.9992

ancies in the partial and general equilibrium shadow values. For the low q-share case, the partial equilibrium value is about 5% larger than the general equilibrium value. This discrepancy increases to 6% when the q share is larger. The substitution elasticity (σ_{Lq}) is 0.146, larger with the low q share.

The next two rows in each section of the table, distinguished by the preference specification, consider alternative ways of evaluating the effects of quality change versus price changes.[53] They compute the ratio of shadow values comparing the marginal rate of substitution for the baseline solution to the marginal rate of substitution postpolicy using the quality change alone and holding the baseline prices constant. This case is labeled as "turning off" the price change. To implement it we hold the value for quality at the new equilibrium value implied by the solution, allowing both to change as part of the general equilibrium. Since the prices are determined exogenously by the productivity assumption and the specified cost increase for the regulation, we can hold the price for G fixed at the value implied by just the productivity increase to 2005, and the economy is allowed to reoptimize. To maintain quality at the fixed level we remove the feedback effect between G and q. The representative household responds to the new quality without the cost effect of the regulation. As a result the values for the variables selected by the representative consumer will be different from those when both quality and price are changed.[54]

In the case of turning off the quality change, we hold quality at the baseline level and consider only the price changes. In this case only the price of G changes due to the policy (see note 54 for qualifications). Once again the feedback effect is "turned off" to assure quality remains at the baseline level. This case indicates that the quality change is the dominant determinant of general equilibrium effects, and its importance increases slightly with increases in the size of the q share used in calibration. That is comparing the value of our index for the total general equilibrium effect with that computed with quality "turned off," the ratio is 0.957 with the low share and the home-production specification and 0.963 with the high share. These ratios are 0.949 and 0.942 for the case of the leisure subfunction with low and high value shares suggesting more comparability between total general equilibrium and the quality-turned-off cases, but these effects are small.

Appendix B reports the values for our index using the smaller cost increase and the

[53] Thanks are due an anonymous referee for suggesting this approach and for providing R code to illustrate it.

[54] There are several possible strategies for implementing this thought experiment. When environmental quality changes, the marginal rate of substitution for goods and services would change (depending on the preference specification) even though there is no price effect. A similar comment applies in the case of the price-only change, because quality must change on the level of consumption of change. In our examples we turned off the feedback effect. Introducing it for one or both of these cases would offer slightly different results, because the levels of variables determined as part of the equilibrium would be affected by how the feedback effect is included.

same effect on air quality. Our conclusions about the general equilibrium effects are a bit smaller—2% to 4%—and all of the difference is attributed to the feedback effects on realized environmental quality. Price effects play a small part in the difference. This finding reinforces our arguments about the importance of including nonmarket feedbacks in any framework used to evaluate the difference between partial and general equilibrium benefit measures. Overall then, the economy-wide effects of our stylized description for this policy would not be judged to have a large impact on the conventional methods used in developing benefit estimates for a BCA in this case.

Our second example uses the benefit estimates for 2010 presented in the Second Prospective Analysis. This benefit-cost study was a response to a requirement for periodic analyses of the performance of air quality regulations, which was part of the 1990 CAAA. We use the study's comparison of "current" (2010) conditions with the 1990 CAAA regulations in place to a counterfactual representing the air pollution conditions that might have been expected "without" the regulations. We use the population-weighted average of the changes in PM10 for New York, Chicago, Los Angeles, and Pittsburgh to approximate the "with" and "without" conditions.[55] This estimate implies a 55.3% reduction in PM10.

Our cost estimates for the program use the annualized cost estimate derived in the CGE analysis along with the annual operating costs plus an estimate of annualized capital costs from the 2010 Annual Survey of Manufacturers. In 2006 dollars these abatement costs were approximately 1% of our estimate of the total costs. Assuming they were experienced each year for 20 years implies that our static comparison of the reduction in emissions and associated costs would consider a 55.3% decrease in emissions that required an approximately 15% increase in costs.

The last two columns of Table 3 provide estimates for the coefficients of the second-order approximation evaluated using the general equilibrium solution with this policy example. All of the terms associated with environmental quality display large changes in absolute value, much larger than with the CPP. They confirm the importance of having these coefficients to separate preference effects from the policy impacts on judgments about the importance of general equilibrium feedbacks. The Second Prospective Analysis calls for a much larger change in environmental quality. With the diminishing marginal value of q, we should expect these large changes in both b and $b_q - bb_m$. The change in q in this case $(q_1 - q_0)$ was about 0.0524, 20 times larger than with the CPP, and the price effect $(p_1 - p_0)$ was about four times larger at 0.0444. The conclusions about the importance of environmental quality versus price effects on WTP are consistent across preference specification. Here we see that the magnitude of the general equilibrium effects attributed to this policy does depend on the q share used to calibrate the model.

The last two columns of Table 4 repeat the exercises in computing our index of the magnitude of the economy-wide effects for this case. The overall comparison of the partial equilibrium marginal values to the general equilibrium marginal rate of substitution implies partial equilibrium values that are 68% to 80% larger than the general equilibrium values, using the preference specification that includes q in the household-production subfunction. When q is assumed to be a part of the leisure subfunction, the difference is larger with the larger q share. Partial equilibrium marginal values are twice as large as the general equilibrium measures. The findings are similar for the low and high q-share calibrations, but the numerical magnitudes of the differences are larger. The decomposition analysis considering turning off price and quality effects is consistent with the CPP. The effects of the change in environmental quality are the dominant factor accounting for differences in the partial and general equilibrium benefit measures.

7. Discussion

Our proposed methodology is a first step in what, in our view, should be a more general

[55] These estimates are reported in terms of PM2.5. We used a simple conversion (PM2.5 = 0.55 × PM10) to approximate the implied change in PM10.

research agenda. Large regulations can impact multiple sectors. Over time households and firms will adapt through reorganizing their activities and moving. Indeed, the policies are intended to induce these responses. However, these adjustments, if large enough, will affect relative prices and incomes along with the measures for environmental quality. The net gains from the policy depend on all of these changes. As the Science Advisory Board's panel on the importance of economy-wide effects concluded, CGE modeling has not advanced to the point where it offers a practical basis for judgments about the importance of these other influences to net benefits within the time and resource constraints associated with most RIAs.[56] This situation is due in part to their complexity as well as to the absence of a clear connection to nonmarket activities in all of the major CGE models available today. Our framework considers a different strategy. We argue that an assessment of economy-wide effects begins with a simple, transparent model that allows parameters to be calibrated with readily available information. The model can be adapted to capture the effects of the reallocations that arise from general equilibrium changes in prices and incomes on measures of the benefits from environmental improvements. The issues in extending this macro-oriented approach for evaluating the importance of general equilibrium effects with environmental policies are more complex than with policies that exclusively impact the prices for marketed goods and services. While the marginal WTP functions are different across individuals in both cases, arbitrage can reduce the importance of the differences in these marginal values for small changes in the prices of marketed goods. Moreover, there are differences in the extent of the market, or the set of people who care about different types of environmental services that are not easily detected.

The first of these issues parallels the heterogeneity Wallenius and Prescott (2011) discussed in comparing aggregate and micro labor supply elasticities. The second does not. In the case of the extensive margin decisions underlying what is assumed about the people who would pay to improve environmental quality, there is not an unambiguous "signal" implied by people's observable behaviors that analysts can use to evaluate these decisions. The environmental services often have some public good attributes that make it difficult to exclude people from enjoying them. The extensive margin choices (i.e., such as to participate or not in a camping or fishing trip depending on environmental conditions) reveal information about use-related values, not the nonuse values for the improvements.

The second issue concerns the link between G and environmental quality. This equation is the mechanism that introduces policy into the model. We combined estimates of the emissions from production activities that are represented by G with an estimate of the average effect of atmospheric diffusion on PM10. There is no "geography" in our model.[57] There have been extensive efforts to include detailed analysis of spatial differences in the effects of emissions on ambient air quality. Baker et al. (2018) provide a recent comparison that documents large differences in how a sample of the current atmospheric diffusion models differ in their measure of the effects of reductions in emissions from sources. Three of the five models they compared included gridded county-level changes in annual PM2.5. These differences can lead to large differences in the geographic distribution of the benefits of policies. All of the models considered are reduced-form frameworks that use a partial equilibrium framework to measure benefits that does not allow for households to adjust.

The process of calibrating the three specifications for our models' parameters has also

[56] The Thorne-Wilcoxen (2017) letter identifies a number of issues with the current CGE models, noting that research is needed because, among other things, with current models " it can be difficult to map the detail of a proposed regulation into a set of appropriate inputs for a CGE model" (p. ii), and "although CGE models can be broadly suitable for the analysis of social costs, they have not achieved their potential for analysis of the benefits of air regulations" (p. iii).

[57] Espinosa and Smith's (1995) is the only large-scale CGE model that includes an air diffusion model and feedbacks as part of CGE solutions. They included a simple diffusion model to link emissions between the 11 economies represented in their adaptation of the Harrison-Rutherford-Wooten model. Carbone and Smith (2013) considered the effects of nonlinear functions linking emissions and services but did not consider the spatial effects in their analysis.

identified research issues that have not received attention in the literature on nonmarket valuation. There is an extensive literature estimating the marginal WTP and/or Marshallian and Hicksian consumer surplus measures for a representative individual (or household) for different types of changes in environmental services. However, there are a few efforts to develop monetary measures of the importance of "typical" changes in each amenity compared to comparable measures for the market economy. Muller's (2019) recent work is a notable exception. So for the most part we do not know what to expect for different types of environmental resources. Expanding our understanding of valuation measures developed in these terms would be important to practical implementation of our approach.

About 20 years ago, Costanza et al. (1997) estimated the value of Earth's current set of natural and environmental resources. The study was widely criticized due to the objective of the exercise: the value of Earth's resources compared to an earth with no resources. However, what has been overlooked is the basic question of how monetary measures for the values for air and water quality improvements compare to the value of other improvements in marketed goods and services that have taken place over the same time scale. What is their relative magnitude in comparison to other indicators of economic performance with marketed goods? As we noted, Muller's (2019) estimates would suggest the reductions in particulate matter alone from the 1950s to 2016 would dramatically increase an assessment of the growth. His measure of aggregate output (real GDP less the economic loss due to particulate matter) tripled over this period, while real GDP without adjustment doubled. Finally, we might ask whether additional moments including nonmarket benefit measures should be included in the calibration process. It could be considered a way to introduce geography indirectly by allowing the differences in benefit estimates at different locations to calibrate the transfer coefficients.

All of these questions seem to have been overlooked in the literature on nonmarket valuation. An important reason for the oversight stems from the focus on measures of trade-offs at an individual level that do not recognize the distinction highlighted by Wallenius and Prescottt (2011) in the macro context for labor supply discrepancies. The comparisons have focused on estimating trade-offs for different types of agents—old versus young or users versus nonusers. They do not consider situations where a representative agent is used as a macro construct. In this case the preference specification is reflecting both the diversity of individual trade-offs for different types of people as well as the extent of the market. For most macro models, the market provides a direct definition for importance of the extent of the market through aggregate shares of output for classes of goods and services. It does not require analysts to deal with how the diversity in micro trade-offs is related to the extensive margin decisions that define the realized extent of the market. In the case of the labor-leisure choice, which Wallenius and Prescott acknowledge was central to the growth model's ability to account for cycles, the challenges parallel some of what we face in representing the economy-wide effects of environmental rules. To resolve the issues arising because of the differences in micro labor supply elasticities with those attributed to the aggregate representative agent, the original work by Kydland and Prescott (1982) focused on time allocation for nonmarket housework. As time allocation data have become more available, they have played an increasingly important role in the more recent macro modeling we cited. Our extension to the Rogerson model follows this logic and adds the concept of a share to combine micro trade-off measures with a specification for the extent of the market. It is unrealistic to expect a "one-size-fits-all" general equilibrium model for the economic and ambient environmental system will be developed to accommodate all air and water policies in the near future.[58] The analysis must be designed to fit the policy questions that are relevant to specific regulations. Our model illustrates how this might be done.

[58] Indeed one might argue that experience with simple Rogerson-style general equilibrium models should come first to gain experience with the assumptions that affect feedbacks and the nonmarket general equilibrium process.

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