Reflections—In Search of Crosswalks between Macroeconomics and Environmental Economics

V. Kerry Smith*

Introduction

It is hard to miss the interactions between macroeconomic conditions and environmental rules in current debates over regulatory policy. President Obama's decision in September 2011 to abandon tightening the ozone rule and the recent U.S. Office of Management and Budget request (posted March 2012) for comments on how federal agencies should assess the impacts of proposed and final regulations on employment are just two examples that illustrate this point. Expecting these debates to intensify as the presidential election approached, Edward Prescott and I organized a conference in the spring of 2011 on macroeconomics and the environment.[1] Our objective was to explore research opportunities at the intersection of these two fields. Most of this *Reflections* column describes what I learned from preparing for that conference and the research interactions during it.

There is a common strategy used in much of macroeconomic research. The typical macro paper motivates its proposed analysis by assembling specific data to support a set of assumptions or by providing a summary of commonly accepted beliefs about the state of the economy. This information is often described as the *stylized facts* characterizing the background conditions that influence the problem being investigated. These stylized facts are used in a variety of ways. When the facts are derived from data, models are calibrated to reproduce them. When

*I owe thanks to a large number of people for suggestions and comments, including Ujjayant Chakravorty, William Harbaugh, Bryan Hubbell, William Jaeger, Nicolai Kuminoff, Arik Levinson, Claire Montgomery, Ed Prescott, Randy Rosenberger, Todd Schoellman, and Kent Zhao. Matt Kahn also provided a careful and very constructive review of an earlier draft. Suzy Leonard always makes my writing better than I thought it could ever be. None of these people are responsible for any of my errors or interpretations. Special thanks to Carlos Valcarcel Wolloh, who assembled most of the information and developed the code that assured all the analysis of aggregate trends in air quality could be completed. Jesse Snook and Michael Kaminsky also helped at earlier stages in the analysis and Natalie Cardita prepared many drafts of this paper. Partial support for this research was provided by the Sloan Foundation and the W. P. Carey School of Business.

[1]Support for this conference was provided by the W. P. Carey School of Business, the Center for the Advanced Study in Economic Efficiency, the Sloan Foundation, the Decision Center for a Desert City and the Center for Environmental Economics and Sustainability Policy. See www.wpcarey.asu.edu/ceesp for the conference agenda.

Review of Environmental Economics and Policy, volume 6, issue 2, summer 2012, pp. 298–317
doi:10.1093/reep/res009

research ideas comprising the stylized facts are derived from a set of past theoretical or empirical findings, this consensus of views reflects the attributes that any new model is expected to reproduce before it is considered "relevant". Using these basic principles to define and usually to calibrate new models, the next step evaluates policy interventions within the resulting models, with the policy assessment based on its ability to alter undesirable outcomes. This policy analysis is conducted within a general equilibrium setting that can be linked to a description of the economy *before* any intervention is introduced. This template is intended to document the relevance of the analysis and establish the likelihood that the policy will accomplish the intended goals.

One way to develop a "crosswalk" between macroeconomics and environmental economics is to consider whether this research strategy could be applied in evaluating large-scale environmental policies. With this in mind, the next section develops the concept of *stylized facts* further and then explores whether such facts can be found in what environmental economics has to say about the aggregate economy. My starting point for this discussion is the Environmental Kuznets Curve.

The third section discusses efforts by the Environmental Protection Agency (EPA) to assess the net benefits of large-scale regulatory programs. The Second Prospective Study (EPA 2011), released in March 2011, is the first major benefit-cost assessment to include a general equilibrium analysis. Thus, it begins the process of considering how economic analysis should evaluate the aggregate impacts of new rules. The report includes both partial and general equilibrium analyses of the net benefits of the 1990 Clean Air Act Amendments.[2] This analysis and the OMB request for comments noted earlier both confirm the need to re-think the conventional practices used in benefit-cost analyses and consider how each new set of rules fits within the larger context of pre-existing regulations.

The concluding section reiterates some of the observations made by Tom Tietenberg (2011) in his recent *Reflections* column. That is, we learn in different ways, and the best ideas often come from being open to suggestions from outside the "comfort zone" of familiar research methods. His arguments are relevant to efforts to use insights from other disciplines as well as to draw on neighboring fields within our own discipline. Thus, one of the main implications of both of these *Reflections* columns is that "crosswalks" between the fields of macroeconomics and environmental economics run both ways and are likely to have high payoffs for both fields.

Stylized Facts

The starting point for my discussion of "stylized facts" is Nicholas Kaldor (1961), who fifty years ago summarized what had been learned from analyses of twentieth century patterns of economic growth and their implications for developed economies. His stylized facts crystallized the research findings of a generation, and proved to be important beyond their role as a synthesis of what had been learned from past research. He observed, among other things, that labor productivity has grown at a sustained rate; the amount of capital used per worker

[2]The two analyses are developed with completely different economic models. The general equilibrium analysis of the Clean Air Act is in chapter 8 of U.S. EPA (2011). The results for costs only are presented in Table 8-7 and the results for costs plus "beneficial" effects of improved air quality are presented in Table 8-8.

has also consistently grown; the shares of national income going to capital and labor have been stable; the real return to capital has been stable; the ratio of capital to output has also been stable; and the growth rates among rapidly growing economies have exhibited appreciable variation. In the years following publication of his paper, these stylized facts served to condition the design, "estimation", and use of a wide range of subsequent macro models. This influence can be seen in a number of ways. For example, these stylized facts have supported the use of aggregate production relationships, such as the Cobb-Douglas specification, in macro-models.

Kaldor's approach also influenced the design of subsequent research programs by encouraging reviews of past research to emphasize the areas where there is some consensus among the ideas being developed in a field. Kaldor expected scientific progress, and implicitly assumed that debates from paper to paper or seminar to seminar would ultimately lead to consensus among researchers in a field.[3] To see how Kaldor's approach for synthesizing research has been influential I discuss an example from the macro literature and then consider how we might use the strategy of developing stylized facts to re-examine some issues from applied research in environmental economics.

Macro Context

To set the stage for this discussion, it is important to recognize that although macro analyses of regulations were part of the economic analysis during the early stages of using economics to evaluate environmental rules, macro analyses gradually disappeared from agency assessments. There are likely several reasons for this shift. First, macro assessments did not have a clear place in the benefit-cost framework developed in response to President Reagan's Executive Order 12291. This order issued, in 1981, mandated benefit-cost analyses for new major rules. In addition, they had been based on models that were discredited by the Lucas Critique. Research by Lucas (1972) and Kydland and Prescott (1977) implied that relationships like aggregate consumption or investment functions were not policy invariant. Thus, without additional information, the underlying structure of the models could not be identified. As Prescott (2004) notes in his Nobel lecture:

> "Preferences and technology are policy invariant . . . With the general equilibrium approach, empirical knowledge is organized around preferences and technology, in sharp contrast to the systems -of- equations approach, which organizes knowledge about equations that specify the behavior of aggregations of households or firms." (p. 373).

His essay outlines the "steps" in a new approach to macro models that now characterizes much of macroeconomic research. The first few steps in this approach illustrate why Kaldor's (1961) stylized facts were important to the macroeconomics literature. Under this new approach, the analyst begins with the specifications for preferences, production, and the equations governing resource allocation. Next, the available data need to be reconciled with this theory. Here the structural models are not matched to the national accounts. Rather, the statistics in the accounts are adapted to match the economic features important to the general equilibrium

[3]This is the way that Jones and Romer (2009) described some of the important features of the strategy Kaldor initiated and they used it to propose their updates to his stylized facts.

model used for describing the economy. This means that the model is calibrated to be consistent with what are taken to be the "facts" describing the economy.

I focus here on two aspects of this research strategy: (a) the use of established "facts", regardless of whether they are empirical findings or features of a model that are widely accepted, and (b) the evaluation of the model as an integrated process for scientific inference. This second task requires that the macro model reproduce, at some level of resolution, outcomes that are actually observed from an economy before it can be considered as a plausible basis for evaluating what would be accomplished by new policies.

To illustrate how this process works, consider an example from a recent article by Rogerson (2008), which is part of the broader literature seeking to understand structural transformations in developed economies. Rogerson examines hours worked in continental Europe and the U.S. between 1956 and 2003.[4] His stylized facts relate to the finding that the hours worked in Europe declined by nearly 45 percent compared to the hours worked in the U.S. He uses a static, two-sector, general equilibrium model with non-homothetic preferences and uneven rates of productivity increases. The productivity and tax rate differences between the U.S. and Europe are considered as potential sources of the differences in the hours worked and the size of the service sectors in these two economic systems that might otherwise be considered comparable.

Rogerson's model has eleven parameters, and he calibrates it in two steps. First, he sets values for several parameters based on the findings from past research. For example, the levels of productivity in U.S. goods and service sectors and tax rates at the beginning and ending years in the period are set to empirical estimates that are developed from the available data. The remaining parameters are determined by the three equations derived from the conditions for consumer optimization, market clearing, and balancing the government budget constraint. These conditions are assumed to hold in each of two years. Thus, this process allows six parameters to be recovered from these equations, which describe features of the equilibrium in each of two periods. With this calibrated model for the U.S. economy, Rogerson then asks whether differences in taxes and productivity rates could lead to the different pattern of hours worked and expenditures on market-provided household services in Europe. Thus, the fundamentals—preferences and production—remain fixed based on the U.S. experience, and the analysis considers whether this structure could have led to different outcomes based on the policy choices made in Europe.

Could we use this type of research strategy to evaluate the macroeconomic impacts of environmental policy? The answer is not obvious. Environmental policies are very detailed and those details matter. However, there are a wide range of important *general* questions that can be overlooked if the analysis is always done "in the trenches". For example, are there broad tendencies in the way developed economies degrade or enhance environmental services? Do our policies improve the overall quality of life experienced by a representative person?

[4]The questions associated with structural transformations, productivity differentials, and their implications for the composition of an economy have parallels in the early literature of environmental economics. Krutilla's (1967) famous article, credited with calling attention to existence values and the special problems in evaluating preservation versus development decisions, argues that one reason for paying special attention to irreversible changes in natural environments is the asymmetric effects of technological change. That is, productivity advance reduces the unit costs of acquiring manufactured goods compared to the services of unique natural environments. The later are in fixed supply. This same differential effect of technical change on amenity services versus produced goods also parallels Baumol's (1967) work, which Rogerson (2008) cites.

Environmental Stylized Facts

One way to answer these types of questions would be to follow the macro research strategy just described. To do this we need to agree on the empirical facts that describe how environmental quality contributes to the economy and people's well being. At first, this task probably doesn't seem difficult. We all agree that poor environmental quality has a negative effect on a population's health and that, all else equal, people want to live in areas with high levels of environmental quality. Making the transition from these general facts to a description of how demands for environmental services change with the overall level of economic activity is not as clear. These empirical facts are harder to come by. The Environmental Kuznets Curve (EKC) would likely be where many economists would begin their efforts to frame the relationship between the level of development achieved in an economy and the corresponding level of environmental quality. Introduced more than twenty years ago by Grossman and Krueger (1991), the EKC has stimulated a wide array of empirical and theoretical research. The EKC is motivated by reversing the question. It asks whether economic growth must lead to continuous deterioration in environmental quality. These authors observe that environmental quality does *not* continuously deteriorate with economic growth. Rather, there is an initial phase of deterioration followed by a phase of improvement, resulting in an inverted U-shaped curve. Grossman and Krueger's empirical findings have led to a great deal of "storytelling". That is, the literature is filled with loose explanations of an economic process combined with a large number of multivariate regression models from a large number of authors (see Carson (2010) for a review).

Two recent articles have attempted to provide an analytical foundation for the EKC. Smulders et al. (2010) presents a growth model with endogenous innovations and intra-sectoral changes in the patterns of economic activity. However, these authors assume that the EKC pattern arises from different policy regimes rather than as an endogenous outcome "created" by the features of the preferences and production relationships used to describe the economic structure. By contrast, Brock and Taylor (2010) provide a structural explanation derived from the joint effects of diminishing returns and differential technological progress in pollution abatement. In their model, emissions levels rise initially as growth overwhelms the impact of technological progress in abatement. Then, as economies approach their balanced growth path, the pace of growth slows and the increase in emissions also slows to the point where technological progress in abatement serves to reduce emission levels.

The key to the Brock and Taylor explanation lies in their assumption about the exogenous technological progress in abatement. This rate of innovation must exceed the growth rate in aggregate output. Thus, neither of the models developed in these two recent papers treats pollution control as a societal choice that is influenced by income levels. This is important because the explanation offered by Grossman and Krueger, as well as a number of authors describing different sets of empirical findings, explains the shape of the EKC using hypothesized features of society's preferences for environmental quality. Their argument suggests that as average income levels grow the population can "afford" the pollution abatement required for enhanced quality.

Thus, there is an important disconnect between the stories about the EKC and the models developed to reproduce it analytically. As Carson (2010) documents in his detailed review of the EKC literature, there is another problem confounding efforts to connect the empirical work to the preference based explanation. Most studies have used emissions to measure environmental quality rather than an index of ambient pollution. For conventional air pollutants (and stationary sources of pollution, like power plants) emissions are what come out of the smoke stacks. However, the air diffusion system is often complex and can create pollution effects far from the source of the emissions. Some authors of the formal models of the EKC have recognized this difference and embrace the use of emissions. For example, Brock and Taylor (2010) argue for the use of emissions measures because their model deals with CO2 and derives the EKC pattern as a technical outcome of the interplay of capital accumulation, balanced growth, and an exogenously assumed rate of technological progress in abatement. This argument implicitly assumes that societal choices about environmental quality are somehow responsible for the forces that cause the exogenously specified differential pace of progress in abatement technology.

In short, the Brock and Taylor (2010) approach provides us with a balanced growth model to display the EKC pattern, as long as we assume the abatement technology improves exogenously to the growth process itself. To support their model, Brock and Taylor use evidence for carbon emission rates to show empirical patterns consistent with what their model implies. This approach is not the same as the typical macro calibration. The latter would select values for some of the model's parameters (where there is broad agreement on their values) and use a separate set of variables, along with the conditions for consistent general equilibrium, to calibrate the rest of the model. Once that was done, the challenge would be to show that the model can reproduce EKC patterns as being the result of equilibrium choices that motivate the improvements in the abatement technology.

There are at least two reasons why the full model calibration approach has not taken hold in environmental economics. The first reason stems from the absence of a shared understanding of how environmental quality should contribute to the function used to describe the well being of households in the economy. These aggregate growth models assume all people can be represented using a single agent's preference function. When environmental quality has been included in these models, it is routinely assumed to make a separable contribution to well being. This means the contribution that consumption goods make to well being is not influenced by the level of environmental quality. Although we know this is not the case, the papers presenting this position argue that the interactions between consumption and environmental quality are not "first order effects," and thus their simplified structures can be used instead.

The second reason can be found in the modeling tactics used in non-market valuation. Environmental economists have relied on using consumer choices in the presence of varying levels of pollution across different locations to recover measures of the tradeoffs people make to enhance environmental quality. Beginning with a single aggregate measure of quality would ignore all of this variation. Equally important, unlike the situation for private goods with ideal markets, where we can assume people face the same prices, the differences in environmental conditions allowing these tradeoffs to be measured also imply that people experience different levels of quality. Each person may well have a different level of quality and a different marginal willingness to pay for increases in it. Under these conditions, the task of constructing a single aggregate to represent the diverse quality levels becomes more complex.

Illustrations of the implications of these oversights in the existing literature can be found in the two theoretical models underlying the EKC. The Smulders et al. (2010) model makes the assumption that environmental quality is separable. This setup makes it difficult to induce the pattern that Grossman and Krueger (1991) suggested would explain their estimates.

The Smulders et al. model "builds in" a set of exogenously determined incentives that would reproduce the EKC. This is accomplished by assuming an "alarm phase" for policy, whereby the government acts to reduce emissions when emissions reach a specified level. Thus, the Smulders et al. (2010) approach embodies the EKC hypothesis as a maintained assumption in the model. It is not the result of a structural attribute of household preferences responding, with income growth, to pollution. As noted earlier, Brock and Taylor (2010) reproduce the EKC through assumptions about the rate of technological change in abatement compared to a balanced growth path. As long as this rate of cost reduction to control pollution is high enough it can counteract output growth.

There is probably something of a chicken or egg problem here. We can't find discussions of the role of environmental quality in preferences for a representative agent because there have been so few attempts to use such models for the design or evaluation of aggregate environmental policy. If we consider static general equilibrium models, theoretical work also routinely treats environmental quality as making a separable contribution to preferences.[5] By contrast, most research in environmental economics focuses on specific dimensions of environmental quality and increasingly is concerned with characterizing heterogeneity in individual preferences. These studies are usually associated with a single resource or a spatially delineated amenity disconnected from the macro economy. The focus is on refining measurement methods so they consistently treat heterogeneity. Each refinement makes it harder to envision how these details could ever be captured in a manageable aggregate analysis where we could ask how concerns about environmental quality overall compare with growth in income and increasing levels of real consumption of material goods and services. Until we develop ways to address these questions in aggregate models, a discussion of the aggregate tradeoff will not be possible.

We might also ask how Grossman and Krueger developed their aggregate measures for environmental quality. In their empirical analysis, Grossman and Krueger (1991) used data for urban areas from the Global Environmental Monitoring System (GEMS), which reports summary statistics for cities. Their model uses the median values of readings in a year that are available at a specific location for particular air pollutants to measure the *country-wide* environmental pollution. Their empirical model then compares these measures to GDP per capita. For Grossman and Krueger (1991), the readings on air pollution within a city offer the basis for characterizing what the average person in a country experiences. Thus this strategy avoids addressing the key question—what is the relevant aggregate measure of environmental quality? *None of the other EKC studies addressed this question either.*[6]

The question of how to characterize environmental quality in empirical models is not an entirely new one. One research area that might be considered relevant to this issue is the effort to include the environment in the ratings of the quality of life (QOL) for different metropolitan areas (see Blomquist et al. 1988, Albouy 2008, and Bieri, Kuminoff, and Pope 2012). However, there are important differences between the objectives of the QOL research and the needs of a national environmental quality index. The QOL research seeks to consistently represent differences between regional levels of environmental quality as components of the non-market

[5]Jared Carbone and I found that if we relax this assumption, the pattern of substitution or complementarity between air pollution and leisure is quite important for the results (see Carbone and Smith 2008).
[6]Most studies used data on emissions of either the criteria air pollutants such as SO_2 and NO_x (List and Gallet 1999) or CO_2 (Aldy 2005). As Carson (2010) notes, concerns have been raised over the patchy nature of cross country data and the quality of the measures themselves.

services households receive when they live in a particular area. Other non-environmental services would include the crime level, the quality of public schools, the nature and reliability of public transportation, and so forth. To adequately gauge what is happening over time to all aspects of the market and non-market services contributing to the QOL (and the full cost of living in an area), we need an index at the aggregate level that reflects *both* the regional differences at a point in time and how these levels change over time. Thus, this research is similar to efforts to exploit the heterogeneity in environmental conditions to estimate the tradeoffs people make for improvements in specific features of environmental quality. In this case, the research assesses how much the spatial differences affect judgments about the economic value of living in one area versus another. A separate task would consider how to characterize the time trend in overall environmental quality across all these areas in a single composite index.

Trends in Aggregate Air Quality

Aggregate economic statistics are second nature to most of us. We hear reports of them on public radio or routinely see them on current events blogs as reporters attempt to describe how the economy is faring. Although we might not remember the precise definition of GDP or the consumer price index, most economics graduate students (and likely many undergraduates) could explain what each statistic is intended to describe. Turning to environmental indexes, there are many available but none of them is structured to serve the needs of a macro model of economic growth. In contrast to most macro papers, discussions in environmental economics about environmental quality tend to focus on spatial heterogeneity rather than aggregate trends over time. There are two notable exceptions. The first is Hayward's (1996) research since 1994, which focuses on leading environmental indicators.[7] The second is Chay and Greenstone (2005), which includes a description of the national trend in total suspended particulates (TSP) from 1969 to 1990 (based on county-level data) as part of a detailed assessment of the reliability of existing measures of the effects of particulate matter on housing values. This section considers the implications of developing national indexes for air quality trends. It is a "scoping" exercise aimed at gauging how we can develop these types of indexes and identifying next steps for research related to introducing environmental quality into modern macro models.

Data Collection Systems

In the United States we have extraordinary data on various air pollutant concentrations through a spatially delineated system of monitors. These data are aggregated in ways suited to evaluating compliance with the national air quality standards for each criteria pollutant. Under this

[7]Hayward (1996) reports trends in ambient concentrations as reported by EPA. Because his analysis relies on what EPA presents, Hayward's most recent Almanac (Hayward 2011) shifts from ambient concentrations of pollutants to the EPA Air Quality Index. This index was developed as a summary guide for the lay public to alert them of unhealthy conditions in any pollutant and is only available for recent years, starting in 1990. Since this paper was written, two recent papers from the MIT Joint Program on the Science and Policy of Global Change came to my attention. Matus et al. (2008) used average urban pollution levels in the U.S. to construct trends from 1970 to 2000 (see pages 77–78 and footnote number 5). Nam et al. (2010) used model results from the European Monitoring and Evaluation database for ozone and PM10 to construct trends for countries in Europe from 1980 to 2004.

system, an assessment that the national standard has been met in all locations is viewed as indicating that human health is protected. However, this analysis never considers the economic question—how does this protection affect people's well being when compared to the economic capacity to purchase market goods and services? This is the tradeoff that the EKC hypothesis seeks to describe.

Of course, a link between people and environmental quality is implicit in the design of the data collection system used to ensure that national ambient standards are met. However, even though monitors are generally located in urban areas, there is no attempt to design the sampling process to match a representative household's day-to-day pattern of exposure and overall experience with ambient air quality conditions. As a result, we never address the question of how these readings of air pollutant concentrations should be aggregated for assessing air quality conditions from the perspective of people's "consumption" of this important component of any overall index of environmental quality.

To illustrate this point I reproduce two figures from the latest EPA (2010) air quality trends report. Figure 1a compares averages of all monitoring stations in each year relative to the most current ambient standard.[8] Figure 1b considers, over a shorter time interval, the annual average across stations and the 98th percentile of the 24-hour concentration measures for small particulates, measured as PM 2.5. This analysis relates to the monitoring stations *not people*. Moreover, the data are reported in relative terms, with readings compared to the relevant standard for each pollutant in each year. Thus, the trend can change due to reductions in ambient conditions or changes in the standard. A measure of the pure trend is confined to the time spans during which the standard is constant (see the notes to Figure 1a).

Standards for Measuring Health Effects of Particulate Matter

Going further back in time is difficult. Chay and Greenstone (2005) provides an example. The standard for measuring the health effects of particulate matter was originally defined using TSP, but as research evolved it changed to focus on smaller particles. The standard was first changed to PM10 (particles less than 10 microns in size) and then to PM 2.5 in order to add a standard based on smaller particles (those less than 2.5 microns). The older measure, TSP, is no longer recorded and little effort has been made to provide a basis for bridging the records. Thus, the process of constructing the long term record for air pollution is not easy, even for a well-recognized pollutant like particulate matter. Figure 2 is the best a former student and I could come up with. We used available published sources, which required combining records from EPA, the World Bank, and the OECD.[9] In some years, TSP was converted to PM10 using a rule of thumb.[10] In the end, I was not confident that I could accurately describe and reproduce how all of these sources developed their respective annual summary measures. Most of the measures were averages across available readings in a given year. Clearly, we would like to know more about how the indexes were constructed in order to develop hypotheses about how

[8]Although it is not described in the report, this is the difference between the relevant annual average and the most recent standard as a percentage of that standard. When reviewing different pollutants two things change: the measure for the ambient concentration of each pollutant and the standard that is the benchmark for computing the percentage change in each year (based on discussion with EPA staff 9/26/2011).

[9]Thanks are due to Jesse Snook for his efforts in assembling all of this material. See the on-line supplementary materials for this article, at http://www.reep.oxfordjournals.org.

[10]The rule of thumb is PM10=.55*TSP, which is the same one used in Carbone and Smith (2008).

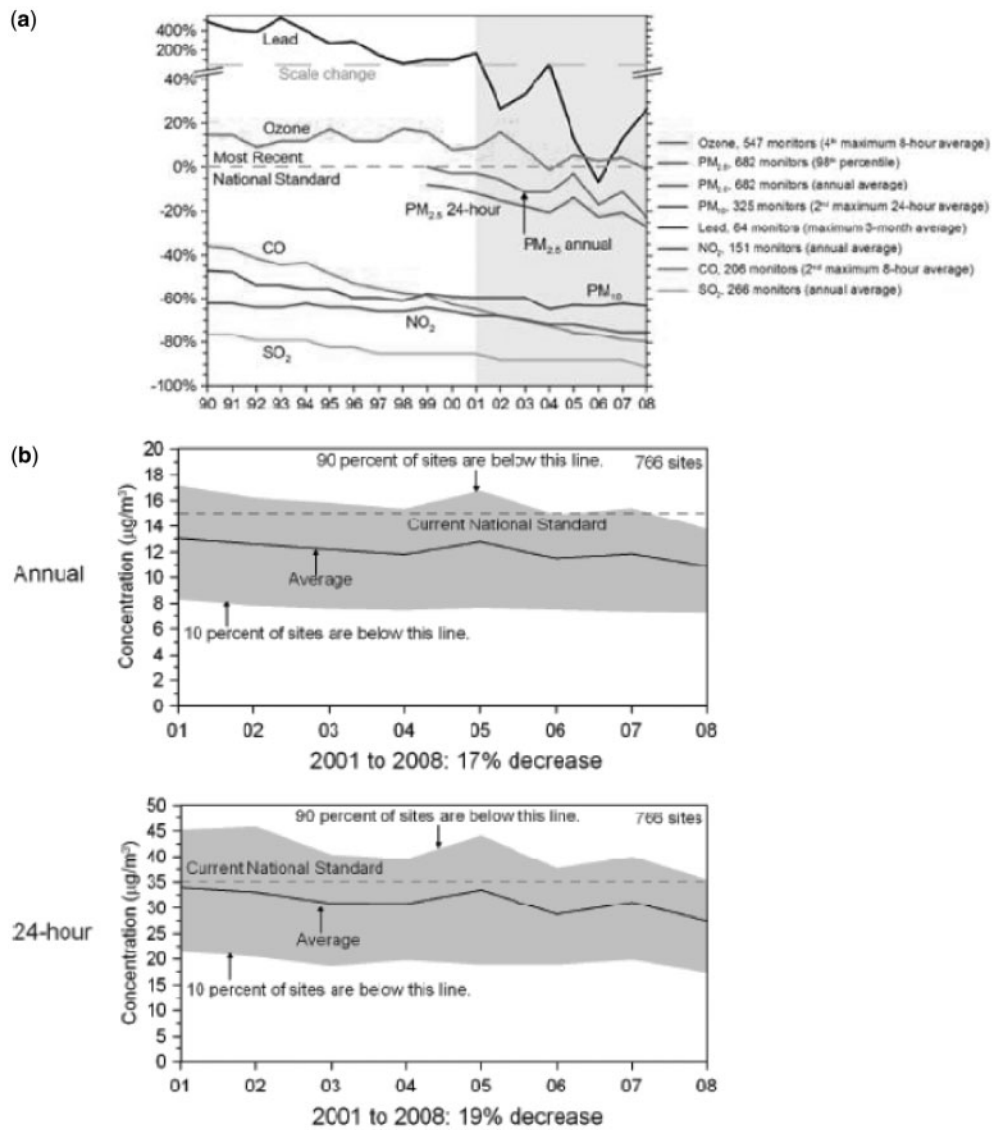

Figure 1 (a) EPA's Summary of Record for U.S. Criteria Air Pollutants and (b) Recent Trend in U.S. PM2.5
Source: U.S. Environmental Protection Agency, 2010, "Our Nation's Air; Status and Trends Through 2008," Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, EPA-454/R-09-002, February 2010.

aggregate economic conditions or policies have affected these patterns. For example, could we use these data to suggest that the downturn in air pollution in the early 1980s was due to a slowdown in economic conditions? Aggregate assessments of environmental quality appear to be in a position that is akin to the state of macroeconomics before publication of the Lucas Critique. That is, we are adapting our measures of air quality to fit data that have been assembled to meet regulatory objectives rather than adapting the data to meet the needs of a consistent economic model.

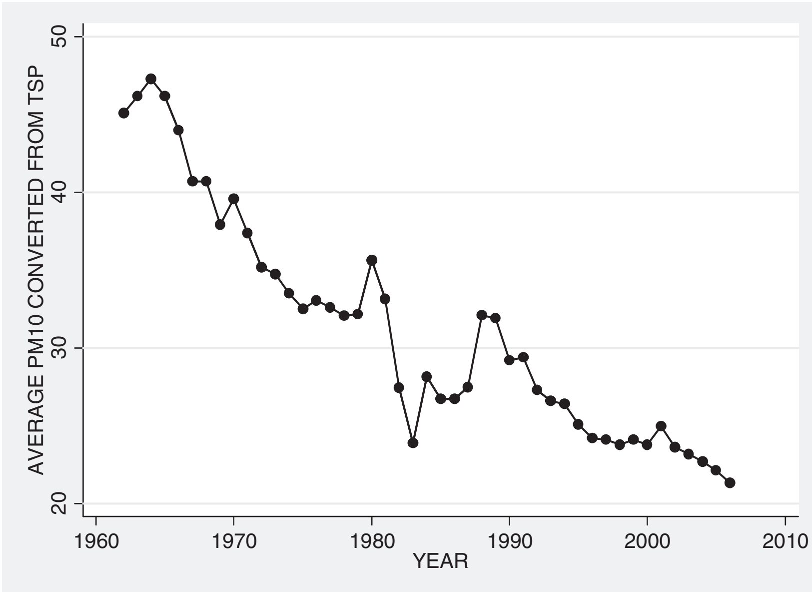

Figure 2 Historical Trend of PM10 in the United States Using a "Patchwork" of Data.
Notes: PM10 is measured in micrograms per cubic meter. A detailed description of the sources for the data underlying this figure is provided in the on-line supplementary materials.

Measuring Air Quality from a Macroeconomic Perspective

How might we go about measuring aggregate air quality from a macro perspective and would our assessments of trends be altered if we used different measures? To highlight the importance of answering this question, I present information on trends in particulate matter for the U.S. and a sample of European Union (EU) countries using various measures of aggregate air quality.[11] In this case, the analysis starts with information at the individual monitor level.

Measuring Particulate Matter Trends in the United States

Figure 3 presents U.S. trends in PM10 from 1990 to 2008 using four different indexes.[12] The first index, labeled "unweighted," is the simple mean of the average PM10 readings for each year based on assigning monitors to each of the Core Based Statistical Areas (CBSAs). The second index, labeled "weighted," uses the means from each CBSA and weights them according to the population in each area to develop an annual measure for the U.S. as a whole. The remaining two indexes are weighted in different ways. Each is motivated by a different aspect of the health effects of air pollution.

[11]Thanks are due Michael Kaminsky, Jesse Snook, and Carlos Valcarcel Wolloh for their assistance in developing this information.
[12]These data were developed for another project (see Evans, Smith and Snook 2011), whose objective was to evaluate how older adults respond to air pollution. Nonetheless, the records offer the basis for investigating potential aggregate air pollution measures. See the on-line supplementary materials for a description of the procedure used to calculate these measures.

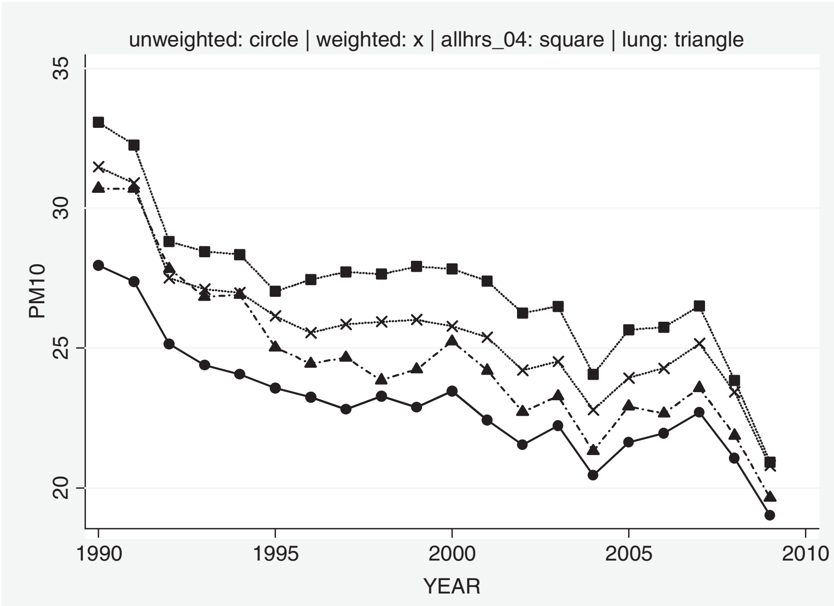

Figure 3 Trends in PM10 in the US; Role of Alternative Weights.
Notes: PM10 is measured in micrograms per cubic meter. A detailed description of the sources for the data underlying this figure is provided in the on-line supplementary materials.

Epidemiological research identifies older adults as one of the groups most sensitive to air pollution.[13] With this in mind, the first measure constructs a mean weighted by the locations of the Health and Retirement Survey (HRS) respondents in 2004. This index is intended to provide a "rough and ready" example of how we might judge air quality trends if we focused on a "sensitive group". It is based on a specific rhetorical question. That is, suppose we consider where the HRS sample was located in 2004 and use the distribution of these older respondents to weigh PM10 readings in each year. How would the trend be judged? We could also use the health attributes of the HRS respondents to consider, for example, those with self-identified serious lung conditions.[14] Thus, the fourth index constructs a mean that is weighted by the locations of the HRS respondents with these conditions in 2004, again assuming this distribution is held constant and weighted in each year by the proportion of respondents living near the values assigned to each CBSA. A more rigorous policy exercise would design the weights to ensure that a well-defined population is represented I did not use the HRS sampling weights because my objective here is simply illustrative.

The trends based on any of these weighting schemes suggest particulate matter has been declining over the entire study period. Looking at the 1990-2004 time period, the constructed national index for PM10 is lowest when we don't weight for population and highest when we

[13]For example, using the HRS sample, Evans and Smith (2005) found that older populations experience serious health effects from air pollution.
[14]The HRS health question asked whether a doctor had told the respondent he/she had a chronic lung disease. The response was limited to the wave used for the weighting of the sample. For this example I used the locations for the 2004 wave and the responses to the lung-related conditions in that year.

use a weighting scheme based on where the 2004 wave of the HRS respondents lived. Indeed, if we compare the effects of weighting on the measures of air quality between 1995 and 2005, the difference between the unweighted measure and the measure using the HRS weights is nearly as large as the improvement in PM10 between 1990 and 2008. Thus, it appears that weighting *can* matter. It also appears that the HRS respondents live in dirty locations, suggesting that even those with serious respiratory problems would experience conditions that would likely be misrepresented by the unweighted averages.

These differences in the effects of different weighting schemes for national trends in particulates suggest that the aggregate trend assessment might offer a different perspective on the distributional effects of air pollution policy, depending on which index and associated weights are used. Micro assessments of the distributional effects of environmental policies have found conflicting results, but these assessments are based on different outcome measures. For example, Banzhaf and Walsh (2008) find evidence that richer households avoid locations with higher levels of air pollution. Moreover, they find that poorer households migrate into these neighborhoods. By contrast, Bento et al. (2011) argue that price appreciation due to air quality improvements has been greatest around the dirtiest air quality monitors. They conclude that this finding implies that since poorer households tend to live near these dirty monitors, the gains from the Clean Air Act have been progressive. However, a time series perspective that tracks the air quality experienced by the same households might lead to different conclusions.

Measuring Particulate Matter Trends in Europe

The processes for regulating air pollution in Europe are quite different from those in the United States. A common strategy in macro-economic research is to compare different developed economies to illustrate how policy constraints affect economic outcomes.[15] Following this strategy, consider the air pollution (particulate matter) trends over time across different countries in the EU. Here I report three measures of the trends in PM10. The first is a simple average for the monitors in each country. The other two measures are intended to parallel the HRS analysis for the U.S. In this case the weights are based on panel data from the Survey of Health, Aging and Retirement in Europe (SHARE), a survey of older adults in Europe that is comparable to the HRS.[16]

Figures 4a through 4d present PM10 trends from 1995-2009 for France, Germany, Greece, and Spain, respectively.[17] Several interesting results emerge from these graphs. First, France and Germany have conditions that are comparable to those in the U.S., with both experiencing lower levels of PM10 around 2004-2005, and then an uptick, presumably reflecting accelerated economic activity up to 2007. After 2007, Germany experiences a decline in air pollution, while France would appear to have a net upward trend over the whole period. The ambient concentration of PM10 in France is about the same as the U.S. in the early part of the period (actually somewhat lower) and then increases by the close of the sample. These are the types of differences we might suggest could be due to different policy regimes or different economic conditions.

[15]This was the logic in the Rogerson (2008) example.
[16]See the on-line supplementary materials for details about the SHARE data.
[17]These countries were selected from among those participating in the SHARE survey.

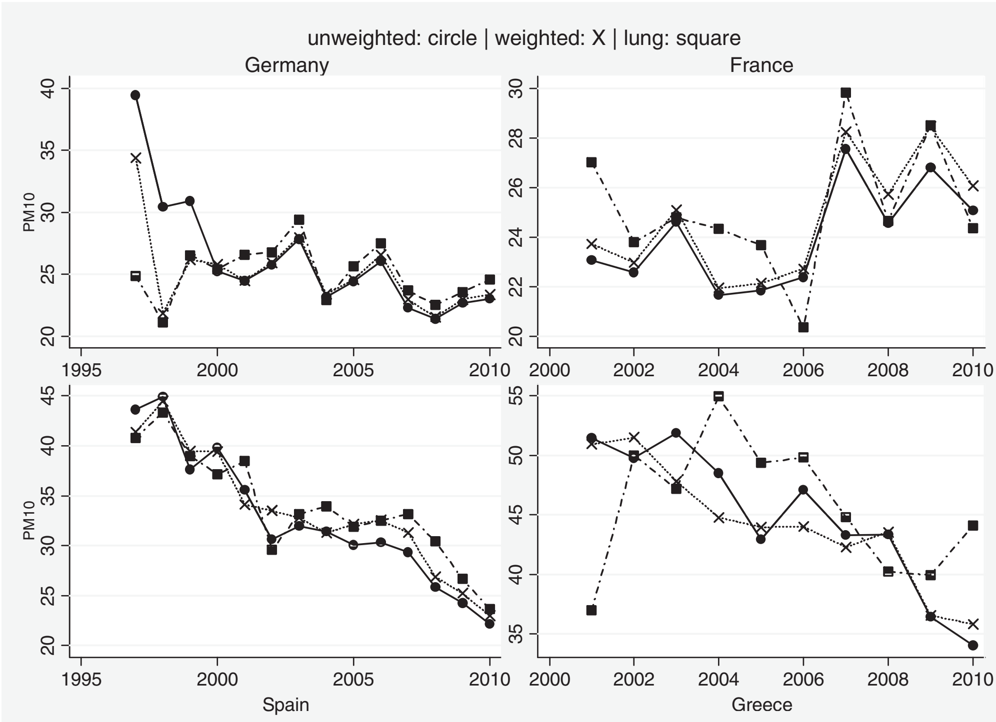

Figure 4 Trends in PM10 in Four European Countries.
Notes: PM10 is measured in micrograms per cubic meter. A detailed description of the sources for the data underlying this figure is provided in the on-line supplementary materials.

Spain and Greece have declining trends, but they are at uniformly higher levels than the U.S., France, or Germany in the early part of the time period.

The weighting scheme for older respondents does not appear to have as large of an effect for these countries as for the United States. This could be due to geographic resolution for the monitors. These data are available for regions whose size varies depending on the population density. Areas with high population density have more monitors for a geographic region than areas with low population density. Thus, when the population density is lower, the size of the reporting area for linking monitors to the SHARE respondents is larger. When different weights are used to compare sensitive groups in the EU samples, the differences in the PM10 trends are not as large as they appear to be when comparable definitions for the weights are used for the U.S. readings. For Spain, and for France for most of the time period, the SHARE respondents with serious health problems seem to be experiencing worse air quality conditions. However, this does not appear to be the case for Germany.

These graphs are a first step in the types of scoping activities that could be used to frame a macro-economic analysis of air quality in these economies. These graphs also suggest that measuring aggregate air pollution trends *across* countries offers a different perspective on the effects of weights. For small countries weighting schemes that attempt to identify sensitive groups do not appear to be as important as separately describing locations that may be under different policy regimes. At this stage, these graphs are simply grist for the next step—a much more detailed assessment of the criteria for weighting measures of air quality and the implications of using different weights.[18]

Next Steps

If the EKC literature reviewed by Carson (2010) is representative, then we should not expect empirical analyses to produce *stylized facts* concerning environmental economics and the aggregate economy anytime soon.[19] To date, empirical analyses have overlooked the important first step in the analysis chain, which is illustrated in modern neoclassical macro models. That is, the available information must be matched to concepts that are grounded in a model of how environmental quality affects and is affected by the level of aggregate economic activity and the pace of economic growth.

Thus, the literature needs to start with a set of policy invariant features of preferences and technology that link environmental quality measures to what people care about. This means introducing measures for *aggregate* environmental quality into the function used to describe society's preferences. Insights about these links can be found in the earliest work in environmental economics. In the case of the link between environmental quality and production activities, the description of these activities must be modified so residuals and emissions arise by accounting for materials and energy balances (Kneese, Ayres, and d'Arge 1970). Measures of environmental quality are then constructed by describing how the environmental media receiving emissions of pollutants influence the environmental quality experienced by people. The previous section suggests that although we have extensive experience at the micro level, it has focused on modeling the role of environmental quality using individual choices. Thus, translating these findings into aggregate measures is relatively uncharted territory.

Overall, this scoping analysis of what can be accomplished with existing data suggests that there are clear opportunities for using economic analysis to expand EPA's indexes that measure several dimensions of environmental quality. There is also potential for evaluating these indexes by using insights from micro-level studies of how people respond to different levels of environmental quality. These evaluations would all be part of the first steps toward developing consistent macro models that include environmental quality in a meaningful way.

Examining EPA's Second Prospective Report Through the Lens of Macroeconomics

As I noted in the Introduction, another signal of the importance of using a macro perspective in evaluating environmental quality can be found in EPA's recently released Second Prospective Analysis report (EPA 2011). Two aspects of this study are particularly relevant to the issues I have been discussing here. The first concerns the report's general equilibrium analysis of air pollution policy and the contribution of air quality to the functions used to describe

[18] In the context of the quality of life studies, weights are sometimes developed based on the complicit expenditures relative to income that are made in the form of higher rents and lower wages to live in areas with better air quality conditions. This strategy would parallel (roughly) the treatment of price changes in the construction of conventional price indexes.

[19] I believe it would be possible to develop stylized facts based on applied micro-econometric analyses of issues in environmental economics. This is where the majority of the empirical research has been focused.

representative consumers. The second concerns how the state of the economy should influence an assessment of environmental regulations.

The study's objective was to evaluate the costs and benefits of implementing the 1990 Clean Air Act Amendments at different times. Net benefits in 2010 are estimated to be about 9 percent of GDP in that year. Based on these estimates, the aggregate annual gains people experienced (net of costs) could not be considered marginal impacts on the U.S. economy. This is important because the methods used to derive the net benefit estimates are consistent with a partial equilibrium framework. This perspective assumes the changes due to policy are not large enough to impact the overall economy. Given the magnitude of the annual gains, it is hard to accept this assumption. To partially recognize the scale of the marginal impacts of implementing the Clean Air Act Amendments, the report includes (for the first time) a separate analysis of their effects using a static computable general equilibrium (CGE) model. One of the scenarios in this analysis was designed to reflect both the benefits and costs of the policy, and the estimates of the net gain provide a sharp contrast with the study's main findings. They suggest that the annual net benefits of the rules are only 0.7 percent of GDP in 2010. However, no attempt is made to reconcile this thirteen-fold discrepancy in the estimates! It is hard to imagine a better motivation for research on how to develop consistent indexes of environmental quality and their role in the specification of preferences for the representative agents in these models.

A major reason for this wide discrepancy in the estimates of net benefits is the strategy used to introduce the effects of the improvements in air quality into the EPA-CGE model. Air pollution's effects on mortality and morbidity are represented as annual changes in the endowment of labor available to the modeled economy and through the use of avoided medical expenditures as an exogenous "cost". The EPA analysis assumes air pollution does not affect well being beyond the estimated health effects that lead to increased availability of labor time that can be allocated between work and leisure. It also assumes air quality does not change the tradeoffs people would make for other goods and services such as outdoor recreation or housing services in areas with good air quality. These assumptions implicitly contradict the logic used in developing the report's partial equilibrium measures. Thus, it should come as no surprise that there are dramatic differences in the estimates because they are not consistent representations of the effects of the pollution changes.

The second issue with the report concerns the state of the economy and its implications for how we propose to assess environmental rules. Although this issue is clearly a political "hot potato", it also has important implications for how we perform benefit-cost analyses. The Second Prospective Analysis was underway before the full implications of the economic downturn had been realized. No doubt, the structure of the analysis and the maintained assumptions for the models had to be made far in advance of the planned publication date of the final report. So it is not clear how much the EPA report's details could have been changed once the downturn was recognized. Nonetheless, the state of the economy cannot be ignored in describing what the report's findings mean.

The EPA analysis used the Department of Energy (DOE) 2007 Annual Economic Outlook's forecast of aggregate economic activity in 2002 and 2020.[20] Based on DOE's projections from

[20]There appears to be a difference in the assumptions used for the partial equilibrium and general equilibrium analyses. Chapter 2 suggests the 2005 Annual Economic Outlook (AEO) as the basis for the growth assumptions

2002 to 2010, the EPA analysis assumed a 2.9% growth rate in real GDP. However, the actual average growth rate over this period was only 1.77%.[21] The actual level of GDP in 2010 (in 2000 weighted dollars) was $11,745 billion, compared to $13,248 billion assumed in the analysis. Perhaps the most important discrepancy concerns the assumptions about unemployment. The EPA analysis used historical unemployment rates of 4 to 5 percent. However, the actual unemployment rate was 9.6 percent in 2010.

Masur and Posner (2011) recently argued that regulatory agencies need to re-think their conventional practices and use benefit-cost analysis to account for the unemployment effects of regulations. I agree with Masur and Posner that the conventional strategy of relying on a simple shadow value will not work. However, in this case, as with the aggregate relationship between environmental quality and growth, we need to start with first principles and consider how large-scale policies should be evaluated within models that allow for unemployment as a structural feature of the economic system.[22] The assumption that a simple partial equilibrium shadow value can be defined ignores the source of the problems with the current benefit-cost methods.

It may well be possible to adjust the current practices used in applied benefit-cost analysis to account for the effect of environmental rules on employment within a framework that recognizes the role of the business cycle.[23] However, these adjustments must follow from a consistent macro model of the process. Moreover, such adjustments should consider not only the effects of environmental regulations on employment but also other effects on the non-market activities that contribute to the labor/leisure tradeoff, the consumption choices of market goods, and the size of the tradeoffs people can make (given their incomes) for non-market goods.

Concluding Reflections

I hope the discussion to this point has piqued readers' interest in pursuing "crosswalks" between the macroeconomics and environmental economics literatures. Most of what I have discussed considers what environmental economists can learn from macro. However, I believe that the benefits go both ways. Macroeconomists can also gain from reading our work. One especially relevant example can be found in developing aggregate measures of economic well-being.[24] Forty years ago, Nordhaus and Tobin (1972) proposed and implemented a strategy for developing aggregate measures of economic welfare using data that supplemented the national accounts.[25] They used a county level model to estimate the "income compensation" required to live in areas with urban disamenities. The details are not important here, but the questions they posed are.

(see table 2.3). Chapter 8 suggests the 2005 AEO was used for emissions and the 2007 AEO was used for the growth assumption (see note #109 and discussion on page 8-8 of the report).

[21]These estimates are taken from the Economic Report of the President 2011, which included preliminary estimates for 2010. The growth rate is a simple average of annual growth rates rather than a cumulative rate.

[22]Recently EPA has started this process by sponsoring research on these issues and organizing a conference to frame how these issues should be considered. More will be available on these activities in the late fall of 2012.

[23]Bartik [forthcoming] has started this process. He argues for the use of the reservation wage as the appropriate welfare measure for considering the effects of policy in the context of involuntary unemployment. His argument builds on research by Shimer and Werning (2007).

[24]I am grateful to Matt Kahn for suggesting this example.

[25]Their essay was part of a colloquium series marking the fiftieth anniversary of the National Bureau of Economic Research. It would be nice to have this underway for the hundreth!

Today we know that the implicit logic underlying the Nordhaus-Tobin approach requires a Rosen (1979)-Roback (1982) framework that considers both housing values and wage differentials to measure the expenditure differentials that would compensate for variations in positive and negative amenities across local areas.[26] Linking this framework to the national accounting challenge posed by Nordhaus and Tobin's efforts to measure changes in aggregate well being requires both reconsidering the current strategies for measuring the dollar value of the services associated with owner-occupied housing and using the insights from these micro analyses. Bieri, Kuminoff and Pope (2012) (BKP) note that current measures in the national accounts treat the services from owner-occupied housing in a framework that recognizes regional differences in housing markets by using rental equivalency based on regional surveys to collect information about housing rents. However, these measures do not include all the factors captured in the BKP user cost analysis. What we need to do is compare the way in which the national accounts currently measure housing services with an update of the Rosen-Roback framework and then develop corrections to the approach used for housing in the national accounts. This means amending the Nordhaus-Tobin logic to reflect insights from both the current macro literature (see Prescott 1997 as one example) and environmental economics as reflected in BKP. No doubt both macroeconomists and environmental economists would learn from this process. As Tietenberg (2011) has suggested, insights from one discipline can help lead to new strategies for problem solving in other disciplines. I have argued here that the same potential exists for the specialized fields within a single discipline. Hopefully, the discussions in this column have convinced you that such "crosswalking" adds value to both sides of the road.

References

Albouy, David. 2008. "Are Big Cities Really Bad Places to Live? Improving Quality-of-Life Estimates Across Cities", NBER Working Paper #14472, November.

Aldy, Joseph E. 2005. "An Environmental Kuznets Curve Analysis of U.S. State-Level Carbon Dioxide Emissions", *The Journal of Environmental & Development* Vol. 14 (1): 48–72.

Bäck, Danielle, Eric Van Buren, and Scott Van Buren. 2012. "National Evidence on Behavioral Responses to Information about Air Quality: EPA's Air Quality Index", unpublished paper.

Banzhaf, H. Spencer, and Randall P. Walsh. 2008. "Do People Role with Their Feet? An Empirical Test of Tiebout's Mechanism", *American Economic Review* Vol. 98 (3): 843–863.

Bartik, Timothy J., "Including Jobs in Benefit-Cost Analyses," Annual Review of Resource Economics, forthcoming.

Baumol, William J. 1967. "Macroeconomics of Unbalanced Growth", *American Economic Review* Vol. 57 (3): 415–426.

Bento, Antonio, Matthew Freedman, and Corey Lang. 2011. "Spatial and Social Disparities in the Benefits from Air Quality Improvements", Cornell University, unpublished paper, September.

Bieri, David S., Nicolai V. Kuminoff, and Jaren C. Pope. 2012. "Expenditures on Localized Amenities in the United States", unpublished working paper.

Blomquist, Glenn, Mark Berger, and John Hoehn. 1988. "New Estimates of Quality of Life in Urban Areas", *American Economic Review* Vol. 78 (1): 89–107.

Brock, William A., and M. Scott Taylor. 2010. "The Green Solow Model", *Journal of Economic Growth* Vol. 15 (2): 127–153.

Carbone, Jared C., and V. Kerry Smith. 2008. "Evaluating Policy Interventions with General

[26] Bieri, Kuminoff and Pope (2012) have done the most comprehensive recent evaluation of local quality of life measures using this logic.

Equilibrium Externalities", *Journal of Public Economics* Vol. 92 (June): 1254–1274.

Carson, Richard T. 1997. "The Relationship Between Air Pollution and Emissions: U.S. Data", *Environmental and Development Economics* Vol. 2 (4): 433–450.

Carson, Richard T. 2010. "The Environmental Kuznets Curve: Seeking Empirical Regularity and Theoretical Structure", *Review of Environmental Economics and Policy* Vol. 4 (1): 3–23.

Chay, Kenneth Y., and Michael Greenstone. 2005. "Does Air Quality Matter? Evidence from the Housing Market", *Journal of Political Economy* Vol. 113 (April): 376–424.

The European Air Quality Database. European Environment Agency(Database Accessed 2011).

Gorbachev, Olga. 2011. "Did Household Consumption Become More Volatile?", *The American Economic Review* Vol 101 (5): 2248–2270.

Evans, Mary F., and V. Kerry Smith. 2005. "Do New Health Conditions Support Mortality-Air Pollution Effects?", *Journal of Environmental Economics and Management* Vol 50 (3): 496–518.

Evans, Mary F., V. Kerry Smith, and Jesse Snook. 2011. "Air Quality, Caregiving Needs, and Location Decisions of Older Adults." Presented at the AERE Summer Meeting.

Grossman, Gene M., and Alan B. Krueger. 1991. "Environmental Impacts of a North American Free Trade Agreement", NBER Working Paper #3914, November.

Harbaugh, William T., Arik Levinson, and David Molloy Wilson. 2002. "Reexamining the Empirical Evidence for an Environmental Kuznets Curve", *The Review of Economics and Statistics* Vol. 84 (3): 541–551.

Hayward, Stephen F. 2011. 2011 Almanac of Environmental Trends, (San Francisco, Ca: The Pacific Research Institute).

Hayward, Stephen F., Job Nelson, and Sam Threnstrom. 1996. The Index of Leading Environmental Indicators: A Citizen's Guide on How to Think About Environmental Quality in the United States, (San Francisco, Ca:The Pacific Research Institute).

Jones, Charles I., and Paul M. Romer. 2009. "The New Kaldor Facts: Ideas, Institutions, Population, and Human Capital", NBER Working Paper #15094, June.

Just, Richard E. 2011. "Behavior, Robustness and Sufficient Statistics in Welfare Measurement", Annual Review of Resource Economics, edited by Gordon Rausser, Vol. 3, pp. 37-70.

Kaldor, Nicholas. 1961. "Capital Accumulation and Economic Growth". In *The Theory of Capital*, ed. E.A. Lutz, and D.C. Hague, 177–222. St. Martins Press.

Kneese, Allen V., Robert U. Ayres, and Ralph C. d'Arge. 1970. Economics and the Environment: A Materials Balance Approach, (Baltimore: Johns Hopkins University for Resources for the Future).

Krutilla, John V. 1967. "Conservation Reconsidered", *American Economic Review* Vol. 57 (September): 777–786.

Kydland, Finn E., and Edward C. Prescott. 1977. "Rules Rather than Discretion: The Inconsistency of Optimal Plans.", *J. Polit. Economy* Vol. 85 (June): 473–492.

List, John A., and Craig A. Gallet. 1999. "The Environmental Kuznets Curve: Does One Size Fit All?", *Ecological Economics* Vol 31 (3): 409–423.

Lucas, Robert E. 1972. "Expectations and the Neutrality of Money", *Journal of Economic Theory* Vol. 4: 103–124.

Masur, Jonathan S., and Eric A. Posner. 2011. "Regulation, Unemployment, and Cost-Benefit Analysis", John M. Olin Law & Economics Working Paper #571 and Public Law and Legal Theory Working Paper #359, University of Chicago, August.

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

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

National Air Pollutant and Emission Trends. 1900-1998. U.S. Environmental Protection Agency.

Nordhaus, William, and James Tobin. 1972. "Is Growth Obsolete?" in *Economic*

Research: Retrospect and Prospect-Economic Growth, Fiftieth Anniversary Colloquium V, (New York: Columbia University Press for National Bureau of Economic Research).

OECD. Environmental Data Compendium, Organization for Economic Co-operation and Development(Database Accessed 2011).

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

Prescott, Edward C. 2004. "The Transformation of Macroeconomic Policy and Research", Prize Lecture, The Nobel Foundation, December 8.

Roback, J. 1982. "Wages, Rents, and the Quality of Life", *Journal of Political Economy* Vol. 90 (6): 1257–1278.

Rogerson, Richard. 2008. "Structural Transformation and the Deterioration of European Labor Market Outcomes", *Journal of Political Economy* Vol. 116 (2): 235–259.

Rosen, S. 1979. "Wage Based Indices of Quality of Life", *Current Issues in Urban Economics.* Baltimore, MD: John Hopkins Press.

Shimer, Robert, and Iván Werning. 2007. "Reservation Wages and Unemployment Insurance", *Quarterly Journal of Economics* Vol. 122 (August): 1145–1186.

Smulders, Sjak, Lucas Bretschger, and Hannes Egli. 2010. "Economic Growth and the Diffusion of Clean Technologies: Explaining Environmental Kuznets Curves", *Environmental and Resource Economics* Vol. 49 (1): 79–99.

Solomon, Deborah, and Tennille Tracy. 2011. "Obama Asks EPA to Pull Ozone Rule", Wall Street Journal, September 3.

Tietenberg, Tom. 2011. "Reflections—In Praise of Consilience", *Review of Environmental Economics and Policy* Vol. 5 (2): 314–329.

U.S. Environmental Protection Agency. 2010. "Our Nation's Air; Status and Trends Through 2008", Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, EPA-454/R-09-002, February.

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