

Environmental Macroeconomics: Environmental Policy, Business Cycles, and Directed Technical Change

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Abstract

Environmental economics has traditionally fallen in the domain of microeconomics, but approaches from macroeconomics have recently been applied to studying environmental policy. We focus on two macroeconomic tools and their application to environmental economics. First, real-business-cycle models can incorporate pollution and pollution policy and can be used to answer several questions. For example, how should environmental policy adjust to business cycles? How do different types of policies fare in a context with business cycles? Second, endogenous technological growth is an important component of environmental policy. Several studies ask how policy can be designed both to tackle emissions directly and to influence the adoption of clean technologies. We focus on these two aspects of environmental macroeconomics but emphasize that there are many other potential applications.

1. INTRODUCTION

Environmental policy papers typically approach their issues from a microeconomic perspective. Microeconomic theoretical analysis and empirical analysis are usually used to answer questions about the effect of pollution on health, the effect of policy on pollution, and the optimal design of resource policy. However, there has recently been a growth in research that combines methods from macroeconomics with policy questions related to environmental economics.

Why should economists consider macroeconomic models for evaluating environmental policy? Quite simply, many estimates find that the domestic costs of environmental rules are big. Greenstone et al. (2012) find that air quality regulations cost the manufacturing industry roughly \$21 billion per year, approximately 8.8% of profits. The Second Prospective Report conducted by the US Environmental Protection Agency estimates that the direct benefits from the 1990 Clean Air Act Amendments are \$2 trillion for the year 2020, or 9% of GDP (US EPA 2011). Ignoring the interaction between environmental policy and macroeconomic indicators risks overlooking some important feedback effects in the economy.

In this article, we survey some recent literature in two particular areas that combine environmental economics and macroeconomics. First, we discuss the literature combining real-business-cycle (RBC) models with environmental policy. Incorporating pollution into a standard RBC framework allows the model to address questions about the relationship between environmental policies and economics fluctuations. Second, we discuss a new strand in the endogenous growth literature on environmental policy and induced technological progress. This directed technical change (DTC) literature stresses the importance of path dependency in environmental technology policy.

This article does not comprehensively list every paper that could fall into the category of environmental economics and macroeconomics. Indeed, nearly every integrated assessment model of environmental policy, such as the dynamic integrated climate change (DICE) model (Nordhaus 2008), could qualify as a macroeconomic model, as could multisector general equilibrium models used to evaluate economy-wide policies. Any study that incorporates endogenous growth (e.g., Xepapadeas 2005), examines the effect of environmental policy on unemployment (e.g., Greenstone 2002), or uses the new dynamic public finance models to study environmental policy (e.g., Golosov et al. 2011) could also fall under this category. Instead, we choose to focus on two particular areas at the nexus of environmental economics and macroeconomics in which work is being done. For each area, we summarize what the growing literature has so far found, how it relates to past related literature, and directions for future research.

2. REAL BUSINESS CYCLES AND ENVIRONMENTAL POLICY

Several recent papers have begun a literature using standard macroeconomic business cycle models to address questions of environmental policy design. These papers merely scratch the surface of the large body of literature on macroeconomics on business cycles, but they provide some interesting insights into policy design. They also provide a guideline for how future research can address questions at the intersection of macroeconomics and environmental economics.

Three recent papers start with the basic RBC framework and add pollution; these are, in the order discussed below, Fischer & Springborn (2011), Heutel (2012), and Angelopoulos et al. (2010). The standard RBC model was developed in papers such as Kydland & Prescott (1982). The model is a dynamic stochastic general equilibrium (DSGE) model. A representative consumer optimizes over consumption, leisure, and investment. A representative firm optimizes over capital and labor inputs. The cycles are caused by exogenous, persistent shocks to total factor productivity (TFP). These real shocks affect returns to inputs and therefore prices in general equilibrium, and

consumers and firms respond rationally to these cyclical changes. The standard RBC model has been used as a template for many extensions, including modeling labor as indivisible (Hansen 1985).

The primary extension to the RBC model provided by Fischer & Springborn (2011), Heutel (2012), and Angelopoulos et al. (2010) is to include pollution in the model. Pollution is modeled slightly differently in the three papers. In Fischer & Springborn (2011), pollution is directly proportional to the quantity employed of an intermediate input M_t (e.g., energy). The production technology is modeled as Cobb-Douglas:

$$F(K_t, M_t, L_t) = K_t^\alpha M_t^\gamma L_t^{1-\alpha-\gamma}.$$

The intermediate input's share of total factor inputs is given by the standard Cobb-Douglas solution:

$$\frac{M_t}{Y_t} = \frac{\gamma(1 + \widehat{\phi}_t A_{t,Y})}{1 + \widehat{\phi}_t}.$$

The normalized shadow value of the emissions policy is $\widehat{\phi}_t$, and $A_{t,Y}$ represents the derivative of the emissions constraint with respect to output (allowing the cap to be a function of total output). In Fischer & Springborn (2011), abatement technology is not modeled explicitly; emissions changes occur through factor substitution and changes in output.

In Heutel (2012), emissions are a by-product of production; total output is directly correlated with total emissions. Abatement technology is available, whereby higher spending on abatement technology reduces the ratio of emissions to output. The equation representing the relationship between emissions (e_t) and output (y_t) is

$$e_t = (1 - \mu_t)b(y_t),$$

where $\mu \in [0, 1]$ represents the fraction of emissions abated and the function b represents the nonlinear relationship between output and emissions, holding abatement constant. Achieving a given level of abatement requires spending on abatement technology (z_t):

$$z_t = g(\mu_t)y_t.$$

This specification of pollution and abatement comes from the DICE model (Nordhaus 2008).

In Angelopoulos et al. (2010), emissions are also a by-product of production. The pollution abatement technology varies (i.e., the ratio of emissions to output is not fixed), but the change in this technology is stochastic, not endogenous. The pollution flow (p_t) is modeled as

$$p_t = \phi_t y_t,$$

where ϕ_t is a stochastic, exogenous variable representing pollution technology. The flow of pollution affects the stock of environmental quality (Q_t) according to

$$Q_{t+1} = (1 - \delta^q)\overline{Q} + \delta^q Q_t - p_t + \nu g_t.$$

The pollution stock is affected by the last period's stock, current emissions flows, and government spending on abatement g_t .

In Heutel (2012) and Angelopoulos et al. (2010), pollution is a stock variable. In contrast, Fischer & Springborn (2011) do not model damages explicitly.

In addition to the different ways in which these three papers model pollution, the papers differ in the questions they address. Fischer & Springborn (2011) compare how three types of emissions policies perform in an economy with TFP shocks: an emissions tax, an emissions cap, and an intensity target (a limit on emissions per unit of output). In particular, they look at the differences in the expected costs of the policies and in the volatility of economic variables. For each policy, they examine how a static policy (e.g., an emissions tax whose rate does not change with the business cycle) performs in response to TFP shocks. Each policy keeps the expected level of emissions at the same level to allow for a direct comparison between the other economic variables among the policies.

Fischer & Springborn (2011) find that the intensity target policy can achieve the emissions goal at the lowest expected costs in the steady state. The intensity target yields a higher expected level of labor, capital, and output than do the other two policies. In contrast, the cap and tax policies offer lower present value costs due to higher consumption, whereas capital stocks adjust downward during the transition to the steady state. The cap yields the lowest volatility of all economic variables except the shadow value of pollution. Under the tax, the shadow value of pollution is constant (because the tax rate is constant), but the other economic variables exhibit higher volatility. As shown in a deterministic model that provides intuition for the main dynamic model, the intensity target provides a higher level of the capital stock than the other policies do. In fact, the intensity target provides a higher level of capital than in the no-policy case. Because the intensity target allows for more emissions when there is more output, it provides an incentive for increased investment and capital during a positive productivity shock. This ability of the intensity target to better adapt to economic fluctuations is what gives it the advantage relative to the two other policies. This result is echoed in Sue Wing et al. (2009).

Heutel (2012) also considers both a tax policy and a cap policy, but the question at hand is not a comparison between the performances of those two policies. Rather, he asks how either policy variable should adapt to the business cycle. Neither the tax rate nor the value of the cap is constant over the business cycle. If, say, the tax rate is allowed to respond to the business cycle, should it be procyclical (such that the tax rate increases during expansions) or countercyclical (such that the tax rate decreases during expansions)? It is reasonable to believe that an inflexible policy (e.g., a tax rate that does not vary with the business cycle) is not likely to be first best and may yield significant welfare losses relative to the first-best policy. Metcalf (2009) suggests that the clearing price of emissions permits in the initial auction of the Regional Greenhouse Gas Initiative was much lower than expected because the cap did not adjust to the reduced demand brought on by the recession.

Heutel (2012) finds that both the optimal tax policy and the optimal cap policy are procyclical. Both an emissions tax and an emissions quota should increase during expansions but should decrease during recessions. At first glance, those two results seem to be in conflict with each other. An increased tax rate is a strengthening of the policy, whereas an increased quota is a weakening of the policy (more emissions are allowed). These two policy responses are consistent with each other because optimal policy allows emissions to increase during expansions and decrease during recessions, but not by as much as they otherwise would without any policy. Therefore, a cap should allow emissions to rise during expansions, but by less than they would have risen without the cap. The same result can be achieved with an emissions tax, whereby the tax rate increases in an expansion by just enough to dampen the increase in emissions but not enough to reverse the increase and lead to a decrease in emissions.

Like Fischer & Springborn (2011), Angelopoulos et al. (2010) use an RBC model with pollution to compare the performance of three different policies: a tax; a cap; and what they term Kyoto-like rules, which specify how fast emissions must decrease from one period to the next. The

Angelopoulos et al. (2010) model differs from the standard RBC framework and from the previous two RBC pollution papers in two important respects. First, their economy consists of two different exogenous shocks. One is the standard RBC TFP shock. The other is a shock to the ratio of emissions to output. They term these two shocks economic uncertainty and environmental uncertainty, respectively. The second difference between their model and the models in Fischer & Springborn (2011) and Heutel (2012) is in their modeling of government abatement. In Fischer & Springborn (2011), abatement results from reductions in energy use in production. In Heutel (2012), firms choose to reduce their emissions intensities in response to policy. In Angelopoulos et al. (2010), abatement can be made only by the government. Government abatement does not affect the flow of emissions but instead affects the stock of pollution. The representative consumer or the representative firm cannot engage in this abatement.

The availability of government abatement and the inability of private individuals and firms to do it mean that there is a need in this model for government revenue from environmental policy. All the revenue, from either tax receipts or the auctioning of permits, goes toward government abatement. The third policy of Angelopoulos et al. (2010), the Kyoto-like rules, does not generate any revenue, and thus it is at a disadvantage relative to the other two policies. To make the three policies comparable, the authors include lump-sum taxes in the rules policy. These lump-sum tax revenues are used for government abatement.

Once the three policies are directly comparable, Angelopoulos et al. (2010) find that the cap policy is always the worst: It leads to a lower level of expected lifetime utility than does a tax policy or a rules policy, for any combination of parameter values that the authors simulate. This is because the cap policy fixes environmental quality at a specified level but allows all other economic variables (e.g., consumption, capital) to be exposed to higher variability, reducing social welfare. The ranking between the tax policy and the rules policy is indeterminate. It depends on the relative importance of the two types of shocks. When economic uncertainty (i.e., the TFP shock) is the dominant source of uncertainty, then taxes dominate rules. When environmental uncertainty (i.e., the shock to the ratio of emissions to output) is the dominant source of uncertainty, then rules dominate taxes. Because rules fix emissions in each period but allow for a change in emissions over time, they eliminate environmental volatility. This gives the rules policy the advantage when environmental uncertainty is high.

A fourth paper that uses an RBC model to analyze pollution policy is Dissou & Karnizova (2012). The focus of this paper is again ranking between alternative policy instruments in the presence of persistent productivity shocks. In this case, two policies, taxes and permits, are compared with each other. The innovation of Dissou & Karnizova (2012) relative to the other papers is the disaggregation of the economy into multiple sectors. Rather than a single representative firm accounting for the entire production side of the economy, this model disaggregates the economy into six sectors. Three sectors—coal, electricity, and oil and gas—are in energy. The other three sectors are services, energy-intensive goods, and non-energy-intensive goods. Each of the six sectors experiences its own autocorrelated productivity shock.

As do Fischer & Springborn (2011), Dissou & Karnizova (2012) find that the cap policy leads to lower volatility of economic variables than does the tax policy. This finding holds regardless of the source of the economic shock. However, the welfare ranking between the tax and the cap depends on the source of the shock. For shocks to nonenergy sectors, there is no difference between the cap and the tax. For shocks to one of the energy sectors, the tax dominates the cap. This result is puzzling because the cap results in lower volatility than does the tax. The explanation is that, in the Dissou & Karnizova (2012) model, the cap reduces, relative to the tax, not just the variance but the means of economic variables such as consumption. The cap limits the ability of the economy to respond to energy-sector productivity shocks more so than does the tax.

All these papers use the RBC framework to analyze environmental policy. Three of the four papers are about ranking different static policies, whereas the other (Heutel 2012) is about finding the optimal dynamic policy. Both the Fischer & Springborn (2011) and Heutel (2012) papers contain just a single type of TFP shock, whereas the Angelopoulos et al. (2010) paper contains both a TFP shock and a shock to emissions, and the Dissou & Karnizova (2012) paper contains a separate productivity shock for each sector of the economy. All papers include pollution as a by-product of production (either by modeling it as such or as an input to the production process), whereas only Heutel (2012) includes the damages from pollution in welfare analysis.

Pizer (1999), although not a paper that is explicitly about business cycles, nevertheless uses tools similar to those of RBC models. The question motivating this paper is how uncertainty, rather than shocks to productivity, affects the optimal design of climate change policy. Pizer employs a stochastic growth model in which shocks to labor productivity are present. These shocks provide uncertainty, but the uncertainty that this paper focuses on is in the deep parameter values of the model. For several such parameters, a distribution of parameter values is employed, and the model is solved under different draws of the parameter vector. Monte Carlo simulations across the parameter space provide measures of the impact of uncertainty on optimal policy. The key takeaway is that uncertainty increases the optimal level of abatement and increases the dominance of taxes over policies that fix quantities (what he terms rate controls).

These papers represent just the start of a literature using macroeconomic tools, in particular DSGE models, to assess the relationship between environmental policy and the business cycle. This literature could be expanded in numerous ways. For instance, many of the innovations to the RBC literature could be incorporated into models with environmental policy. Hansen's (1985) modeling of labor as indivisible enriches the RBC model by more closely fitting the predicted correlation between real wages and hours to the correlation found in the data. In fact, of the papers cited, only Fischer & Springborn (2011) and Dissou & Karnizova (2012) even include labor as a factor of production. The effect of environmental policy on labor markets is politically relevant ("do regulations kill jobs?"), and there is a great opportunity to use this literature to address this question.¹ In particular, there is a need for analysis with models that do not assume full employment but rather allow for involuntary unemployment, as occurs in business cycle downturns. Lastly, there is an opportunity to combine models of cycles with growth models. Cai et al. (2013) proceed in this direction by combining the deterministic IAM (integrated assessment model) DICE with a DSGE extension that incorporates stochastic productivity shocks.

Other extensions to the standard RBC model that could be included in models of environmental policy include allowing for home production (Benhabib et al. 1991) or for preference shocks (Bencivenga 1992). Chang & Kim (2007) include heterogeneous agents, incomplete capital markets, and indivisible labor supply.

Additionally, alternate models of business cycles could be employed. Keynesian price dynamics and monetary policy, rather than real productivity shocks, are often modeled as drivers of the business cycle. In fact, Galí (1999, 2004) argues that productivity shocks do not explain business cycles, whereas Christiano et al. (2003) defend productivity shocks. Although debates over the source of the business cycle may not be relevant to all environmental policies, there are conceivably some situations in which different shocks would yield different policy prescriptions. For instance, price levels may impact the relative success of taxes versus standards if the tax rate is set in nominal

¹Bartik (2012) examines the literature on including benefits from reducing unemployment in benefit-cost analysis of public policies, including environmental policies.

terms. In such a case, a Keynesian model or a model with monetary policy shocks may prove important.

Only these few papers begin to evaluate the performance of environmental policy in the context of business cycle models. But other papers tackle similar issues. One literature examines the role of energy prices in business cycles. Kim & Loungani (1992) add to the standard RBC model energy as an intermediate input. Energy prices are determined exogenously and, like productivity shocks, are autocorrelated. Although Kim & Loungani (1992) do not model emissions or environmental policy, these results are relevant to environmental policy, given energy's contribution to many pollutants. Energy price shocks are negatively correlated with output and pollution. These researchers find that including oil price shocks in addition to TFP shocks improves the predictions of the RBC model. In particular, this approach reduces the model's predicted correlation between wages and hours worked, which is too high in the standard RBC model. The fraction of output volatility that can be explained by the RBC model is increased from 80% to 90% after oil price shocks are included.

Several other papers follow Kim & Loungani (1992) by adding oil price shocks to a standard RBC model. Davis & Haltiwanger (2001) examine how oil price shocks affect the creation and destruction of manufacturing jobs. They do not use an agent-based DSGE model; rather, they use sectoral vector autoregressions. They find that oil price shocks account for twice as much volatility in employment growth as do monetary shocks. Dhawan et al. (2010) argue that oil price shocks and TFP shocks were negatively correlated prior to 1982. Afterward, that link disappeared, and the disappearance of that correlation helped explain the great moderation starting in 1982. Dhawan et al. (2010) estimate that before the link disappeared, 51% of the variance in TFP was due to spillovers from volatility in oil price shocks. However, their data set extends only through 2005, and thus it misses large oil price changes that have occurred since then. Narayan et al. (2011) start with a Keynesian macroeconomic model of business cycles (drawn from Fischer 1977 and Blanchard & Quah 1989) and add energy. They want to know whether permanent shocks or transitory shocks explain variance in energy consumption. They find that permanent shocks at short horizons account for the bulk of the variations, except for the first month of transitory shocks.

One important question relevant to the relationship between environmental policy and business cycles is not a normative question but rather a positive question: How does environmental quality vary with the business cycle? Although the previous RBC papers examine how environmental policy ought to vary with the business cycle, in fact it does not. However, it seems reasonable to assume that the quality of the environment, whether measured by the stock of greenhouse gases or by the flow of air or water pollution emissions, likely varies with the business cycle. When output increases, pollution increases, and when output contracts, pollution contracts—but by how much?

Surprisingly, few studies have addressed this question. Smith & Wolloh (2012) examine trends in water quality in the 40 years since the passage of the Clean Water Act. They find that not much has changed in that time; water is approximately as clean as it was 40 years ago. Although their primary focus is on trends, they also examine the effect of the business cycle on water quality. They develop three different indexes of aggregate water quality in the United States from 1975 to 2011. For each index, they run a regression at the annual level, with the water quality index as the dependent variable and the unemployment rate (with and without its square) as an independent variable, along with a constant. For most of the specifications, the water quality index is positively correlated with the unemployment rate. During recessions (as measured by the unemployment rate), water is cleaner. The coefficient on the square of the unemployment rate is negative, indicating a nonlinear relationship between the business cycle and water quality. The regression is

very rudimentary, and the explanatory power is rather low. However, as the authors argue, it is difficult to explain this correlation other than through the causal effect of the business cycle on water pollution.

Although the primary purpose of the model in Heutel (2012) is to derive optimal policy in the presence of business cycles, he also estimates the response of carbon dioxide (CO₂) emissions to the business cycle. This estimation occurs because, in the normative model, the response of CO₂ emissions to output is a necessary parameter, and it has not been previously estimated. Heutel (2012) uses quarterly data on total CO₂ emissions in the United States and estimates a series of regressions, with CO₂ emissions as the dependent variable and with GDP as the independent variable, to measure the response of emissions to the business cycle. Several estimation routines, including seasonal ARIMA models and regression on Hodrick-Prescott-filtered data, are performed. Heutel (2012) finds that, across regressions, emissions are positively correlated with GDP but that the response of emissions is inelastic. The estimated elasticity coefficient is between 0.55 and 0.86. When GDP rises by one percentage point above trend, emissions increase, but by less than one percentage point above trend.² These estimated coefficient values are consistent with the empirical result found in Kim & Loungani (1992). In that paper, the estimated correlation between the cyclical components of energy use and output is 0.72. Although Kim & Loungani (1992) estimate the correlation between energy use and output, and not the correlation between carbon emissions and output, the high correlation between carbon and energy explains the consistency of these two estimates. Doda (2012) also examines the cyclical nature of emissions, looking at data across a panel of countries, rather than at data for just the United States. He finds that emissions are procyclical and more volatile than GDP and that their volatility is negatively correlated with GDP.

Heutel & Ruhm (2012) estimate how the procyclicality of pollution contributes to the observed procyclicality of mortality (documented in, e.g., Ruhm 2000). To do so, they estimate the procyclicality of pollution. They examine ambient concentrations of two types of air pollutants: carbon monoxide (CO) and particulate matter smaller than 10 μm in diameter (PM10). They develop a state-year level measure of ambient pollution for each pollutant on the basis of readings of ambient air quality at various monitors around the United States. They regress a standardized measure of ambient pollution on the unemployment rate in a state and demographic controls in a state-fixed-effect framework. A one-percentage-point increase in a state's unemployment rate is correlated with a decrease in the state's ambient PM10 concentration of one-tenth of a standard deviation, and with a decrease in the state's ambient CO concentration of one-twentieth of a standard deviation, significant at the 1% level.

The response of emissions or environmental quality to the business cycle is an area in which further research is needed. Cyclical fluctuations in CO₂ emissions and other greenhouse gases are likely unimportant because these are stock pollutants with very low decay rates. However, for flow pollutants, their volatility over the business cycle may have important policy implications.

3. DIRECTED TECHNICAL CHANGE AND ENVIRONMENTAL POLICY

In this section, we discuss another strand of literature that studies macroeconomic transitions. The RBC literature explores how transitory fluctuations in productivity over time interact with the performance of environmental policies. The literature on directed technical change (DTC)

²The emissions data in Heutel (2012) are actually estimates based on aggregate indexes of fossil fuel consumption, whereas Smith & Wolloh (2012) use monitor data on ambient water quality.

explores how transitory environmental policy can engender permanent changes in the sustainability of macroeconomic growth.

As noted above, there exists a substantial literature on endogenous growth, natural or exhaustible resources, and the environment. In the 1970s, great attention was paid to the limits to growth that reliance on exhaustible resources might pose, and to how those resources might be optimally exploited (e.g., Dasgupta & Heal 1974, Stiglitz 1974). In more recent years, the damages and constraints imposed by pollution, including climate change, have refocused attention toward questions related to optimal growth and emissions taxes and to the sustainability of growth with pollution damages (see, e.g., Brock & Taylor 2005, Xepapadeas 2005, Peretto 2009, Smulders & Di Maria 2012). The theoretical work draws some inspirations from observations in the empirical Kuznets curve literature. Similarly, there exists a long literature on induced technical change, in which theoretical work establishes how optimal policy should respond when technological innovation is endogenous and empirical studies establish the responsiveness of innovation measures to environmental policies (see, e.g., Popp 2004, 2010; Fischer & Newell 2008; Gillingham et al. 2008; Adao et al. 2012).

The DTC literature combines aspects of these two strands but has the distinguishing feature of focusing on a particular kind of transition. It recognizes that innovation can occur in pollution-creating applications as well as in pollution-abating applications and hypothesizes that temporary environmental or technology policies can lead to permanent changes in the sustainability of the economy. As Stiglitz (1974) aptly observes, “There are at least three economic forces offsetting the limitations imposed by natural resources: technical change, the substitution of man-made factors of production (capital) for natural resources, and returns to scale.” The DTC literature also explores the roles of these forces, elaborating a particular framework of endogenous technological change.

Acemoglu, Aghion, Bursztyn & Hémous (2012) (henceforth AABH) introduce environmental constraints into a growth model with competing applications of innovation. A single final good is created by using dirty inputs and clean inputs, and monopolistically competitive researchers can direct their innovation toward improving the quality of either input. Innovation in this model builds on the shoulders of giants, becoming more productive as the preceding research base in that sector grows. Innovation is drawn to input sectors with larger market sizes and higher prices. In the absence of environmental policy, given an initial advantage for the dirty sector, continually expanding innovation and production in that sector lead the economy to drive the environment beyond a critical threshold.³

A carbon price alone can influence technical change by lowering the relative price of the dirty sector and by expanding the market for clean energy. However, the effects depend critically on the elasticity of substitution between the two sectors in producing the final good,⁴ as well as on the relative level of development of the technologies. Directed research subsidies can have a much stronger effect on technical change, in part because research scientists do not look ahead to future benefits of innovation, as patent horizons are a single year. The optimal policy thus combines a carbon tax and a research subsidy (internalizing both market failures), and AABH find a more important role for the latter. Furthermore, they find interesting effects on the time profile of policy interventions largely on the basis of the substitutability of clean inputs and dirty inputs.

³The notion of a threshold or technological regime switching in environmental and resource policy extends at least as far back as Dasgupta & Heal (1974). They consider the effect of uncertainty in the arrival date of an advanced technology on the optimal extraction of an exhaustible resource in a growth model.

⁴This result harkens to that of Dasgupta & Heal (1974) and Stiglitz (1974), who identify the substitutability of capital for exhaustible resources as an important determinant of sustainable growth.

AABH find that when dirty inputs and clean inputs are highly substitutable, environmental policies need apply for only a temporary period, until technological change is sufficiently redirected and the clean technologies outcompete the dirty ones. However, action must be immediate, as delay raises the cost and duration of the necessary interventions. When the two sectors are less substitutable, policy interventions may need to be permanent. Finally, if the sectors are complements, growth must be halted to avert environmental disaster. In all cases, optimal policy includes a carbon tax, but research subsidies are even more important to direct technical change.

Hémous (2012) extends this analysis to a two-country model, with which he examines emissions leakage from the regulating North to the laissez-faire South. Two final goods, one nonpolluting and the other polluting, are produced; innovation can be directed toward either sector and within the polluting sector toward dirty or clean technologies, the balance of which determines emissions in that sector. Taxing dirty production in the North tends to reinforce specialization and innovation in the dirty sector in the South. However, subsidizing clean research in the North, particularly in combination with a tariff, can redirect innovation. This scenario allows the North to develop a comparative advantage in the polluting sector, reducing emissions in the South, which then specializes in the cleaner good, and in the North because production of the polluting good becomes cleaner. Again, these interventions can be temporary; furthermore, with emissions leakage, DTC is the only means by which environmental disaster can be averted.

Aghion et al. (2012) bring data to the model by testing for path dependence in auto industry innovation. They use international data on patents and find that firms redirect technical change in response to fuel prices (which is a stand-in for an environmental policy like a carbon tax): Higher fuel prices are correlated with more innovation in clean auto technologies. Importantly, they find not only evidence of induced innovation but also evidence of path dependency in that firms are more likely to innovate in clean technologies when they have previously been exposed to clean technologies.

Critiques of AABH focus on the specific set of modeling and parameter assumptions used, particularly in the appealing case of a temporary intervention. Hourcade et al. (2012) replicate the AABH model and find that a modest carbon tax that phases out over time is possible with a high enough elasticity of substitution between the clean sector and the dirty sector. However, although this case appears optimistic, the implications for growth are much more substantial than previously interpreted; Hourcade et al. (2012) find a 40-year-long transition phase with growth rates slowed to 0.5% (from a baseline of 2% average growth), which they argue is politically infeasible. Mattauch et al. (2012) model a version with learning spillovers, rather than directed R&D, in the clean technology sector. They also find that a scenario with a high elasticity of substitution between the sectors allows for more modest policy interventions but that the welfare cost implications are larger because technology lock in is stronger in a laissez-faire scenario.

Some of the implications of the recent DTC literature can be put into context by considering previous studies of induced technological change in models with multiple industries. Gillingham et al. (2008) compare approaches to modeling R&D-induced technological change and identify several key aspects: preexisting distortions in R&D markets, whether there is substitutability or complementarity between the generation of output and knowledge, and the elasticity of the supply of R&D. The latter two modeling choices help determine whether climate policy-induced R&D in cleaner technologies crowds out innovation in other sectors, which can decrease aggregate output. The fact that knowledge spillovers create positive externalities—that is, social returns exceed private returns to R&D—plays an important role in the ultimate cost of climate and technology policies.

According to AABH, R&D is allocated from a fixed and finite supply of scientists, implying perfect crowding out of research effort. Although there are no spillovers from other firms' research,

market imperfections arise from the limited horizon of the technology patent (one year) and from monopolistic competition in intermediate goods. The presence of intertemporal spillovers does not imply an overall undersupply of research (because the supply of research is fixed), but imperfect appropriation of the future benefits of innovation can influence the direction of technical change if the relative future benefits diverge. Such is the case in AABH, as sectoral productivity accelerates with research over time. Greaker & Heggedal (2012) introduce long-lived patents into the AABH model and find that the research subsidy for clean technologies becomes much less important than the carbon tax. In other words, the effectiveness of the carbon tax at inducing directed innovation significantly depends on the degree of spillovers, in this case intertemporal ones.

Smulders & de Nooij (2003) consider whether a change in the direction of technical change can accelerate aggregate growth; i.e., can there be a win-win scenario for climate policy? They use a variation of the framework utilized in AABH, adding intrasectoral spillovers. They find that the direct costs of a policy to conserve energy still outweigh the benefits of induced innovation. Gillingham et al. (2008) point out that, more generally, climate policy under endogenous technical change is likely to raise output in the long run only if knowledge spillovers are higher among clean technologies than among dirty ones, to which the R&D effort would otherwise be directed.

Goulder & Schneider (1999) distinguish between appropriable knowledge and nonexcludable knowledge as a way to incorporate intrasectoral spillovers into their multisector general equilibrium model. Furthermore, they assume diminishing returns to both types of knowledge in the production function of each intermediate-good industry. They find that endogenous technical change lowers the cost of meeting a given abatement target, but policy costs are still positive in their parameterization, meaning that the crowding-out effect is more important than the spillover effect.

Sue Wing (2003) builds on this dynamic general equilibrium approach and considers sector-specific knowledge services that are a function of both relative prices and economy-wide knowledge, with decreasing returns to innovation as knowledge accumulates. He finds that with a fixed-saving rule and without knowledge spillovers, a carbon tax reduces aggregate R&D and slows growth; however, the shifting of knowledge-producing resources toward cleaner production technologies lowers the cost of the carbon tax relative to the cost in a situation without endogenous technical change. Golosov et al. (2011) use a new dynamic public finance model to study optimal carbon taxes. They include endogenous technological change in their model and find that the degree of substitutability between alternate energy sources is an important determinant of the magnitude of the welfare gains of optimal policy.

In sum, the literature for the most part agrees that opportunities for technological change tend to lower the cost of meeting environmental goals. However, it also indicates that, unless knowledge spillovers are substantial—and in particular much larger in clean technologies than in dirty ones—climate policies are still likely to have negative consequences for growth.

4. CONCLUSION

We survey two topics in which economists are using methods from macroeconomics to address issues related to environmental economics. First, several recent papers utilize RBC models to study environmental policy, asking questions about optimal policy design in the presence of autocorrelated productivity shocks. Second, a recent literature on DTC has emerged, combining growth theory with endogenous progress in clean energy technology.

The literature incorporating pollution into the RBC model addresses questions about policy responses to business cycles. It finds that, in an optimal framework, both emissions and emissions prices should respond in procyclical fashion to macroeconomic shocks. For policies that are fixed ex ante, it finds that, although emissions caps do play a role as an automatic stabilizer and limit

economic volatility to some extent, the policy is not necessarily preferred from a welfare perspective. For example, emissions taxes allow for more flexible responses to a wider range of shocks, and intensity targets can preserve incentives for capital investment and long-run growth. More work can be done to provide the same analysis in more refined and detailed business cycle models, including models with shocks besides factor productivity shocks. Besides addressing optimal policy design, empirical papers can estimate the magnitude and direction of emissions response to macroeconomic shocks, as well as the variation of health effects and other damages from emissions over the business cycle.

The DTC literature emphasizes the importance of endogenous technological growth for environmental policy. Although this finding is not new, the emphasis on path dependency in this literature highlights the potential need for immediate action. In particular, this literature offers the intriguing result that temporary interventions, with a heavy focus on supporting innovation in clean technologies, may be sufficient to meet climate policy goals. Although this literature provides valuable theoretical intuition, more work must be done to identify reasonable model parameters before specific policy recommendations are derived. Several areas that require attention include the nature of technological progress, the degree and form of spillovers, and particularly the substitutability between clean production technologies and dirty production technologies.

Both areas of research are in the preliminary stage, and many opportunities for expansions remain. For instance, none of the papers cited, and none of the other papers using macroeconomic models to address environmental policy, include models that treat pollution or environmental services as contributing to preferences in a nonseparable fashion. This oversight exists despite the decades of research finding that nonseparability matters (e.g., Carbone & Smith 2008).

Fundamentally, both of these nascent strains of literature ask how environmental policies should cope with transitions in the broader economy, whether from exogenous macroeconomic shocks or from endogenous technological change. Given the current economic situation of well-below-full employment, as well as the growing economic scale of environmental challenges like climate change, environmental policy makers are arguably facing more complex trade-offs than ever before. As these kinds of trade-offs cannot be represented in the traditional workhorse models of environmental microeconomics, more researchers will need to explore and expand the frontier with macroeconomics.

DISCLOSURE STATEMENT

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LITERATURE CITED

- Acemoglu D, Aghion P, Bursztyn L, Hémous D. 2012. The environment and directed technical change. *Am. Econ. Rev.* 102:131–66
- Adao B, Narajabad B, Temzelides T. 2012. *A model with spillovers in the adaptation of new renewable technologies*. Work. Pap., Dep. Econ., Rice Univ., Houston

- Aghion P, Dechezleprêtre A, Hémous D, Martin R, Van Reenan J. 2012. *Carbon taxes, path dependency and directed technical change: evidence from the auto industry*. Work. Pap., Natl. Bur. Econ. Res. (NBER), Cambridge, Mass.
- Angelopoulos K, Economides G, Philippopoulos A. 2010. *What is the best environmental policy? Taxes, permits and rules under economic and environmental uncertainty*. Work. Pap., CESifo
- Bartik TJ. 2012. Including jobs in benefit-cost analysis. *Annu. Rev. Resour. Econ.* 4:55–73
- Bencivenga V. 1992. An econometric study of hours and output variation with preference shocks. *Int. Econ. Rev.* 33:449–71
- Benhabib J, Rogerson R, Wright R. 1991. Homework in macroeconomics: household production and aggregate fluctuations. *J. Polit. Econ.* 99:1166–87
- Blanchard O, Quah D. 1989. The dynamic effects of aggregate demand and supply disturbances. *Am. Econ. Rev.* 79:655–73
- Brock W, Taylor MS. 2005. Economic growth and the environment: a review of theory and empirics. In *Handbook of Economic Growth*, ed. P Aghion, S Durlauf, pp. 1,749–1,821. Amsterdam: North-Holland
- Cai Y, Judd K, Lontzek T. 2013. *The social cost of stochastic and irreversible climate change*. Work. Pap., NBER, Cambridge, Mass.
- Carbone J, Smith VK. 2008. Evaluating policy interventions with general equilibrium externalities. *J. Public Econ.* 92:1254–74
- Chang Y, Kim S-B. 2007. Heterogeneity and aggregation: implications for labor-market fluctuations. *Am. Econ. Rev.* 97:1939–56
- Christiano L, Eichenbaum M, Vigfusson R. 2003. *What happens after a technology shock?* Work. Pap., NBER, Cambridge, Mass.
- Dasgupta P, Heal G. 1974. The optimal depletion of exhaustible resources. *Rev. Econ. Stud.* 41:3–28
- Davis S, Haltiwanger J. 2001. Sectoral job creation and destruction responses to oil price changes. *J. Monet. Econ.* 48:465–512
- Dhawan R, Jeske K, Silos P. 2010. Productivity, energy prices and the great moderation: a new link. *Rev. Econ. Dyn.* 13:715–24
- Dissou Y, Karnizova L. 2012. *Emissions cap or emissions tax? A multi-sector business cycle analysis*. Work. Pap., Dep. Econ., Univ. Ottawa
- Doda B. 2012. *Evidence on CO₂ emissions and business cycles*. Work. Pap., Grantham Res. Inst. Clim. Change Environ.
- Fischer C, Newell R. 2008. Environmental and technology policies for climate mitigation. *J. Environ. Econ. Manag.* 55:142–62
- Fischer C, Springborn M. 2011. Emissions targets and the real business cycle: intensity targets versus caps or taxes. *J. Environ. Econ. Manag.* 62:352–66
- Fischer S. 1977. Long-term contracts, rational expectations, and the optimal money supply rule. *J. Polit. Econ.* 85:191–205
- Galí J. 1999. Technology, employment, and the business cycle: Do technology shocks explain aggregate fluctuations? *Am. Econ. Rev.* 89:249–71
- Galí J. 2004. On the role of technology shocks as a source of business cycles: some new evidence. *J. Eur. Econ. Assoc.* 2:372–80
- Gillingham K, Newell R, Pizer W. 2008. Modeling endogenous technological change for climate policy analysis. *Energy Econ.* 30:2734–53
- Golosov M, Hassler J, Krusell P, Tsyvinski A. 2011. *Optimal taxes on fossil fuel in general equilibrium*. Work. Pap., NBER, Cambridge, Mass.
- Goulder L, Schneider S. 1999. Induced technological change and the attractiveness of CO₂ abatement policies. *Resour. Energy Econ.* 21:211–53
- Greaker M, Heggedal T-R. 2012. *A comment on the environment and directed technical change*. CREE Work. Pap. 13/2012, Frisch Cent., Oslo, Nor.
- Greenstone M. 2002. The impacts of environmental regulations on industrial activity: evidence from the 1970 and 1977 Clean Air Act amendments and the Census of Manufactures. *J. Polit. Econ.* 110:1175–219

- Greenstone M, List J, Syverson C. 2012. *The effects of environmental regulation on the competitiveness of US manufacturing*. Work. Pap., NBER, Cambridge, Mass.
- Hansen G. 1985. Indivisible labor and the business cycle. *J. Monet. Econ.* 16:309–27
- Hémous D. 2012. *Environmental policy and directed technical change in a global economy: the dynamic impact of unilateral environmental policies*. Work. Pap., INSEAD, Fontainebleau, Fr.
- Heutel G. 2012. How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks. *Rev. Econ. Dyn.* 15:244–64
- Heutel G, Ruhm C. 2012. *Air pollution and procyclical mortality*. Work. Pap., Univ. N. C., Greensboro
- Hourcade J-C, Pottier A, Espagne E. 2012. *The environment and directed technical change: comment*. Work. Pap. 646, Fond. Eni Enrico Mattei. <http://www.bepress.com/feem/paper646>
- Kim I-M, Loungani P. 1992. The role of energy in real business cycle models. *J. Monet. Econ.* 29:173–89
- Kydland F, Prescott E. 1982. Time to build and aggregate fluctuation. *Econometrica* 50:1345–69
- Mattauch L, Creutzig F, Edenhofer O. 2012. *Avoiding carbon lock-in: policy options for advancing structural change*. Work. Pap. 1, Dep. Clim. Change Econ., Tech. Univ. Berlin
- Metcalf G. 2009. Market-based policy options to control US greenhouse gas emissions. *J. Econ. Perspect.* 23:5–27
- Narayan P, Narayan S, Smyth R. 2011. Energy consumption at business cycle horizons: the case of the United States. *Energy Econ.* 33:161–67
- Nordhaus W. 2008. *A Question of Balance*. New Haven, CT: Yale Univ. Press
- Peretto P. 2009. Energy taxes and endogenous technological change. *J. Environ. Econ. Manag.* 57:269–83
- Pizer W. 1999. The optimal choice of climate change policy in the presence of uncertainty. *Resour. Energy Econ.* 21:255–87
- Popp D. 2004. ENTICE: endogenous technological change in the DICE model of global warming. *J. Environ. Econ. Manag.* 48:742–68
- Popp D. 2010. Innovation and climate policy. *Annu. Rev. Resour. Econ.* 2:275–98
- Ruhm C. 2000. Are recessions good for your health? *Q. J. Econ.* 115:617–50
- Smith V, Wolloch C. 2012. *Has surface water quality improved since the Clean Water Act?* Work. Pap., NBER, Cambridge, Mass.
- Smulders S, de Nooij M. 2003. The impact of energy conservation on technology and economic growth. *Resour. Energy Econ.* 25(1):59–79
- Smulders S, Di Maria C. 2012. *The cost of environmental policy under induced technical change*. Work. Pap. 3,886, CESifo
- Stiglitz J. 1974. Growth with exhaustible natural resources: efficient and optimal growth paths. *Rev. Econ. Stud.* 41:123–37
- Sue Wing I. 2003. *Induced technical change and the cost of climate policy*. Rep. 112, Jt. Program Sci. Policy Glob. Change, Mass. Inst. Technol., Cambridge, Mass.
- Sue Wing I, Ellerman A, Song J. 2009. Absolute vs. intensity limits for CO₂ emission control: performance under uncertainty. In *The Design of Climate Policy*, ed. H Tulkens, R Guesnerie, pp. 221–52. Cambridge, MA: Mass. Inst. Technol. Press
- US Environ. Prot. Agency Off. Air Radiat. (US EPA). 2011. *The benefits and costs of the Clean Air Act from 1990 to 2020*. Rep., EPA, Washington, DC. http://www.epa.gov/air/sect812/feb11/fullreport_rev_a.pdf
- Xepapadeas A. 2005. Economic growth and the environment. In *Handbook of Environmental Economics*, ed. K-G Mäler, J Vincent, pp. 1,219–71. Amsterdam: North-Holland



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Errata

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