ENVIRONMENTAL MACROECONOMICS:
ENVIRONMENTAL POLICY, BUSINESS CYCLES, AND DIRECTED TECHNICAL CHANGE

Garth Heutel
Carolyn Fischer

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Garth Heutel and Carolyn Fischer
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## ABSTRACT

Environmental economics has traditionally fallen in the domain of microeconomics, but recently approaches
from macroeconomics have 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 be used to answer several questions. How can 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 to both tackle emissions directly and influence the adoption
of clean technologies. We focus on these two aspects of environmental macroeconomics but emphasize
that there are many other potential applications.

Garth Heutel
Bryan 466, Department of Economics
University of North Carolina at Greensboro
P. O. Box 26170
Greensboro, NC 27402
and NBER
gaheutel@uncg.edu

Carolyn Fischer
Resources for the Future
1616 P Street, NW
Washington, DC 20036
fischer@rff.org

I. Introduction

        Environmental policy papers typically approach their issues from a microeconomic perspective. Microeconomic theoretical and empirical analysis are usually used to answer questions about the effect of pollution on health, the effect of policy on pollution, or 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 costs of environmental rules domestically are big. Greenstone et. al. (2012) find that air quality regulations cost the manufacturing industry roughly $21 billion per year, about 8.8% of profits. The Second Prospective Report conducted by the 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 paper, we survey some recent literature in two particular areas that combine environmental and macroeconomics. First, we discuss the literature combining real business cycle models with environmental policy. Incorporating pollution into a standard real business cycle framework allows the model to address questions about the relationship between environmental policies and economics fluctuations. Second, we discuss a new strand in the growth literature on environmental policy and induced technological progress. This directed technical change literature stresses the importance of path dependency in environmental technology policy.

We stress that this is not a comprehensive listing of every paper that could fall into the category of environmental and macroeconomics. Indeed, nearly every integrated assessment model of environmental policy, such as the DICE model (Nordhaus 2008), could qualify as a macroeconomic model, as could multi-sector general equilibrium models used to evaluate economywide policies. Likewise for any study that incorporates endogenous growth (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). Instead, we choose to focus on two particular areas at the nexus of environmental 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.

## II. 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 long literature in 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 real business cycle (RBC) framework and add pollution; these are Fischer and Springborn (2011), Heutel (2012), and Angelopoulos et. al (2010). The standard RBC model was developed in papers including Kydland and Prescott (1982). The model is a dynamic stochastic general equilibrium (DSGE) model. A representative consumer is optimizing 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 and 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 and 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 is $M_t$, and its share of total factor inputs is given by the standard Cobb-

Douglas solution:

$$\frac{M_t}{Y_t} = \frac{\gamma\left(1 + \hat{\phi}_t A_{t,Y}\right)}{1 + \hat{\phi}_t}$$

The normalized shadow value of the emissions policy is $\hat{\phi}_t$, and $A_{t,Y}$ represents the derivative

of the emissions constraint with respect to output (allowing for the cap to be a function of total

output).In Fischer and Springborn (2011), abatement technology is not modeled explicitly;

emissions changes occur through factor substitution and changes in output.

In Heutel (2012), emissions are a byproduct of production; total output is directly

correlated with total emissions.  Abatement technology is available, where 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

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

where $\mu \in [0,1]$ represents the fraction of emissions abated, and the function $h$ 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 byproduct 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 $\phi_t$ is a stochastic, exogenous variable representing pollution technology. The flow of pollution affects the stock of environmental quality ($Q_t$) according to

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

The pollution stock is affected by 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, while Fischer and Springborn (2011) do not model damages explicitly.

In addition to the different ways in which the papers model pollution, the papers differ in the questions they address. Fischer and 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.

They 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 does the other two policies. On the other hand, the cap and tax policies offer lower present value costs due to higher consumption while 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 (since 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 does. In fact, it provides a higher level of capital than in the no policy case. Because the intensity target allows 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 and 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 can adapt to the business cycle to maximize social welfare. Neither the tax rate nor the value of the cap is constant over the business cycle. If, say, the optimal tax rate is allowed to respond to the business cycle, will it be procyclical (the tax rate increases during expansions) or countercyclical (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. It has been suggested that the clearing price of emissions permits in the initial auction of the Regional Greenhouse Gas Initiative (RGGI) was much lower than expected because the cap did not adjust to reduced demand brought on by the recession (Metcalf 2009).

Heutel (2012) finds that both the optimal tax policy and the optimal cap policy are procyclical. Both an emissions tax and an emissions quota increase during expansions but 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, while 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 vary without any policy. Therefore, a cap allows emissions to rise during expansions, but by less so than they would have risen without the cap. The same result can be achieved with an emissions tax, where 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 and Springborn (2011), Angelopoulos et. al (2010) uses a RBC model with pollution to compare the performance of three different policies. They compare a tax, a cap, and what they call "Kyoto-like rules," which are rules that specify how fast emissions must decrease from one period to the next. Their 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. The first they call "economic uncertainty" and the second "environmental uncertainty." The second difference between their model and the models in

Fischer and Springborn (2011) and Heutel (2012) is in their modeling of government abatement. In Fischer and 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 only be made by the government. Government abatement does not affect the flow of emissions, instead it 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 means that there is a need in this model for government revenue from environmental policy. The revenue, from either tax receipts or the auctioning of permits, all goes towards government abatement. Their third policy, 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 they 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 them the advantage when environmental uncertainty is high.

A fourth paper that uses an RBC model to analyze pollution policy is Dissou and Karnizova (2012). The focus of this paper is again a ranking between alternative policy instruments in the presence of persistent productivity shocks. In this case, two policies are compared to each other: taxes and permits. The innovation of Dissou and 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 are in energy: coal, electricity, and oil and gas. The other three sectors are services, energy-intensive goods, and energy non-intensive goods. Each of the six sectors experiences its own autocorrelated productivity shock.

As do Fischer and Springborn (2011), Dissou and 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 non-energy 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 is puzzling, since the cap results in lower volatility than does the tax. The explanation is that in their model the cap reduces, relative to the tax, not just the variance of economic variables like consumption but also their means. The cap limits the ability of the economy to respond to energy-sector productivity shocks more so than does the tax.

All of these papers share the use of the RBC framework for analysis of environmental policy. Three of the four papers are about ranking different static policies, while the other (Heutel 2012) is about finding the optimal dynamic policy. Both Fischer and Springborn (2011)

and Heutel (2012) contain just a single type of TFP shock, while Angelopoulos et. al (2010) contains both a TFP shock and a shock to emissions, and Dissou and Karnizova (2012) contains a separate productivity shock for each sector of the economy. All include pollution as a byproduct of production (either by modeling it as such or as an input to the production process), while only Heutel (2012) includes the damages from pollution in welfare analysis.

Pizer (1999), while not a paper that is explicitly about business cycles, nevertheless uses tools similar to RBC models. The question motivating this paper is how uncertainty, rather than shocks to productivity, affect the optimal design of climate change policy. He employs a stochastic growth model in which shocks to labor productivity are present. These shocks provide uncertainty, but the uncertainty that this paper is focused 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 calls "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 enriched 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 and Springborn (2011) and Dissou and 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 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 (Benzivinga 1988). Chang and 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 are often modeled as drivers of the business cycle rather than real productivity shocks. In fact, Gali (1994, 2004) argues business cycles are not explained by productivity shocks, while Christiano et. al. (1993) defend productivity shocks. While 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 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 have tackled similar issues. One literature examines the role of energy prices in business cycles. Kim and Loungani (1992) add to the

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

standard RBC model energy as an intermediate input.  Energy prices are determined exogenously

and, like productivity shocks, are autocorrelated.  Although Kim and 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.  They find that including oil price shocks in addition to TFP shocks

improves the predictions of the RBC model.  In particular, it 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 including oil price shocks.

Several other papers follow Kim and Loungani (1992) by adding oil price shocks to a

standard RBC model.  Davis and Haltiwanger (2001) examine how oil price shocks affect the

creation and destruction of manufacturing jobs.  Theirs is not an agent-based DSGE model;

rather, they use sectoral vector autoregressions (VARs).  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.

Afterwards, that link disappeared, and the disappearance of that correlation helped explain the

great moderation starting in 1982.  They 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 and Quah (1989)) and add energy.  They want to

know if permanent or transitory shocks explain variance in energy consumption.  It was

permanent shocks at short horizons that 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? While the previous RBC papers examine how environmental policy ought to vary with the business cycle, in fact it does not. On the other hand, it seems reasonable to assume that the quality of the environment, whether measured by the stock of greenhouse gases or 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 and 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 about as clean as it was 40 years ago. Though 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 U.S. from 1975-2011. 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 how this correlation would come about other than 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 ($CO_2$) emissions to the business cycle. This is estimated because, in the normative model, the response of $CO_2$ emissions to output is a necessary parameter, and it is one that has not been estimated previously. Heutel (2012) uses quarterly data on total $CO_2$ emissions in the United States and estimates a series of regressions with $CO_2$ 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 are performed, including seasonal ARIMA models and regression on HP-filtered data. Across regressions, Heutel (2012) finds that 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 1 percentage point above trend, emissions increases but by less than one percentage point above trend.[2] These estimated coefficient values are consistent with an empirical result found in Kim and Loungani (1992). In that paper, the estimated correlation between the cyclical components of energy use and output is 0.72. Though Kim and Loungani (1992) estimate the correlation for energy use and not for carbon emissions, the high correlation between those two explains the consistency of these two estimates. Doda (2012) also examines the cyclicality of emissions, looking at data across a panel of countries, rather than just the US. He finds that emissions are procyclical and more volatile than GDP, and their volatility is negatively correlated with GDP.

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

Heutel and 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 microns in diameter (PM10).  They develop a state-year level measure of ambient pollution for each pollutant, based on readings of ambient air quality at various monitors around the US.  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 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.  It is likely that cyclical fluctuations in emissions of carbon dioxide and other greenhouse gases are unimportant because these are stock pollutants with very low decay rates.  However, for other, flow, pollutants, their volatility over the business cycle may have important policy implications.

III. Directed Technical Change and Environmental Policy

In this section, we discuss another strand of literature that studies macroeconomic transitions. The real business cycle literature explores how transitory fluctuations in productivity over time interact with the performance of environmental policies. The literature on directed technical change (DTC) explores how transitory environmental policy can engender permanent changes in the sustainability of macroeconomic growth.

As noted, there exists a substantial literature on endogenous growth, natural or exhaustible resources, and the environment. In the 1970's, great attention was paid to the limits to growth that reliance on exhaustible resources might pose, and how those resources might be optimally exploited (e.g., Dasgupta and Heal 1974; Stiglitz 1974). In more recent years, the damages or constraints imposed by pollution, including climate change, have refocused attention toward questions related to optimal growth and emissions taxes, or the sustainability of growth with pollution damages (see, e.g., Xepapadeas 2005, Brock and Taylor 2005, Peretto 2009, Smulders and 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 responds when technological innovation is endogenous, and empirical studies establish the responsiveness of innovation measures to environmental policies (see, e.g. Popp 2004, Gillingham et al. 2008, Fischer and Newell 2008, Popp 2010, Adao et. al. 2012).

The DTC literature combines aspects of these two strands, but has a distinguishing feature of focusing on a particular kind of transition. It recognizes that innovation can occur in pollution-creating as well as 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 observed, "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, and Hémous (2012, henceforth AABH) introduce environmental constraints into a growth model with competing applications of innovation. A single final good is created using dirty 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 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 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, since patent horizons are a single year. The optimal policy thus combines a carbon tax and a research subsidy (internalizing both market failures), and they find a more important role for the latter. Furthermore, they find interesting effects on the time profile of policy interventions, based largely on the substitutability of clean and dirty inputs.

AABH find that when the dirty and clean inputs are highly substitutable, environmental policies need only apply for a temporary period, until technological change is sufficiently redirected and the clean technologies outcompete the dirty ones. However, action must be

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[3] The notion of a threshold or technological regime switching in environmental and resource policy extends at least as far back as Dasgupta and 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.

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

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 model with two countries, and thus emissions leakage from the regulating "North" to the laissez-faire "South." Two final goods are produced, one nonpolluting and the other polluting; 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 and allow the North to develop a comparative advantage in the polluting sector, reducing emissions in the South, which then specializes in the cleaner good, and also in the North, as production of the polluting good becomes cleaner. Again these interventions can be temporary; furthermore, with emissions leakage, directed technical change 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 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 have focused on the specific set of modeling and parameter assumptions used, particularly for the appealing case of a temporary intervention. Hourcade et al. (2011) 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 and dirty sectors. However, although this case appears optimistic, the implications for growth are much more substantial than previously interpreted; they 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 in the clean technology sector, rather than directed R&D. They also find that a scenario with a high elasticity of substitution between the sectors allows for more modest policy interventions, but the welfare cost implications are larger, since technology "lock-in" is stronger under laissez-faire in this 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) compared approaches to modeling R&D-induced technological change and identified several key aspects: pre-existing 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.

In AABH, R&D is allocated from a fixed and finite supply of scientists, implying perfect crowding out of research effort. While 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 (since that is fixed), but it 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 and Heggedahl (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 depends importantly on the degree of spillovers, in this case intertemporal ones.

Smulders and 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 to climate policy? The 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 only likely to raise output in the long run if knowledge spillovers are higher among clean technologies than dirty ones, where the R&D effort would otherwise be directed.

Goulder and Schneider (1999) distinguish between appropriable and non-excludable knowledge, as a way to incorporate intrasectoral spillovers in their multi-sector general

equilibrium model. Furthermore, they assume diminishing returns to both types of knowledge in the production function of each intermediate good industry. The find that endogenous technical change lowers the cost of meeting a given abatement target, but policy costs are still positive in their parameterization, meaning 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 economywide 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 a situation without endogenous technical change. Golosov et. al. (2011) use a new dynamic public finance model to study optimal carbon taxes. Included in their model is endogenous technological change, and they find that the degree of substitutability between alternate energy sources is an important determinant for 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.


IV. 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 real

business cycle models to study environmental policy, asking questions about optimal policy design in the presence of autocorrelated productivity shocks. Second, a recent literature on directed technical change has emerged, combining growth theory with endogenous progress in clean energy technology.

The literature incorporating pollution into the real business cycle model has addressed questions about policy responses to business cycles. It finds that, in an optimal framework, both emissions and emissions prices respond in pro-cyclical fashion to macroeconomic shocks. For policies that are fixed *ex ante*, it finds that while emissions caps do play a role as an automatic stabilizer, limiting 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 optimal policy design, empirical papers can estimate how cyclical emissions are, and how the health effects and other damages from emissions vary over the business cycle.

The directed technical change literature emphasizes the importance of endogenous technological growth for environmental policy. While this finding is not new, the emphasis on path dependency in this literature highlights the potential need for immediate action. In particular, it offers the intriguing result that temporary interventions, with a heavy focus on supporting innovation in clean technologies, might be sufficient to meet climate policy goals. While this literature provides valuable theoretical intuition, more work must be done to identify reasonable model parameters before deriving specific policy recommendations. Several areas

require attention, including the nature of technological progress, the degree and form of spillovers, and particularly the substitutability between clean 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, nor any other papers using macroeconomic models to address environmental policy, include models that treat pollution or environmental services as contributing to preferences in a non-separable fashion. This oversight exists despite the decades of research finding that non-separability matters (e.g. Carbone and Smith 2008).

Fundamentally, both of these nascent strains of literature ask how environmental policies can cope with transitions in the broader economy, whether from exogenous macroeconomic shocks or 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 policymakers are arguably facing more complex tradeoffs than ever before. As these kinds of tradeoffs cannot be represented in the traditional workhorse models of environmental microeconomics, more researchers will need to explore and expand the frontier with macroeconomics.

**References**

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hémous. 2012. The Environment and Directed Technical Change. American Economic Review 102, 131–166.

Adao B, Narajabad B, Temzelides T. 2012. *A model with spillovers in the adaptation of new renewable technologies*. Work. Pap., Rice University.

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., NBER.

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 T. 2012. Including jobs in benefit-cost analysis. *Annu. Rev. Resour. Econ.* 4: 55–73.

Benhabib J, Rogerson R, Wright R. 1991. Homework in macroeconomics: Household production and aggregate fluctuations. *J. Political Econ.* 99: 1166–1187.

Bencivenga V. 1992. An econometric study of hours and output variation with preference shocks. *International Econ. Rev.* 33: 449–471.

Blanchard O, Quah D. 1989. The dynamic effects of aggregate demand and supply disturbances. *Amer. Econ. Rev.* 79: 655–673.

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. North-Holland, Amsterdam.

Cai Y, Judd K, Lontzek T. 2013. *The Social Cost of Stochastic and Irreversible Climate Change*. Work. Pap., NBER.

Carbone J, Smith VK. 2008. Evaluating policy interventions with general equilibrium externalities. *J. Pub. Econ.* 92: 1254–1274.

Chang Y, Kim S-B. 2007. Heterogeneity and aggregation: Implications for labor-market fluctuations. *Amer. Econ. Rev.* 97: 1939–1956.

Christiano L, Eichenbaum M, Vigfusson R. 2003. *What happens after a technology shock?*. Work. Pap., NBER.

Dasgupta P, Heal G. 1974. The optimal depletion of exhaustible resources. *Rev. Econ. Stud.* 41(Symposium on the Economics of Exhaustible Resources): 3–28.

Davis S, Haltiwanger J. 2001. Sectoral job creation and destruction responses to oil price changes. *J. Monetary Econ.* 48: 465–512.

Dhawan R, Jeske K, Silos P. 2010. Productivity, energy prices and the great moderation: A new link. *Rev. Econ. Dynamics.* 13: 715–724.

Dissouu Y, Karnizova L. 2012. *Emissions cap or emissions tax? A multi-sector business cycle analysis*. Work. Pap., Univ. of Ottawa.

Doda B. 2012. *Evidence on $CO_2$ emissions and business cycles*. Work. Pap., Grantham Research Institute on Climate Change and the Environment.

Fischer S. 1977. Long-term contracts, rational expectations, and the optimal money supply rule. *J. Political Econ.* 85: 191–205.

Fischer C, Newell R. 2008. Environmental and technology policies for climate mitigation. *J. Environ. Econ. Manag.* 55: 142–162.

Fischer C, Springborn M. 2011. Emissions targets and the real business cycle: Intensity targets versus caps or taxes. *J. Environ. Econ. Manag.* 62: 352–366.

Galí J. 1999. Technology, employment, and the business cycle: Do technology shocks explain aggregate fluctuations? *Amer. Econ. Rev.* 89: 249–271.

Galí J. 2004. On the role of technology shocks as a source of business cycles: Some new evidence. *J. European Econ. Assoc.* 2: 372–380.

Gillingham K, Newell R, Pizer W. 2008. Modeling endogenous technological change for climate policy analysis. *Energy Econ.* 30: 2734–2753.

Golosov M, Hassler J, Krusell P, Tsyvinski A. 2011. *Optimal taxes on fossil fuel in general equilibrium*. Work. Pap., NBER.

Goulder, L., Schneider, S., 1999. Induced technological change and the attractiveness of CO2 abatement policies. *Resour. Energy Econ.* 21, 211–253.

Greaker, Mads and Tom-Reiel Heggedal. 2012. A Comment on the Environment and Directed Technical Change. CREE Working Paper 13/2012. Oslo, Norway: Frisch Center.

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: 1175–1219.

Greenstone M, List J, Syverson C. 2012. *The effects of environmental regulation on the competitiveness of U.S. manufacturing*. Work. Pap., NBER.

Hansen G. 1985. Indivisible labor and the business cycle. *J. Monetary Econ.* 16: 309–327.

Hémous D. 2012. *Environmental policy and directed technical change in a global economy: the dynamic impact of unilateral environmental policies*. Work. Pap., INSEAD.

Heutel G. 2012. How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks. *Rev. Econ. Dynamics*. 15: 244–264.

Heutel G, Ruhm C.  2012.  *Air pollution and procyclical mortality*.  Work. Pap., Univ. of North

   Carolina at Greensboro.

Hourcade, Jean-Charles, Antonin Pottier, and Etienne Espagne, The Environment and Directed

   Technical Change: Comment (January 31, 2012). Fondazione Eni Enrico Mattei Working

   Papers. Working Paper 646. http: //www.bepress.com/feem/paper646

Kim I-M, Loungani P.  1992.  The role of energy in real business cycle models.  *J. of Monetary*

   *Econ.*  29: 173-189.

Kydland F, Prescott E.  1982.  Time to build and aggregate fluctuation.  *Econometrica*.  50:

   1345-1369.

Mattauch, Linus, Felix Creutzig, and Ottmar Edenhofer. 2012. Avoiding Carbon Lock-In: Policy

   Options for Advancing Structural Change. Working Paper 1, Department of Climate

   Change Economics, TU Berlin.

Metcalf G.  2009.  Market-based policy options to control US greenhouse gas emissions. *J. Econ.*

   *Perspectives.*  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: 161-167.

Nordhaus W. 2008.  *A Question of Balance*.  New Haven: Yale University Press.

Peretto P.  2009.  Energy taxes and endogenous technological change.  *J. Environ. Econ. Manag*.

   57: 269-283.

Pizer W.  1999.  The optimal choice of climate change policy in the presence of uncertainty.

   *Resource Energy Econ.*  21: 255-287.

Popp D.  2004.  ENTICE: endogenous technological change in the DICE model of global

   warming.  *J. Environ. Econ. Manag*.  48: 742-768.

Popp, D. 2010. Innovation and Climate Policy. Annual Review of Resource Economics 2(1): 275-298.

Ruhm C. 2000. Are recessions good for your health? *Quarterly J. Econ.* 115: 617-650.

Smith V, Wolloh C. 2012. *Has surface water quality improved since the Clean Water Act?* Work. Pap., NBER.

Smulders, S., de Nooij, M., 2003. The impact of energy conservation on technology and economic growth. Resource and Energy Economics 25 (1), 59–79.

Smulders, Sjak and Corrado Di Maria. 2012. The Cost of Environmental Policy under Induced Technical Change. CESifo Working Paper No. 3886 (July 2012).

Stiglitz J. 1974. Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths. *Rev. Econ. Stud.* 41(Symposium on the Economics of Exhaustible Resources): 123–137.

Sue Wing, I., 2003. Induced technical change and the cost of climate policy. Joint Program on the Science and Policy of Global Change Report no. 112. Massachusetts Institute of Technology, Cambridge, MA.

Sue Wing I, Ellerman A, Song J. 2009. Absolute vs. intensity limits for $CO_2$ emission control: Performance under uncertainty. In *The Design of Climate Policy*, ed. H Tulkens, R Guesnerie. Cambridge: MIT Press.

U.S. Environmental Protection Agency Office of Air and Radiation. 2011. The benefits and costs of the Clean Air Act from 1990 to 2020.

Xepapadeas, Anastasios. 2005. Economic Growth and the Environment. Handbook of Environmental Economics, edited by KarlGöran Mäler and Jeffrey Vincent.