What is the Best Environmental Policy? Taxes, Permits and Rules under Economic and Environmental Uncertainty

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Abstract

We study the importance of uncertainty and public finance to the welfare ranking of three environmental policy instruments: pollution taxes, pollution permits and Kyoto-like numerical rules for emissions. The setup is the basic stochastic neoclassical growth model augmented with the assumptions that pollution occurs as a by-product of output produced and environmental quality is treated as a public good. To compare alternative policies, we compute welfare-maximizing values for the second-best policy instruments. We find that, in all cases studied, pollution permits are the worst policy choice, even when their revenues finance public abatement. When the main source of uncertainty is economic, the most efficient recipe is to levy pollution taxes and use the collected tax revenues to finance public abatement. However, when environmental uncertainty is the dominant source of extrinsic uncertainty, numerical rules, being combined with tax-financed public abatement, are better than pollution taxes.

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1. Introduction

Environmental degradation caused by human activities is a main concern worldwide. When economic agents do not internalize the effects of their actions on the environment, there is need for government intervention to enact appropriate policies that deal with the negative externalities of pollution emissions. Policy intervention can take many forms. It is thus useful to be able to rank alternative environmental policies according to certain criteria, so that the society can choose the best one.

Examples of environmental policy instruments include pollution taxes, pollution permits (also known as cap-and-trade policy) and numerical targets for cutting emissions (also known as command-and-control policy).[1] All three are distorting and so second best. In the case of taxes, the government raises the price of pollution-generating activities. In the case of permits, the government creates a market for pollution, by issuing a number of permits, and firms pollute as much as they wish to the extent that they pay the price. In the case of numerical targets, the government sets an emission standard directly so that firms have to restrict their production accordingly and/or make particular technology and fuel choices. Although this list is not exhaustive,[2] there has always been a lot of interest in the relative desirability of these three instruments by both policymakers and researchers (among researchers, see e.g. Stokey, 1998, section 6).

Two issues are particularly important to the debate on the choice of the appropriate policy instrument. The first issue has to do with the size and source of uncertainty. In assessing the risks from climate change and the costs of averting it, there is a variety of uncertainties that contribute to big differences of opinion as to how, and how much, to limit emissions (on uncertainty and the environment, see e.g. the Congressional Budget Office paper prepared for the Congress of the US, 2005). The second issue refers to the public finance requirements of environmental protection. It is recognized that the more ambitious is the environmental policy, the higher the finance requirements for adaptation and mitigation actions,[3] and public

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[1] An example of numerical targets is the reduction of emissions by 25-40% compared to 1990 levels by 2020. Such rules were a key part of the Kyoto protocol designed in 1997 and continue to be a debated issue (see the Copenhagen UN Conference in December 2009).

[2] For other second-best policy instruments to reduce pollution, see e.g. Goulder et al. (1999) and Bovenberg and Goulder (2002).

[3] According to the European Commission's estimates, finance requirements could reach 100 billion euros per year by 2020 in developing countries only (see the Communication from the European Commission, 2009).

finance should play a key role in meeting these requirements (on finance and the environment, see e.g. the Communication from the European Commission, 2009).[4]

In this paper, we study the roles of uncertainty and public finance in the welfare ranking of alternative environmental policies in a micro-founded dynamic stochastic general equilibrium (DSGE) model. Motivated by the above, we focus on the three following policy regimes. We first model the case in which the government levies taxes on polluting activities and uses the collected tax revenues to finance public abatement activities. We then study the case in which public abatement activities are financed by the sale of auctioned pollution permits. We finally study the case in which environmental policy takes the form of binding numerical rules à la Kyoto, which specify both a long-term pollution target and the speed to that target over time.

Our setup is a basic stochastic neoclassical growth model augmented with the assumptions that pollution occurs as a by-product of output produced and environmental quality has a public good character. Within this setup, there is reason for policy intervention. There are two exogenous stochastic processes that create uncertainty about future outcomes. The first is uncertainty about production technology (standard shocks to total factor productivity) and the second arises from uncertainty about the impact of economic activity on the environment.[5] Loosely speaking, we call the former shock "economic" and the latter "environmental".

We study the implications of the above three policy regimes for economic outcomes (output, consumption, etc), environmental quality and, ultimately, social welfare. The latter is defined as the conditional expectation of the discounted sum of household's lifetime utility. Since the equilibrium solution in each regime depends on the value of the second-best policy instruments employed, we compare the alternative policy regimes when the policy instruments under each regime take their welfare-maximizing values. We focus on flat over time policy instruments (see also e.g. Stokey and Rebelo, 1995). To solve the model and compute the associated welfare under each policy regime, we approximate both the equilibrium solution and the welfare criterion to second-order around their non-stochastic long-run (in particular, we use the methodology of Schmitt-Grohé and Uribe, 2004).

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[4] Governments undertake a lot of environmental protection activities (known as public abatement). Examples include policies that protect, conserve and generate (via innovation) the natural resources, as well as policies that provide the right environmental incentives. All these are costly activities that require public funds. Actually, the proportion of public expenditure in total expenditure on abatement is high in most countries (see e.g. Hatzipanayotou et al., 2003, and Haibara, 2009).

[5] Future trends in emissions are uncertain depending on the pace of economic growth, the demand for fossil fuel, the development of technologies, etc (see e.g. the Congressional Budget Office paper prepared for the Congress of the US, 2005).

Our main results are as follows. First, public abatement activities constitute an important part of environmental policy. Policies that yield no pollution revenues, and do not allow for public abatement, suffer a disadvantage relative to revenue-yielding policies like pollution taxes and auctioned pollution permits.[6] In our setting, this implies that, without being combined with public abatement policy, pure Kyoto-like rules cannot be comparable to taxes and permits and, at least for a wide range of parameter values, such rules are clearly inferior to taxes and permits. Hence, to make the comparison of alternative regimes meaningful when we move to a stochastic world, instead of studying pure rules, we study a mixed regime that combines (in the long run) rules with public abatement policy financed by, say, pollution taxes. Now, when second-best policy instruments take their welfare-maximizing values, all three policy regimes give the same welfare in a deterministic world. This implication is consistent with Weitzman (1974).

Second, in an uncertain world, permits are clearly the worst regime. They may fix environmental quality at a relatively high level, but only at the cost of exposing this quality to exogenous shocks and damaging private consumption. Actually, the higher the extrinsic (economic or environmental) uncertainty, the higher is the disadvantage of permits relative to taxes and mixed rules. This holds for a wide range of parameters, shocks and relative variances of different categories of shocks. We believe this happens (i.e. permits are inferior to both taxes and mixed rules) because they are a hybrid of price- and quantity-based regulations.[7] As a price-based instrument, they are less closely connected to the heart of the market failure (pollution externality) than pollution taxes. At the same time, as a quantity-based instrument, they provide less controllability than numerical rules that command agents to produce or emit a certain level.

Third, in an uncertain world, the verdict of taxes versus mixed rules is open depending on the relative variances of different categories of shocks affecting the economy. The main advantage of rules over taxes is that they eliminate environmental volatility. But this is achieved at the cost of lower and more volatile consumption. When extrinsic uncertainty arises from economic sources, the latter effects dominate and hence taxes are preferable to rules. However, when environmental uncertainty is the dominant source, the former effects dominate and so rules are preferable. To

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[6] This presupposes that any revenues from pollution taxes or auctioned permits are earmarked for the financing of public abatement. This is a conventional notion in the literature. See e.g. Haibara (2009).

further analyze this finding, we examine the first and second moments of those endogenous variables that determine welfare under each policy regime and each level of uncertainty. Commands to produce a certain level of output enjoy an efficiency advantage when environmental uncertainty is high and the marginal benefits from nature protection are big. By contrast, when environmental uncertainty is relatively low, it is better to name a price and let private agents find the optimal quantities themselves; in this case, policies like numerical rules for emissions, which reduce the number of choices that private agents can make, hurt the macro economy. This intuition is consistent with Weitzman's (1974, pp. 485-6) interpretation, comparing price *vs* quantity controls in a static framework.

The rest of the paper is organized as follows. The next section explains how we differ from the literature. Sections 3, 4 and 5 solve for taxes, permits and rules respectively. The first-best is in section 6. Section 7 compares welfare across regimes. Section 8 closes the paper. An appendix includes details.

2. How we differ from the literature

Our work is the first attempt to welfare-rank these three debated second-best environmental policies (taxes, permits and numerical rules) in a unified micro-founded DSGE model, by paying particular attention to the source of uncertainty faced. Our work also differs because we allow the government to play a mix of roles (to correct externalities, to raise funds to finance public abatement and to shield the economy from shocks) that are important in the policy debate. Finally, we look not only at the final welfare effects, but also at the various channels through which extrinsic uncertainty shapes welfare and, in particular, we look at the first and second moments of endogenous economic and environmental variables.

In his seminal work, Weitzman (1974) compared price- and quantity-based regulations showing that uncertainty causes otherwise equivalent policies to produce different results. Weitzman focused on the case in which the regulator is uncertain about the marginal cost and benefit of pollution and (as Bovenberg and Goulder, 2002, p. 1530, and Schöb, 1996, point out) worked in a first-best setting in the sense that regulation does not distort private decisions. Since then there has been a rich and still expanding literature on the comparison of alternative policy instruments in the

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[7] As explained by Bovenberg and Goulder (2002, p. 1520), they are price-based because market forces determine the price of permits. On the other hand, they are quantity-based because the government sets

presence of uncertainty. However, in most of these papers, the approach has been static and/or partial equilibrium, and the comparison is between taxes and quotas only (see the survey by Bovenberg and Goulders, 2002, section 4.2). An exception is Pizer (1999) who used a DSGE model. However, he compared "rate controls" with taxes only. In addition, as noted above, here we use a second-order approximation to both the equilibrium solution and the welfare criterion. This is important because it allows us to take properly into account the effects of uncertainty on welfare evaluations.

It is worth stressing that the previous environmental literature has not examined the importance of the source of extrinsic uncertainty for the choice of efficient policies; as we find, this is crucial. In addition, the literature has not considered public abatement together with pollution regulation.[8] Finally, none of the previous studies has studied numerical rules for emissions.

3. A model with pollution taxes

We augment the basic stochastic neoclassical growth model with natural resources and environmental policy. The economy is populated by a large number of identical infinitely-lived private agents that derive utility from private consumption and the stock of environmental quality. Private agents consume, save and produce a single good. Output produced generates pollution and this damages environmental quality.[9] Since private agents take economy-wide environmental quality as a public good, i.e. they do not internalize the effects of their actions on the environment, the decentralized equilibrium is inefficient. Hence, there is room for government intervention.

We start by studying the case in which the government imposes taxes on polluting activities and in turn uses the collected tax revenues to finance public abatement policy. This is a usual environmental policy in the growth literature (see e.g. Xepapadeas, 2004, and Economides and Philippopoulos, 2008).

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the total amount of permits and emissions. See also below.

[8] Schöb (1996), Goulder et al. (1999) and Bovenberg and Goulder (2002, section 4.1), among many others, have also emphasized the public-finance aspect of environmental policies. But they focus on the so-called revenue recycling effect, which means that the revenues generated by environmental policy can be used to finance cuts in pre-existing more distorting taxes. Baldursson et al. (2008) focus on the time-consistency of various environmental policy instruments.

[9] Our results do not change if pollution also occurs as a by-product of consumption. On the other hand, modeling pollution as a by-product of economic activity (production or consumption) can differ from the case in which natural resources are extracted from preserved natural environments to be used as inputs in production.

Private agents

For simplicity, the population size is constant and equal to one. The private agent's expected utility is defined over stochastic sequences of private consumption, c_t, and the economy's beginning-of-period environmental quality, Q_t:

$$E_0 \sum_{t=0}^{\infty} \beta^t u(c_t, Q_t) \tag{1a}$$

where $0 < \beta < 1$ is a time preference rate and E_0 is an expectations operator based on the information available at time zero.

Without loss of generality, we use for instantaneous utility:

$$u(c_t, Q_t) = \frac{[(c_t)^{\mu}(Q_t)^{1-\mu}]^{1-\sigma}}{1-\sigma} \tag{1b}$$

where $0 < \mu, 1-\mu < 1$ are the weights given to consumption and environmental quality respectively and $\sigma \geq 1$ is a measure of risk aversion.

The private agent's within-period budget constraint is:

$$k_{t+1} - (1-\delta^k)k_t + c_t = (1-\tau_t)y_t = (1-\tau_t)A_t k_t^{\alpha} \tag{2}$$

where $y_t = A_t k_t^{\alpha}$ is current output,[10] k_{t+1} is the end-of-period capital stock, k_t is the beginning-of-period capital stock, A_t is a standard index of production technology (whose stochastic motion is defined below), $0 < \alpha < 1$ and $0 \leq \delta^k \leq 1$ are usual parameters, and $0 \leq \tau_t < 1$ is the tax rate on (polluting) output.

The agent chooses $\{c_t, k_{t+1}\}_{t=0}^{\infty}$ to maximize (1a-b) subject to (2) taking policy variables and environmental quality as given. The latter is justified by the open-access and public-good features of the environment.

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[10] We abstract from labor-leisure choices to keep the model simpler. We report that this is not important qualitatively.

Natural resources

The stock of environmental quality evolves over time according to:[11]

$$Q_{t+1} = (1-\delta^q)\bar{Q} + \delta^q Q_t - p_t + \nu g_t \tag{3}$$

where $\bar{Q} \geq 0$ represents environmental quality without pollution, p_t is the current pollution flow, g_t is public spending on abatement activities, and $0 \leq \delta^q \leq 1$ and $\nu \geq 0$ are parameters measuring respectively the degree of environmental persistence and how public spending is translated into actual units of renewable natural resources.

The flow of pollution, p_t, is modeled as a by-product of output produced, y_t:

$$p_t = \phi_t y_t = \phi_t A_t k_t^{\alpha} \tag{4}$$

where ϕ_t is an index of pollution technology or a measure of emissions per unit of output.[12] We assume that ϕ_t is stochastic (its motion is defined below).

Government budget constraint

Assuming a balanced budget for the government, we have in each period:

$$g_t = \tau_t y_t = \tau_t A_t k_t^{\alpha} \tag{5}$$

so that clean-up policy, g_t, is financed by taxes on polluting activities.

Exogenous stochastic variables

We assume that the two technologies, A_t and ϕ_t, follow $AR(1)$ stochastic processes of the form:

$$A_{t+1} = A^{(1-\rho_a)} A_t^{\rho_a} e^{\varepsilon_{t+1}^{a}} \tag{6a}$$

$$\phi_{t+1} = \phi^{(1-\rho_\phi)} \phi_t^{\rho_\phi} e^{\varepsilon_{t+1}^{\phi}} \tag{6b}$$

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[11] The motion of natural resources in (3) is as in Jouvet et al. (2005); see p. 1599 in their paper for further details. The inclusion of the parameter $\bar{Q} \geq 0$ is helpful when we solve the model numerically.

[12] One could assume that pollution technology has also an endogenous component depending on e.g. private and public investment in pollution-reducing technology.

where A and ϕ are constants, $0<\rho_a,\rho_\phi<1$ are auto-regressive parameters and $\varepsilon_t^a,\varepsilon_t^\phi$ are Gaussian i.i.d. shocks with zero means and known variances denoted as σ_a^2 and σ_ϕ^2.

Decentralized competitive equilibrium (given pollution tax rates)

The Decentralized Competitive Equilibrium (DCE) of the above economy can be summarized by the following equations at any $t\geq 0$ (see Appendix A for details):

$$k_{t+1}-(1-\delta^k)k_t+c_t=(1-\tau_t)A_t k_t^\alpha \tag{7a}$$

$$\frac{\partial u_t}{\partial c_t}=\beta E_t\left[\frac{\partial u_{t+1}}{\partial c_{t+1}}[1-\delta^k+(1-\tau_{t+1})\alpha A_{t+1}k_{t+1}^{\alpha-1}]\right] \tag{7b}$$

$$Q_{t+1}=(1-\delta^q)\overline{Q}+\delta^q Q_t-(\phi_t-\nu\tau_t)A_t k_t^\alpha \tag{7c}$$

where $\frac{\partial u_t}{\partial c_t}=\mu(c_t)^{\mu(1-\sigma)-1}(Q_t)^{(1-\mu)(1-\sigma)}$.

We thus have a three-equation system in $\{c_t,k_{t+1},Q_{t+1}\}_{t=0}^\infty$. This DCE is for given policy (where the latter is summarized by pollution tax rates $\{\tau_t\}_{t=0}^\infty$ levied by the government), initial conditions for the stock variables, k_0 and Q_0, and stochastic processes for the exogenous variables, A_t and ϕ_t. In section 7, we will choose the pollution tax rate optimally.[13]

4. The same model with pollution permits

The government creates a market for pollution by issuing a number of permits that matches its maximum target amount of pollution. In order to pollute legally, a private agent has to hold a number of permits equal to its own quantity of pollution. In turn, the government uses the collected revenues to finance public abatement policy. The model in this section is similar to that in Jouvet et al. (2005).

In particular, we assume that at each time t, the government issues a quantity of pollution permits, $\overline{P}_t$, and auctions them at a price, q_t. These permits are bought in

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[13] The case of Pigouvian taxes, in which tax rates are chosen to correct for externalities only, can follow as a special case. See Appendix A for details.

the current period but can be used by the polluting private agent/firm in the next time period, $t+1$.[14] Thus, the private agent's budget constraint changes from (2) to:

$$k_{t+1}-(1-\delta^k)k_t+c_t+q_t p_{t+1}=y_t=A_t k_t^{\alpha} \tag{8}$$

where $p_{t+1}=\phi_{t+1}y_{t+1}=\phi_{t+1}A_{t+1}k_{t+1}^{\alpha}$. Thus, although the private agent keeps treating Q_t as given (public good), he now realizes that $p_t=\phi_t y_t=\phi_t A_t k_t^{\alpha}$ when he solves his problem.

The government budget constraint changes from equation (5) to:

$$g_t=q_t\overline{P}_t \tag{9}$$

Decentralized competitive equilibrium (given the quantity of pollution permits)

The Decentralized Competitive Equilibrium (DCE) of the above economy can be summarized by the following equations at any $t\geq 0$ (see Appendix B for details):[15]

$$k_{t+1}-(1-\delta^k)k_t+c_t+q_t\overline{P}_t=\frac{\overline{P}_{t-1}}{\phi_t} \tag{10a}$$

$$\frac{\partial u_t}{\partial c_t}(1+\alpha q_t E_t[\phi_{t+1}A_{t+1}k_{t+1}^{\alpha-1}])=\beta E_t[\frac{\partial u_{t+1}}{\partial c_{t+1}}(1-\delta^k+\alpha A_{t+1}k_{t+1}^{\alpha-1})] \tag{10b}$$

$$Q_{t+1}=(1-\delta^q)\overline{Q}+\delta^q Q_t-\overline{P}_{t-1}+v q_t\overline{P}_t \tag{10c}$$

$$\overline{P}_t=E_t p_{t+1}=E_t[\phi_{t+1}A_{t+1}k_{t+1}^{\alpha}] \tag{10d}$$

We thus have a four-equation system in $\{c_t,k_{t+1},Q_{t+1},q_t\}_{t=0}^{\infty}$. This new DCE is for given policy - where the latter is summarized by the quantity of pollution permits $\{\overline{P}_t\}_{t=0}^{\infty}$ issued by the government - initial conditions for the stock variables, k_0 and Q_0, and stochastic processes for the exogenous variables, A_t and ϕ_t. In section 7, we will choose the quantity of pollution permits optimally.[16]

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[14] This is close to the recent Obama climate-change bill, where the government issues a fixed number of permits to emit carbon dioxide each year, which firms must buy before releasing their stuff into the atmosphere (see e.g. *The Economist*, July 4, 2009, p. 37).

[15] Equation (10d) is a market-clearing condition which states that, in equilibrium, agents' demand for pollution equals supply with the latter determined by the government. See also Jouvet et al. (2005).

[16] We will also report results for the symmetrically opposite case in which the government sets the price of permits $\{q_t\}_{t=0}^{\infty}$ allowing their quantity to be endogenously determined. The case, in which

5. The same model with Kyoto-like numerical rules for emissions

We now study the case in which the government sets a long-term pollution target and also specifies the speed to that target. By speed, we mean that pollution tomorrow will be a fraction of pollution today, where this fraction is also part of environmental policy. In our setup, this approach can be captured by a policy rule like:

$$p_{t+1} = (1-\gamma_t)p + \gamma_t p_t \tag{11}$$

where p is long-run pollution and $0 < \gamma_t \leq 1$ is an autoregressive "parameter". The values of p and $\{\gamma_t\}_{t=0}^{\infty}$ are policy instruments.

Assuming that emission rules are binding all the time, and since $p_t = \phi_t y_t = \phi_t A_t k_t^{\alpha}$ at all t, the motion of pollution in (11) also determines the motion of capital, $\{k_{t+1}\}_{t=0}^{\infty}$; in turn, private consumption follows residually from the private agent's budget constraint.[17] Note that now there are neither public revenues nor public cleanup, $g_t = \tau_t = q_t = 0$ (see below for further details).

Decentralized competitive equilibrium (given pollution rules)

The Decentralized Competitive Equilibrium (DCE) of the above economy can be summarized by the following equations at any $t \geq 0$ (see Appendix C for details):

$$k_{t+1} - (1-\delta^k)k_t + c_t = A_t k_t^{\alpha} \tag{12a}$$

$$k_{t+1} = \left(\frac{(1-\gamma_t)p}{A_{t+1}\phi_{t+1}} + \frac{\gamma_t \phi_t A_t k_t^{\alpha}}{A_{t+1}\phi_{t+1}} \right)^{1/\alpha} \tag{12b}$$

$$Q_{t+1} = (1-\delta^q)\bar{Q} + \delta^q Q_t - \phi_t A_t k_t^{\alpha} \tag{12c}$$

We thus have a three-equation system in $\{c_t, k_{t+1}, Q_{t+1}\}_{t=0}^{\infty}$. This new DCE is for given policy - where the latter is summarized by the long-run pollution target, p, and the autoregressive "parameter" $\{\gamma_t\}_{t=0}^{\infty}$ in (11) - initial conditions for the stock

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permits are chosen to correct for externalities only, can follow as a special case. See Appendix B for details.

[17] See also the discussion in Stokey (1998, p. 18). The property that, in this policy regime, the private agent is left with nothing to choose is a special case of the more general property that all command-and-control policies reduce the number of choices that private agents can make.

variables, k_0 and Q_0, and stochastic processes for the exogenous variables, A_t and ϕ_t. Section 7 below will choose the values of these policy instruments optimally.

6. Social planner solution

We finally present the social planner's solution. This is the first-best serving as a benchmark. The planner chooses allocations $\{c_t, g_t, k_{t+1}, Q_{t+1}\}_{t=0}^{\infty}$ directly to maximize (1a-b) subject to resource constraints only. The solution is (see Appendix D for details):

$$k_{t+1} - (1-\delta^k)k_t + c_t + g_t = A_t k_t^{\alpha} \tag{13a}$$

$$\frac{\partial u_t}{\partial c_t} = \beta \frac{\partial u_{t+1}}{\partial c_{t+1}}(1-\delta^k + \alpha A_{t+1}k_{t+1}^{\alpha-1}) - \beta\xi_{t+1}\phi_{t+1}\alpha A_{t+1}k_{t+1}^{\alpha-1} \tag{13b}$$

$$Q_{t+1} = (1-\delta^q)\bar{Q} + \delta^q Q_t - \phi_t A_t k_t^{\alpha} + \nu g_t \tag{13c}$$

$$\xi_t = \beta \frac{\partial u_{t+1}}{\partial Q_{t+1}} + \beta\delta^q \xi_{t+1} \tag{13d}$$

$$\frac{\partial u_t}{\partial c_t} = \nu \xi_t \tag{13e}$$

where $\frac{\partial u_t}{\partial c_t} = \mu(c_t)^{\mu(1-\sigma)-1}(Q_t)^{(1-\mu)(1-\sigma)}$, $\frac{\partial u_{t+1}}{\partial Q_{t+1}} = (1-\mu)(c_{t+1})^{\mu(1-\sigma)}(Q_{t+1})^{(1-\mu)(1-\sigma)-1}$ and $\xi_t > 0$ is a dynamic multiplier associated with (13c).

We thus have a five-equation system in $\{c_t, g_t, k_{t+1}, Q_{t+1}, \xi_t\}_{t=0}^{\infty}$. This is given initial conditions for the stock variables, k_0 and Q_0, and stochastic processes for the exogenous variables, A_t and ϕ_t. We report that this first-best solution is always welfare superior to the second-best regimes studied in sections 3-5 (this holds for any feasible values of the distorting policy instruments).

7. Evaluation of second-best policies

This section evaluates the alternative second-best policy regimes developed in sections 3-5. Since the DCE solution and the resulting welfare under each policy regime depend on the value(s) of the policy instrument(s), we will compare the optimum welfare across regimes, namely, the welfare resulting from the optimally chosen value(s) of the policy instrument(s) in each regime. Welfare is defined as the conditional expectation of the discounted sum of household's lifetime utility.

In our context, when choosing its distorting policy instruments, the government tries to do the following:[18] First, to correct for pollution externalities (Pigouvian policy). Second, to create revenues that can be used to finance public abatement (and, in richer contexts, to reduce other taxes). Third, to minimize the distorting effects of policy intervention on the economy. For instance, taxes and permits increase the cost of production, while emission/output rules reduce the number of private choices. Fourth, since there is also uncertainty, the government aims to reduce volatility. Optimal policy will reflect all four tasks. Note that the first three tasks have to do with the so-called allocative role of the government.

We start by explaining how we work and by presenting parameter values used in the numerical solutions.

How we work

We focus on flat policy instruments, namely, policy instruments that remain constant over time (see e.g. Stokey and Rebelo, 1995, and Ortigueira, 1998). We then compute welfare for a wide range of values of the flat policy instrument(s) in each regime and then find the welfare maximizing-value of these policy instrument(s) and the associated maximum welfare under that regime. In all cases reported, there is a tradeoff in policy and hence a well-defined welfare-maximizing value of the policy instrument(s).

To this end, we approximate both the DCE solution and the welfare criterion to second-order around the associated non-stochastic steady state solution in each policy regime. Note that, in contrast to solutions that impose certainty equivalence, the solution to second-order approximation allows us to take into account the

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[18] For a discussion of various impacts of environmental policy, see Bovenberg and Goulder (2002, p. 1514).

uncertainty that the agents face when making decisions.[19] In particular, the second-order approximation of welfare follows from equations (1a-b) and is given by:[20]

$$E_0\sum_{t=0}^{\infty}\beta^t u(c_t,Q_t)\cong\frac{u(c,Q)}{1-\beta}+E_0\sum_{t=0}^{\infty}\beta^t\{a_1\hat{c}_t+a_2\hat{Q}_t+a_3(\hat{c}_t)^2+a_4(\hat{Q}_t)^2+a_5(\hat{c}_t\hat{Q}_t)\} \tag{14}$$

where, for any variable x_t, $\hat{x}_t\equiv\ln(x_t/x)\cong(x_t-x)/x$ and x is the long-run value of x_t. Also, $a_1\equiv\mu(1-\sigma)u(c,Q)$, $a_2\equiv(1-\mu)(1-\sigma)u(c,Q)$, $a_3\equiv\frac{\mu^2(1-\sigma)^2u(c,Q)}{2}$, $a_4\equiv\frac{(1-\mu)^2(1-\sigma)^2u(c,Q)}{2}$, $a_5\equiv\mu(1-\mu)(1-\sigma)^2u(c,Q)$. The values of $\hat{c}_t$ and $\hat{Q}_t$ follow from the second-order approximation of the DCE as said above.

Finally, we need a measure of comparison of welfare gains/losses associated with alternative regimes. This measure, denoted as ζ_{ij} in what follows, is obtained by computing the percentage compensation in private consumption that the private agent would require in each time-period under regime j so as to be equally well off between regimes i and $j\neq i$ (see the notes in Table 3 for the value of ζ_{ij}). This is a popular measure in dynamic general equilibrium models (see e.g. Lucas, 1990, and Cooley and Hansen, 1992).

Parameter values

We keep all parameter values the same across different regimes, so that the evaluation of different environmental policies is not blurred by differences in parameter values. Where the parameters are important for the results obtained, we will explicitly discuss their effects and robustness. As said above, the policy instruments in each regime are chosen to maximize welfare. The parameter values used are reported in Table 1.

Table 1 around here

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[19] In addition, as shown by Rotemberg and Woodford (1997), Woodford (2003, chapter 6), Schmitt-Grohé and Uribe (2004) and many others, a second-order approximation to the model's equilibrium solution, as well as to welfare, helps us to avoid potential spurious welfare rankings of various regimes that may arise when the model's equilibrium solution is approximate to first-order only. Actually, Pizer (1999) uses a first-order approximation to the equilibrium solution. To solve and simulate the second-order approximation of the DCE solution under each policy regime, we use the Matlab functions made available by Schmitt-Grohé and Uribe (2004).

[20] To evaluate the expectation in the welfare calculations, we use numerical integration with 1000 simulations. We use 300 years in our evaluation of life-time welfare, as, because of discounting, there is practically a zero weight attached to later outcomes.

The values of the economic parameters are as in most dynamic stochastic general equilibrium calibration and estimation studies. Thus, the baseline values used for the rate of time preference (β), the depreciation rate of capital (δ^k), the capital share in output (α), the intertemporal elasticity of substitution ($1/\sigma$) and the constant term (A) and persistence parameter (ρ_a) of the TFP process are rather standard. As discussed earlier, we will experiment with different values of the standard deviation of the TFP process (σ_a).

There is, of course, much less empirical evidence and consensus on the value of environmental parameters. For reasons discussed below, the most important one is μ, namely, the weight given to private consumption vis-à-vis environmental quality in the utility function, (1b). For our baseline results, we set μ at a relatively low level (0.6) and discuss other results later on. Regarding the parameters characterizing the exogenous process for environmental technology, we choose a high persistence parameter ($\rho_\phi = \rho_\alpha = 0.933$) and normalize its constant term, ϕ, at 0.01. Finally, we set v, namely, how public abatement spending is translated into actual units of environmental quality, at 0.5 (this parameter value helps us to match the units in the environmental quality equation (3) and hence obtain a well-defined trade-off in second-best policy). Since v is fixed across regimes with public abatement spending (pollution taxes and pollution permits), its value does not matter for the comparison of these two regimes. Nevertheless, it does matter when we compare these two regimes to the command-and-control regime which does not allow for public abatement spending (we discuss this issue below).

We are now ready to present numerical results. Before investigating the relatively general case in which exogenous shocks cause fluctuations around steady state, we study the deterministic steady state. This will help us to understand the working of the model and how results change when uncertainty is introduced. We will report results for some key variables as well as for the associated welfare.

Evaluation of regimes at steady state (certainty)

We first present results when the economy remains at its non-stochastic steady state. Results for consumption, c, environmental quality, Q, output, y, as well as the resulting welfare, defined as $u^*(c,Q)$, under each regime are reported in Table 2 (this is when the policy instrument is set at its welfare-maximizing value in each case).

Table 2 around here

The second column in Table 2 gives results for the model in section 3, where the government sets pollution taxes and uses the collected tax revenues to finance its abatement policy. The third column gives results for the model in section 4, where the government sets the quantity of pollution permits and finances its abatement policy from the sale of those permits. In the fourth column, we give results for the model in section 5, where the government sets pollution targets; in contrast to all previous regimes, now there are no revenues and hence no abatement policy on the side of the government. The sixth, last column reports the social planner solution in section 6; this always gives the best outcome as expected (from now on, we do not study this first-best case).

Taxes and permits (see second and third column in Table 2) are equivalent (any second decimal point differences are due to numerical solution approximations of the welfare-maximizing value of policy instruments). Both regimes give the same social welfare in the long run and, in turn, the same welfare loss over the benchmark first-best solution in the last column. However, pure rules (see fourth column) differ from the other two second-best regimes. In particular, according to our baseline parameter values, Kyoto-like rules appear to be welfare inferior to both taxes and permits. In general, however, the welfare comparison is ambiguous depending on parameter values. Specifically, our comparative static exercises imply that rules are welfare inferior to taxes and permits in the long run, when $\nu \geq 0$ (which measures how public spending on cleanup is translated into actual units of nature) is relatively high and/or $0 < \mu < 1$ (which is the weight given to private consumption vis-à-vis environmental quality) is relatively low. Intuitively, when public abatement policy, being financed by tax or permit revenues, is effective in preserving the environment (i.e. when ν is high) and/or we value little the distorting effects of taxes and permits on private consumption (i.e. when μ is low), numerical rules are inferior to taxes and permits. As ν gets smaller and/or μ gets larger, this inferiority diminishes. For very low values of ν and/or very high values of μ, numerical rules turn out to be welfare superior to taxes and permits.

This finding (namely, that optimally chosen competing instruments are found to be nonequivalent in a certainty world) seems, at first sight, to violate Weitzman's (1974) result. However, it arises simply because Kyoto-like rules are not really comparable to the other two regimes: in our setting, such rules do not generate public revenues and hence do not allow for public abatement policy (or, more generally, given tax bases, they allow for less public abatement policy than revenue-raising regimes like taxes and permits). To make the comparison of different regimes meaningful when we introduce uncertainty below, we need to make them equivalent in a deterministic world. We therefore add public abatement policy financed by, say, pollution taxes into the regime of pure Kyoto-like rules (see Appendix C for details).[21] Specifically, we choose the steady state tax rate so as to reproduce the same steady state solution as in the other two second-best regimes. Results are reported in the fifth, second from the end, column in Table 2. In what follows, we will work with this mixed regime – Kyoto-like rules combined (in the long run) with public abatement financed by pollution taxes – and compare this to taxes and permits. All three regimes are now equivalent in a deterministic setup (see also Table 3 below). This respects Weitzman's (1974) logic.

Therefore, public abatement activities constitute an important part of environmental policy. Policies that yield no revenues, and hence do not allow for public abatement, suffer a disadvantage relative to revenue-yielding policies. This of course presupposes that any revenues from pollution taxes or permits are earmarked for the financing of public abatement. As said above, the crucial role of public finance has already been pointed out, although the emphasis has been on the revenue recycling effect (see e.g. Bovenberg and Goulder, 2002, section 4.1). In our model, without being combined with public abatement policy, pure Kyoto-like rules are not really comparable to taxes and permits and, at least for a wide range of parameter values used, such rules are inferior to taxes and permits, especially in terms of environmental quality (see Table 2).

Evaluation of regimes under uncertainty

We now allow for uncertainty coming from the exogenous stochastic autoregressive processes for production and pollution technologies in equations (6a-b). We suppose that the economy is initially at its steady state studied above and, starting from $t = 0$, there are shocks to A_t and ϕ_t.

Working as explained above and using the same baseline parameter values, we compute discounted expected lifetime utility under each regime for a varying degree of uncertainty as summarized by the standard deviations of production and pollution

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[21] This is allowed at steady state only so as to make all policy regimes equivalent in the deterministic fixed point around which the different regimes/solutions fluctuate due to uncertainty. This allows us to

technologies, σ_a and σ_ϕ. Results are reported in Table 3. For expositional reasons, we study: (i) the deterministic case ($\sigma_a = \sigma_\phi = 0$); (ii) when there is only one source of uncertainty ($\sigma_\alpha = 0.01$ and $\sigma_\phi = 0$; $\sigma_\alpha = 0$ and $\sigma_\phi = 0.01$); (iii) a case of relatively low uncertainty in both stochastic variables ($\sigma_\alpha = \sigma_\phi = 0.01$); (iv) two scenarios representing high levels of uncertainty in one of the two stochastic variables ($\sigma_\alpha = 0.01$ and $\sigma_\phi = 0.05$; and $\sigma_\alpha = 0.05$, $\sigma_\phi = 0.01$); (v) a scenario with relatively high uncertainty in both stochastic variables ($\sigma_a = \sigma_\phi = 0.05$).

Table 3 around here

Table 3 confirms that, in a deterministic environment ($\sigma_a = \sigma_\phi = 0$), all regimes imply the same welfare (see also Table 2 above). In other words, to the extent that policy instruments are chosen optimally, and there is no uncertainty, the choice of the policy instrument is irrelevant to welfare. Of course, as said, this applies to regimes that are comparable (in our case, all of them allow for abatement policy).

By contrast, in a stochastic setup where $\sigma_a, \sigma_\phi > 0$, the choice of the policy instrument does matter. Table 3 reports the welfare gain/loss (i.e. the value of ζ_{ij}) when we choose regime i instead of regime $j \neq i$. A positive value of ζ_{ij} means that i is superior to j. For instance, if $\zeta_{ij} = x > 0$, an agent, who happens to be in j, will require a permanent consumption subsidy of $x\%$ to become indifferent between j and i.

Welfare differences between taxes and permits are summarized by the values of ζ_{TP} reported in the second column from the end in Table 3. Taxes are always superior to permits. For instance, when $\sigma_\alpha = \sigma_\phi = 0.01$, a welfare gain of 6.41%, in terms of private consumption, can be obtained if we use taxes instead of permits. The superiority of taxes further increases with the degree of uncertainty. Thus, taxes are superior in all cases even when environmental uncertainty is higher than economic uncertainty. Also notice that these are substantial welfare gains relatively to those found, for instance, in the literature on tax policy regimes (see e.g. Lucas, 1990, who compares Ramsey to suboptimal tax structures).

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get a meaningful evaluation of differences across regimes/solutions that are due to uncertainty only.

We next compare taxes to mixed rules. Welfare differences are summarized by the values of ζ_{TN} reported in the last column of Table 3. When economic uncertainty (σ_a) is higher than, or equal to, environmental uncertainty (σ_ϕ), taxes are superior to rules. For low levels of uncertainty, such welfare differences are small, but the higher σ_a and σ_ϕ become, the higher the superiority of taxes over rules, as long as $\sigma_a \geq \sigma_\phi$. For instance, when $\sigma_a = 0.05$ and $\sigma_\phi = 0.01$, the gain from taxes is 6.08%, while when $\sigma_a = \sigma_\phi = 0.05$, the gain is 4.06%. On the other hand, when environmental uncertainty is higher than economic uncertainty, rules are better than taxes. For instance, when $\sigma_a = 0.01$ and $\sigma_\phi = 0.05$, the gain from rules is 3.85%.

Therefore, as shown first by Weitzman (1974), ex ante uncertainty affects the choice of the policy instrument. Taxes and mixed rules are substantially better than permits; this holds over the whole range of parameter values, the sources of uncertainty, and the size of variances of shocks, that we have experimented with. Welfare benefits from the use of taxes, instead of permits, can be high for high levels of uncertainty irrespectively of where this uncertainty comes from. On the other hand, the comparison between taxes and mixed rules depends on the relative variances of different categories of shocks. Taxes are better than rules when economic uncertainty is no smaller than environmental uncertainty. But, when environmental uncertainty is the dominant source of uncertainty, rules outperform taxes. Details and intuition are discussed in the next subsection that presents means, variances and covariances of the arguments in the welfare criterion.

Before we move on, we report that we also get relatively reasonable values for the welfare-maximizing policy instrument in each regime. Results are included in Table 3. For instance, when $\sigma_\alpha = \sigma_\phi = 0.01$, the pollution tax rate modeled in (5) is found to be 0.197, the quantity of permits in (9) is 0.0136 and the persistence parameter under rules in (11) is 0.94. Note that, in general, the values of the policy instruments are not increasing in the degree of uncertainty; this is because policy intervention is costly and, as explained above, stabilization is only one of the goals of policy.

Looking behind welfare under uncertainty

To understand what is driving the above welfare differences under uncertainty, we study the first and second moments of the two arguments in the utility function, namely, private consumption, c_t, and the stock of environmental quality, Q_t. Note from the second-order approximation to the welfare function (14) that, in addition to the steady state values of c_t and Q_t and their deviations from these steady state values, what also matters for welfare is the squared deviations and cross- products of c_t and Q_t from their steady state values. Given that the steady state solution values are the same across all policy regimes studied, any welfare differences in the stochastic setup are driven by differences in expected means, variances and covariances of the series for c_t and Q_t (see Appendix E for details).

Tables 4a-c present the expected means, standard deviations and correlations of c_t and Q_t for all policy regimes under various levels of uncertainty. Welfare increases when the means of c_t and Q_t increase, their variances decrease and their correlation decreases.

Table 4 around here

As can be seen in Table 4, different policy regimes imply different trade-offs in outcomes whose net, total effect on welfare was summarized in Table 3 above. Some regimes are good for consumption, while others are good for environmental quality.

In particular, taxes (see Table 4a) and mixed rules (see Table 4c) imply higher expected consumption than permits (see Table 4b), while permits are superior in terms of expected environmental quality, especially when uncertainty is high. On the other hand, variances are higher under permits than under taxes and rules; this applies especially to the variance of environmental quality which is substantially higher under permits. The higher volatility in environmental quality, in combination with lower expected consumption, makes permits the worst regime in all cases studied. On the other hand, a weak point of taxes is the high positive correlation between consumption and environmental quality (in most cases, correlation is negative both under permits and rules, and this is good for welfare).

Comparison of the two better regimes, taxes and mixed rules in Tables 4a and 4c respectively, implies that the main advantages of mixed rules are that they fix environmental quality at a higher expected level, practically eliminating all environmental variation, and also allow consumption deviations to move counter-cyclically or a-cyclically with deviations in environmental quality. For this to be achieved, however, all the adjustment from an exogenously caused stochasticity has to be absorbed by consumption. In particular, the expected level of consumption is lower (or equal) and its variance is higher under rules than under taxes. When economic uncertainty is no smaller than environmental uncertainty, as was summarized in Table 3, it is the adverse consumption effects (level and variance) that dominate so that welfare is higher under taxes.[22] But when environmental uncertainty is the dominant source of uncertainty, the benefits from lower variation in environmental quality and the inverse correlation between environment and consumption become important enough to make rules superior to taxes (this happens, for instance, when $\sigma_a = 0.01$ and $\sigma_\phi = 0.05$ in Tables 3 and 4).

Therefore, in an uncertain world, permits are the worst regime. They can fix expected environmental quality at a relatively high level, but only at the cost of exposing this expected quality to exogenous shocks and damaging expected private consumption. The higher the extrinsic uncertainty, the higher is the disadvantage of permits relative to taxes and mixed rules. This holds for a wide range of parameters, shocks and relative variances of different categories of shocks. We believe auctioned permits are inferior because (as pointed out by Bovenberg and Goulder, 2002, p. 1520) they are a hybrid of price- and quantity-based regulations. They are price-based because market forces determine the price of permits. They are quantity-based because the government sets the total amount of permits and hence emissions. The problem is that, as a price-based instrument, they are less closely connected to the heart of the problem (pollution externality) than pollution taxes. At the same time, as a quantity-based instrument, they provide less controllability than numerical emission rules that command agents to produce or emit a certain level. This belief is strengthened by the result that when the government uses the price of pollution permits, instead of their quantity, as a policy instrument (see Appendix B), permits and taxes become fully equivalent on and off steady state (results are available upon request).

The comparison between taxes and mixed rules is open depending on the relative variances of different categories of shocks affecting the economy. When uncertainty arises from economic factors, taxes are preferable. But when environmental uncertainty becomes the dominant source, mixed rules are preferable.

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[22] This is despite a relatively low value for the weight given to consumption versus environmental quality in the utility function in our calibration (see Table 1). Hence, if anything, our calibration does not do any favours to the tax regime.

We believe this is consistent with Weitzman's (1974, pp. 485-6) intuition. As Weitzman has shown in a first-best setting, quantities are better than prices, as planning instruments, when the benefit function is more curved and/or the cost function is more linear. In our model, this seems to be the case under Kyoto-like rules in the presence of high uncertainty over the environment. In particular, better environmental quality gives a direct welfare benefit to private agents; when environmental uncertainty is relatively high, the marginal benefits of an extra unit of natural resources change rapidly and thus the curvature of the benefit function is high. By contrast, when environmental uncertainty is relatively low, the benefit function is closer to being linear. In such a situation, prices are a better instrument; the marginal benefit is almost linear in some range so that it is better to name a price and let private agents find the optimal quantities themselves. In this case, policies like rules, that reduce the number of choices that private agents can make, hurt the macro economy.

8. Conclusions

We evaluated pollution taxes, auctioned pollution permits and Kyoto-like emission rules in a unified micro-founded dynamic stochastic general equilibrium model. We focused on the role of uncertainty and showed the importance of public finance and abatement. The latter is an important ingredient of any environmental policy. Permits, despite their popularity among politicians, are the worst regime. When we compare taxes and rules, taxes are better when economic volatility is the main source of uncertainty. On the other hand, when environmental shocks are the dominant source of extrinsic uncertainty, numerical rules perform better.

We are aware that many issues have not been analyzed. For instance, it would be interesting to search for the best international agreement in our setup and, in particular, the design of international carbon market and international public funding. It is also important to evaluate environmental policies under structural uncertainty resulting from model misspecification of the environmental/pollution process. We leave these issues for future research.

Table 1: Baseline parameter values

Parameter	Description	Value
α	capital share in production	0.33
δ^k	capital depreciation rate	0.1
σ	curvature parameter in utility function	2
β	Time discount factor	0.97
μ	Consumption weight in utility function	0.6
$\overline{Q}$	environmental quality without pollution	1
δ^q	persistence of environmental quality	0.9
A	long-run total factor productivity	1
ρ_a	persistence of total factor productivity	0.933
ϕ	long-run pollution technology	0.01
ρ_ϕ	Persistence of pollution technology	0.933
ν	effectiveness of abatement policy	0.5

Table 2: Different policy regimes at their deterministic steady state

Variable	Taxes financing abatement	Permits financing abatement	Numerical rules	Numerical rules with abatement	Social planner
c	0.85	0.85	1.20	0.85	0.89
Q	2.26	2.24	0.83	2.26	2.27
y	1.41	1.41	1.71	1.41	1.56
$u^*(c,Q)$	-26.56	-26.60	-32.18	-26.56	-25.75

Notes: (i) $u^*(c,Q) \equiv \frac{(1-\beta^t)}{(1-\beta)} u(c,Q)$, where $t = 300$ and $\beta^{300} = 0$. We work with discounted welfare to make it comparable to the results in Tables 3-4, where simulations are run for 300 years. This is also consistent with equation (14). (ii) The fourth regime (numerical rules with abatement) includes tax-financed abatement policy at steady state so that it is equivalent to the other regimes in a deterministic setup.

Table 3: Expected lifetime utility (ELU) under different policy regimes for various levels of uncertainty

σ_a	σ_ϕ	ELU maximizing tax rate (τ)	ELU under taxes	ELU maximizing permit ($\overline{P}$)	ELU under permits	ELU maximizing numerical rule (γ)	ELU under numerical rules with abatement	ζ_{TP} (%)	ζ_{TN} (%)
0	0	0.198	- 26.56	0.0141	- 26.60	-	- 26.56	0.25	0
0	0.01	0.198	- 26.56	0.0139	- 26.96	0.93	- 26.53	2.49	- 0.19
0.01	0	0.197	- 26.77	0.0137	- 27.57	0.95	- 26.81	4.90	0.25
0.01	0.01	0.197	- 26.77	0.0136	- 27.82	0.94	- 26.79	6.41	0.12
0.01	0.05	0.196	- 26.73	0.0126	- 30.63	0.92	- 26.12	22.70	- 3.85
0.05	0.01	0.196	- 32.03	0.0117	- 35.79	0.95	- 33.22	18.50	6.08
0.05	0.05	0.195	- 32.00	0.0115	- 36.34	0.94	- 32.79	21.20	4.06

Notes: (i) The third regime (numerical rules with abatement) includes tax-financed abatement policy at steady state so that it is equivalent to the other regimes in a deterministic setup. (ii) The value of ζ_{ij} is given by $\zeta_{ij} \cong \frac{1}{\mu(1-\sigma)}\log(V_t^i / V_t^j)$, where V_t^i and V_t^j denote the discounted sums of second-order approximations to welfare in equation (14) and averaged over 1000 simulations.

Table 4a: First and second moments for c_t and Q_t under taxes

σ_a	σ_ϕ	$E(c_t)$	$E(Q_t)$	$\sigma(c_t)$	$\sigma(Q_t)$	$\rho(c_t, Q_t)$
0	0.01	0.85	2.26	0.00	0.003	- 0.42
0.01	0	0.85	2.25	0.03	0.04	0.86
0.01	0.01	0.85	2.25	0.03	0.04	0.85
0.01	0.05	0.85	2.25	0.03	0.04	0.80
0.05	0.01	0.88	2.12	0.14	0.16	0.86
0.05	0.05	0.88	2.11	0.14	0.16	0.85

Table 4b: First and second moments for c_t and Q_t under permits

σ_a	σ_ϕ	$E(c_t)$	$E(Q_t)$	$\sigma(c_t)$	$\sigma(Q_t)$	$\rho(c_t, Q_t)$
0	0.01	0.82	2.38	0.04	0.10	- 0.97
0.01	0	0.78	2.50	0.03	0.20	- 0.93
0.01	0.01	0.77	2.55	0.05	0.21	- 0.86
0.01	0.05	0.65	2.98	0.14	0.31	- 0.86
0.05	0.01	0.53	3.22	0.11	0.55	- 0.89
0.05	0.05	0.52	3.28	0.15	0.55	- 0.71

Table 4c: First and second moments for c_t and Q_t under numerical rules

σ_a	σ_ϕ	$E(c_t)$	$E(Q_t)$	$\sigma(c_t)$	$\sigma(Q_t)$	$\rho(c_t, Q_t)$
0	0.01	0.85	2.26	0.00	0.00	0.47
0.01	0	0.85	2.26	0.04	0.00	-0.72
0.01	0.01	0.85	2.26	0.04	0.00	-0.51
0.01	0.05	0.85	2.26	0.04	0.01	0.03
0.05	0.01	0.84	2.26	0.18	0.02	-0.71
0.05	0.05	0.85	2.26	0.18	0.02	-0.52

APPENDICES

Appendix A: DCE with pollution taxes

(i) The first-order conditions of the individual's problem include the budget constraint in (2) and the Euler equation (7b). Then, using (4)-(5) into (3), we get (7c). All this gives (7a-c) which is a three-equation system in $\{c_t, k_{t+1}, Q_{t+1}\}_{t=0}^{\infty}$ in terms of $\{\tau_t\}_{t=0}^{\infty}$. The long-run DCE follows if we simply drop time subscripts.

(ii) A policy of Pigouvian taxes can follow as a special case. Suppose that any revenues from pollution taxes are returned to the individual in the form of lump-sum transfers, S_t. The budget constraint of the individual is:

$$k_{t+1} - (1-\delta^k)k_t + c_t = (1-\tau_t)A_t k_t^{\alpha} + S_t \tag{A.1}$$

while the budget constraint of the government is:

$$S_t = \tau_t A_t k_t^{\alpha} \tag{A.2}$$

and therefore the DCE is:

$$k_{t+1} - (1-\delta^k)k_t + c_t = A_t k_t^{\alpha} \tag{A.3a}$$

$$\frac{\partial u_t}{\partial c_t} = \beta E_t \left[\frac{\partial u_{t+1}}{\partial c_{t+1}} [1-\delta^k + (1-\tau_{t+1})\alpha A_{t+1} k_{t+1}^{\alpha-1}] \right] \tag{A.3b}$$

$$Q_{t+1} = (1-\delta^q)\bar{Q} + \delta^q Q_t - \phi_t A_t k_t^{\alpha} \tag{A.3c}$$

Equations (A.3a)-(A.3c) constitute a new three-equation system in $\{c_t, k_{t+1}, Q_{t+1}\}_{t=0}^{\infty}$ in terms of $\{\tau_t\}_{t=0}^{\infty}$. The long-run DCE follows from (A.3a)-(A.3c) if we simply drop time subscripts.

Appendix B: DCE with pollution permits

(i) The first-order conditions of the individual's problem include the budget constraint in (8) and the Euler equation (10b). Then, using (9) for g_t and $p_t = \phi_t A_t k_t^{\alpha} = \bar{P}_{t-1}$ into (3), we get (10c), while (10d) has been explained in the text. All this gives (10a-d) which is a four-equation system in $\{c_t, k_{t+1}, Q_{t+1}, q_t\}_{t=0}^{\infty}$ in terms of $\{\bar{P}_t\}_{t=0}^{\infty}$. The long-run follows if we simply drop time subscripts.

(ii) A policy of "Pigouvian permits" can follow as a special case. Suppose that any revenues from the same of pollution permits are returned to the individual in the form of lump-sum transfers, S_t. That is, the budget constraint of the agent is:

$$k_{t+1}-(1-\delta^k)k_t+c_t+q_t p_{t+1}=A_t k_t^{\alpha}+S_t \tag{B.1}$$

while the budget constraint of the government is:

$$S_t=q_t p_{t+1}=q_t\bar{P}_t \tag{B.2}$$

and therefore the DCE is:

$$k_{t+1}-(1-\delta^k)k_t+c_t=\frac{\bar{P}_{t-1}}{\phi_t} \tag{B.3a}$$

$$\frac{\partial u_t}{\partial c_t}(1+\alpha q_t E_t[\phi_{t+1}A_{t+1}k_{t+1}^{\alpha-1}])=\beta E_t[\frac{\partial u_{t+1}}{\partial c_{t+1}}(1-\delta^k+\alpha A_{t+1}k_{t+1}^{\alpha-1})] \tag{B.3b}$$

$$Q_{t+1}=(1-\delta^q)\bar{Q}+\delta^q Q_t-\bar{P}_{t-1} \tag{B.3c}$$

$$\bar{P}_t=E_t p_{t+1}=E_t[\phi_{t+1}A_{t+1}k_{t+1}^{\alpha}] \tag{B.3d}$$

Equations (B.3a)-(B.3d) constitute a new four-equation system in $\{c_t,k_{t+1},Q_{t+1},q_t\}_{t=0}^{\infty}$ in terms of $\{\bar{P}_t\}_{t=0}^{\infty}$. The long-run DCE follows from (B.3a)-(B.3d) if we simply drop time subscripts.

(iii) When the instrument is the price of permits, rather than their quantity, the DCE changes from (i) above to:

$$k_{t+1}-(1-\delta^k)k_t+c_t+q_t\phi_{t+1}A_{t+1}k_{t+1}^{\alpha}=A_t k_t^{\alpha} \tag{B.4a}$$

$$\frac{\partial u_t}{\partial c_t}(1+\alpha q_t E_t[\phi_{t+1}A_{t+1}k_{t+1}^{\alpha-1}])=\beta E_t[\frac{\partial u_{t+1}}{\partial c_{t+1}}(1-\delta^k+\alpha A_{t+1}k_{t+1}^{\alpha-1})] \tag{B.4b}$$

$$Q_{t+1}=(1-\delta^q)\bar{Q}+\delta^q Q_t-\phi_t A_t k_t^{\alpha}+\nu q_t\phi_{t+1}A_{t+1}k_{t+1}^{\alpha} \tag{B.4c}$$

Equations (B.4a)-(B.4c) constitute a three-equation system in $\{c_t,k_{t+1},Q_{t+1}\}_{t=0}^{\infty}$ in terms of $\{q_t\}_{t=0}^{\infty}$. The long-run DCE follows from (B.4a)-(B.4c) if we simply drop time subscripts.

Appendix C: DCE with pollution rules

(i) Using (4) into (11), we get (12b) which gives the motion of private capital. All this gives (12-c) as DCE which constitute a three-equation system in $\{c_t,k_{t+1},Q_{t+1}\}_{t=0}^{\infty}$ in terms of the long-run target pollution, p, and the path of $\{\gamma_t\}_{t=0}^{\infty}$. In the long run, equations (12a-c) are reduced to two equations:

$$\delta^k \left(\frac{p}{\phi A} \right)^{1/\alpha} + c = \frac{p}{\phi} \qquad \text{(C.1a)}$$

$$Q = \bar{Q} - \frac{p}{(1-\delta^q)} \qquad \text{(C.1b)}$$

which can be solved for c and Q in terms of p (recall that, in the long-run, p is a policy choice and that, in all periods, $p_t = \phi_t A_t k_t^\alpha$).

(ii) We now add public abatement financed by lump-sum taxes, S_t. That is, the budget constraint of the individual is:

$$k_{t+1} - (1-\delta^k)k_t + c_t = A_t k_t^\alpha - S_t \qquad \text{(C.2)}$$

while the budget constraint of the government is:

$$G_t = S_t \qquad \text{(C.3)}$$

and therefore the DCE is:

$$k_{t+1} - (1-\delta^k)k_t + c_t + G_t = A_t k_t^\alpha \qquad \text{(C.4a)}$$

$$k_{t+1} = \left(\frac{(1-\gamma_t)p}{A_{t+1}\phi_{t+1}} + \frac{\gamma_t \phi_t A_t k_t^\alpha}{A_{t+1}\phi_{t+1}} \right)^{1/\alpha} \qquad \text{(C.4b)}$$

$$Q_{t+1} = (1-\delta^q)\bar{Q} + \delta^q Q_t - \phi_t A_t k_t^\alpha + \nu G_t \qquad \text{(C.4c)}$$

In the long run, equations (C.4a)-(C.4c) are reduced to two equations:

$$\delta^k \left(\frac{p}{\phi A} \right)^{1/\alpha} + c + G = \frac{p}{\phi} \qquad \text{(C.5a)}$$

$$Q = \bar{Q} - \frac{p - \nu G}{(1-\delta^q)} \qquad \text{(C.5b)}$$

which can be solved for c and Q in terms of p and G.

(iii) We now add public abatement financed by output/pollution taxes, τ_t. That is, the budget constraint of the individual is:

$$k_{t+1} - (1-\delta^k)k_t + c_t = (1-\tau_t)A_t k_t^\alpha \qquad \text{(C.6)}$$

while the budget constraint of the government is:

$$G_t = \tau_t A_t k_t^\alpha \qquad \text{(C.7)}$$

and therefore the DCE is:

$$k_{t+1} - (1-\delta^k)k_t + c_t = (1-\tau_t)A_t k_t^\alpha \qquad \text{(C.8a)}$$

$$k_{t+1}=\left(\frac{(1-\gamma_t)p}{A_{t+1}\phi_{t+1}}+\frac{\gamma_t\phi_t A_t k_t^{\alpha}}{A_{t+1}\phi_{t+1}}\right)^{1/\alpha} \tag{C.8b}$$

$$Q_{t+1}=(1-\delta^q)\bar{Q}+\delta^q Q_t-(\phi_t-\nu\tau_t)A_t k_t^{\alpha} \tag{C.8c}$$

In the long run, equations (C.8a)-(C.8c) are reduced to two equations:

$$\delta^k\left(\frac{p}{\phi A}\right)^{1/\alpha}+c=(1-\tau)\frac{p}{\phi} \tag{C.9a}$$

$$Q=\bar{Q}-\frac{\left(1-\frac{\nu\tau}{\phi}\right)p}{(1-\delta^q)} \tag{C.9b}$$

which can be solved for c and Q in terms of p and τ.

Appendix D: Social planner solution

The planner chooses $\{c_t,g_t,k_{t+1},Q_{t+1}\}_{t=0}^{\infty}$ to maximize (1a-b) subject to resource constraints:

$$k_{t+1}-(1-\delta^k)k_t+c_t+g_t=A_t k_t^{\alpha} \tag{D.1a}$$

$$Q_{t+1}=(1-\delta^q)\bar{Q}+\delta^q Q_t-\phi_t A_t k_t^{\alpha}+\nu g_t \tag{D.1b}$$

The optimality conditions include (D.1a), (D.1b) and:

$$\frac{\partial u_t}{\partial c_t}=\beta\frac{\partial u_{t+1}}{\partial c_{t+1}}(1-\delta^k+\alpha A_{t+1}k_{t+1}^{\alpha-1})-\beta\xi_{t+1}\phi_{t+1}\alpha A_{t+1}k_{t+1}^{\alpha-1} \tag{D.2a}$$

$$\xi_t=\beta\frac{\partial u_{t+1}}{\partial Q_{t+1}}+\beta\delta^q\xi_{t+1} \tag{D.2b}$$

$$\frac{\partial u_t}{\partial c_t}=\nu\xi_t \tag{D.2c}$$

where $\xi>0$ is a dynamic multiplier associated with (D.1b), $\frac{\partial u_t}{\partial c_t}=\mu(c_t)^{\mu(1-\sigma)-1}(Q_t)^{(1-\mu)(1-\sigma)}$, and $\frac{\partial u_{t+1}}{\partial Q_{t+1}}=(1-\mu)(c_{t+1})^{\mu(1-\sigma)}(Q_{t+1})^{(1-\mu)(1-\sigma)-1}$. (D.1a)-(D.1b) and (D.2a)-(D.2c) constitute a five-equation system in $\{c_t,k_{t+1},Q_{t+1},g_t,\xi_t\}_{t=0}^{\infty}$. The long-run DCE follows if we simply drop time subscripts.

Appendix E: Statistical moments

To see that examining the means, variances and covariances of the variables in levels is equivalent to examining the same moments for the variables defined as deviations from their (common) steady state, note the following. For the random variables x and

y, define $\hat{x} = x - \bar{x}$ and $\hat{y} = y - \bar{y}$, where $\bar{x}$ (resp. $\bar{y}$) is the average value of x (resp. y). Then, the relationship between the mean of x and the mean of $\hat{x}$ is given by:

$$E(\hat{x}) = E(x) - \bar{x} \tag{E.1}$$

(E.1) implies that, when $\bar{x}$ is the same across regimes, any differences in the mean of x are due to differences in the mean of $\hat{x}$. The relationship between $\hat{x}^2$ and the variance of $\hat{x}$ is given by:

$$\mathrm{var}(\hat{x}) = E[\hat{x} - E(\hat{x})]^2 = E(\hat{x})^2 - [E(\hat{x})]^2 \tag{E.2}$$

Hence, given the mean of $\hat{x}$, any differences in the average value of $\hat{x}^2$ are captured by differences in the variance of $\hat{x}$. Further, the variances of x and $\hat{x}$ are the same, i.e. $\mathrm{var}(\hat{x}) = E[\hat{x} - E(\hat{x})]^2 = E[(x - \bar{x}) - (E(x) - \bar{x})]^2 = \mathrm{var}(x)$. Finally, given their means, any differences in the cross-products of $\hat{x}$ and $\hat{y}$ are captured by their covariance, i.e. $\mathrm{cov}(\hat{x}, \hat{y}) = E[\hat{x}\hat{y}] - E(\hat{x})E(\hat{y})$, where:

$$\mathrm{cov}(\hat{x}, \hat{y}) = E\{[\hat{x} - E(\hat{x})][\hat{y} - E(\hat{y})]\} = E\{[(x - \bar{x}) - (E(x) - \bar{x})][(y - \bar{y}) - (E(y) - \bar{y})]\} = \mathrm{cov}(x, y) \tag{E.3}$$

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