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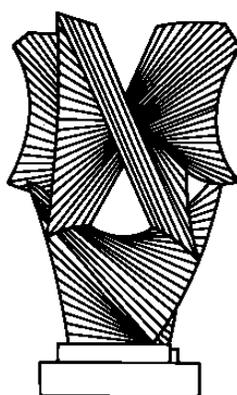
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Should Environmental Taxes Be Precautionary?

David A. Weisbach

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Should Environmental Taxes Be Precautionary?

David A. Weisbach[†]
The University of Chicago Law School

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Abstract

This paper considers whether environmental taxes should be accelerated (or delayed) if the environmental harm from pollution is uncertain and irreversible, and where we are likely to learn more about the nature of the harm or about mitigation technologies in the future. It concludes that environmental taxes should be set equal to expected marginal harm from pollution given the currently available information and should be neither accelerated nor delayed because of the prospect of learning or irreversible harm. The reason is that taxes equal to expected marginal harm decentralize decisions to market participants who will, facing these taxes, make appropriate choices about the timing of pollution. Taxes act similarly to property rights in a complete market where market participants produce Pareto outcomes. There are a number of caveats to this conclusion including the possibility of endogenous learning, in which our understanding of the environmental effects of pollution or the available mitigation technologies depends on the level of taxation.

Keywords: Pigouvian taxation, environmental taxation, precautionary principle, climate change, real options, instrument choice

JEL Codes: H23, K10, Q50

[†] Walter J. Blum Professor, The University of Chicago Law School, Senior Fellow, The Computation Institute, The University of Chicago and Argonne National Laboratories. I thank Jacob Nussim and participants at a University of Chicago Law School workshop for comments.

There is a considerable body of work in environmental law and environmental economics addressing the timing of pollution abatement when there is uncertainty about the potential harms from pollution and when emissions are irreversible. The core idea is that we might want to reduce pollution now more than otherwise to preserve flexibility until we learn more about the size of the harms and the likely abatement costs. As we teach our children, better safe than sorry.

Environmental law implements this idea through the precautionary principle. There are many statements, differing from one another in important details.¹ A commonly used version can be found in the 1992 Framework Convention on Climate Change, Article 3, which states that the parties “should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures.” A prominent legal scholar proposed the following version which is more explicit and stronger:

when regulators are dealing with an irreversible loss, and when they are uncertain about the timing and likelihood of that loss, they should be willing to pay a sum – the option value – in order to maintain flexibility for the future.

Sunstein (2006).

Environmental economists have analyzed the problem as one of decision-making under uncertainty and learning.² In the simplest, two-period models, for example, emissions in the first period irreversibly affect the expected marginal harm from emissions in the second period and we expect to learn more about the harms and to be able to adjust the second period actions accordingly. Under some circumstances, we might want to reduce first period emissions to retain flexibility in the second period, although in other cases the prospect of learning leads to an increase in first period emissions. More complex models include both irreversible harms and irreversible expenditures on abatement, so that concerns about

¹ The essays in Tickner (2003) and Fisher, Jones, and von Schomberg (2006) provide summaries of the precautionary principle.

² Papers include Arrow and Fisher (1974), Henry (1974), Kolstad (1996), Kolstad (1996), Ulph and Ulph (1997), Gollier, Jullien, and Treich (2000), Pindyck (2000), Pindyck (2002), Gollier and Treich (2003), Ingham and Ulph (2005).

flexibility run both ways. You have to be safe and not sorry about both potential environmental harms and about the possibly wasting resources on unnecessary abatement.

To my knowledge, this analysis has never been specifically applied to the optimal timing of environmental (or other Pigouvian) taxes.³ This is so even though environmental taxes are thought by many to be the first best solution to pollution problems, preferable to command and control approaches in many contexts. The question I address is whether environmental taxes should be imposed earlier when there is an uncertain possibility of irreversible environmental harms or later to allow society to learn about the likely harms before regulating. Does a version of the precautionary principle apply to taxes?

The thesis developed here is that as a first order matter, there is no tax precautionary principle: the government should not set taxes to preserve flexibility in the face of irreversible harms and learning. Environmental taxes should be set equal to the expected marginal social harm from an activity, adjusted in each period to reflect new information. The reason is that environmental taxes decentralize decision making. They impose a price on harm-causing activities and let individual actors decide the appropriate level of the activity given that price. Individual actors will take precautions if appropriate. We can think of Pigouvian taxes as completing the market, and like in other situations with complete markets, we rely on individuals to determine the appropriate level and timing of their activities. The government should not additionally accelerate or delay environmental taxes.

This statement is subject to a number of important caveats and limitations. First, there are many versions of the precautionary principle. By saying that the precautionary principle does not apply to taxes, I mean that taxes should not be set higher or lower than the expected marginal harm because of precautionary

³ Ko, Lapan, and Sandler (1992), Ulph and Ulph (1994), Farzin (1996) consider the timing of Pigouvin taxes but do not model the choice of irreversible emissions when there is learning. Pindyck (2002) (p. 1696) indicates that he believes the solutions to the optimal timing problem apply to taxation, but it appears that he assumes that taxes must be adopted on a once-and-for-all basis and can never be adjusted. This case may have optimal timing elements that are different than flexible taxes. Section 3 discusses this issue.

motives. Some versions of the precautionary principle merely require the use of expected values and, therefore, are consistent with such taxes.⁴

Second, to determine marginal harm from an activity, the government may need to understand how individual actors will solve the optimal timing problem. The reason is that for stock pollutants, the marginal harm from current emissions depends on the stock of emissions in the future. This in turn depends on the level of precaution that individual actors take. Therefore, to determine the marginal harm from current emissions, the government must know how individuals respond to uncertainty, irreversibility, and learning. The government cannot simply ignore these problems because it is using taxes instead of a command and control regime even though taxes should be set equal to expected marginal harm. This observation has implications for instrument choice.

Third, optimal Pigouvian taxes are equal to the current estimate of marginal harm given then available information. If taxes do not adjust to new information, they will often be too high or too low, giving rise to timing considerations similar to the precautionary considerations that arise in command and control regime.

Finally, the basic analysis assumes that information arrives exogenously. The price on pollution, however, may affect the pace of technological development. The interaction between technological development and Pigouvian taxes is complex because general technology policies such as research and development incentives will often apply to abatement technologies. Setting abatement policies to, say, increase the pace of technological development may not be appropriate if general technology policies already cause individuals to fully internalize positive externalities from technological development.

This paper comes in three parts. Part 1 reviews the literature on the optimal timing of environmental policies, starting with the Precautionary Principle and then turning to how the issue has been modeled in the economics

⁴ Some versions of the precautionary principle seem to be motivated by ambiguity aversion – the idea that if we cannot determine the probability of certain events, even within a range, we should behave as if we were extremely risk averse. Gilboa and Schmeidler (1989). Ambiguity aversion is beyond the scope of the present analysis. It presents a number of challenging issues that have not fully been worked out in the literature. It is possible that the appropriate Pigouvian taxes when there is ambiguity would be higher than if we could place probabilities on future events.

literature. Part 2 discusses how these models apply (or do not) to Pigouvian taxes. Part 3 considers limitations and extensions.

1. The timing problem in environmental decision making

1.1 *Motivating examples*

I begin with two examples to motivate the analysis. The first is based on Arrow and Fisher (1974), which originated much of the relevant literature. They consider the choice to clear cut and develop a virgin redwood forest. Once the forest is cut, it cannot be restored within a reasonable time period, so the development decision is irreversible. Moreover, the value of the developed land will change as will the value of the land in its undeveloped state, and the owner will learn these values with the passage of time. The question is when the owner should develop the land, if ever. Arrow and Fisher seem to have in mind a *public* choice about the timing of this decision. As will be discussed below, however, if the decision maker is the owner of the property and there are no externalities (none are specified), the decision can be viewed as a problem of *consumer* choice.

The second example is climate change. Carbon has a very long atmospheric life. For policy purposes, substantial portions of it can be treated as staying in the atmosphere indefinitely and there is no way to remove it. Marginal harm from emissions goes up with the stock of emissions, so that emitting a unit of carbon today increases the marginal harm from emissions in the future and this effect may be highly nonlinear. We do not, however, currently know the harm that a unit of emissions will cause and, moreover, we do not know the costs of abatement in the future. The question is whether we should reduce emissions more today because of this uncertainty or perhaps wait to reduce emissions because of the same uncertainty.

In both examples, first period decisions inalterably affect the second period but the amount of the resulting harm is unknown. In deciding what to do in the first period, therefore, we have to consider the future effects. This structure describes some but by no means all pollution problems. Many pollutants only affect the immediate period and then dissipate. For example, the release of a toxic chemical might cause immediate harm and the chemical might then degrade or be absorbed into the environment. Uncertainty about these sorts of flow pollutants might affect how much care is taken for example because of risk aversion. The focus here is on the first type of problem, where emissions today affect the value of actions in the future.

1.2 *The Precautionary Principle*

As noted, the precautionary principle is one of the primary legal tools for answering these sorts of timing questions. The precautionary principle is embodied in numerous treaties and court decisions, although it is accepted much more broadly in Europe than in the United States.⁵

While the precautionary principle is widely used in environmental law, there is no single meaning of the term. It comes in many forms, from a relatively banal claim that uncertainty should not preclude abatement to strong claims about avoiding all serious risks. Most laws and international agreements that adopt the precautionary principle simply specify that it applies without giving it any particular content. For example, the EC Treaty (the Maastricht Treaty), Article 174.2 states:

Community policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the community. It shall be based on the precautionary principle
...

The relevant Commission communication interpreting this provision provides only limited additional detail. It holds that the precautionary principle “applies when scientific evidence is insufficient, inconclusive or uncertain and preliminary scientific evaluation indicates that there are reasonable grounds for concern . . .” EU (2000). It does not, however, indicate clearly what is to be done in these circumstances.

A version of a weak precautionary principle was embedded in the Rio Declaration on Environment and Development (1992), which states:

where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

The Framework Convention on Climate Change (1992) is similar, stating that where there are threats of serious or irreversible damage, lack of full certainty should not be used as a reason for postponing action. It is hard to object to these versions of the precautionary principle. They simply state that lack of certainty is

⁵ The United States, as a signatory to the Framework Convention on Climate Change, has accepted it in some contexts.

not a veto to reducing pollution or other risks of harm. Beyond this, they do not say how uncertainty affects the timing of environmental decisions. They are consistent with simple use of expected values with no acceleration or delay of abatement because of learning or irreversibilities.

The most specific form of the precautionary principle prohibits taking any significant environmental risk. Richard Stewart formulated this version (but did not endorse it) as stating that “activities that present an uncertain potential for significant harm should be prohibited unless the proponent of the activity shows that it presents no appreciable risk of harm.” Stewart (2002) An example of this version can be found in the Final Declaration of the First European Seas at Risk Conference, which says that if “the ‘worst case scenario’ for a certain activity is serious enough then even a small amount of doubt as to the safety of that activity is sufficient to stop it taking place.” Proceedings of the First European Seas at Risk Conference, Annex I (1995). This version of the precautionary principle requires substantial acceleration of pollution abatement (or stopping other harm-causing activities) because of uncertainty and the prospect of serious harms. It goes beyond expected values, weighting even low risks of serious harms higher than their expectation. It also makes no reference to the costs of reducing risks.⁶

Some statements of the precautionary principle are stated explicitly in terms of options to preserve flexibility, although to my knowledge these statements are found only in scholarly articles and have not yet been adopted into law. As quoted above, Cass Sunstein argues that the precautionary principle should take the following form:

when regulators are dealing with an irreversible loss, and when they are uncertain about the timing and likelihood of that loss, they should be willing to pay a sum – the option value – in order to maintain flexibility for the future.

⁶ The World Commission on the Ethics of Scientific Knowledge and Technology, which is part of UNESCO, seemed to adopt a similar version. It defines the precautionary principle as stating that “when human activities lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm.” COMEST (2005) Morally unacceptable harm is defined broadly to include threats to human life or health, so it includes just about any harm. It contains no reference to costs. The Commission, however, then hedged this strong statement by stating that actions should be chosen that are proportional to the harm and with consideration of their positive and negative consequences, making it unclear of the extent to which their version of the precautionary principle is inconsistent with the use of expected values.

Sunstein (2006). A similar version can be found in Posner (2004).

Complementing the different versions of the precautionary principle, there are numerous motivations for the precautionary principle. The most straightforward is to prevent policymakers from using uncertainty as an excuse to ignore environmental harms. Others are based on views about the appropriate reaction to uncertainty or ambiguity, where we do not know enough about the environmental effects of an action to form Bayesian priors.⁷ Sunstein (2006) ties it to real options analysis. Others have justified it as an attempt to overcome a behavioral bias of ignoring uncertain future harms in favor of immediate benefits. Dana (2003).

Different motivations for the precautionary principle may have different implications for Pigouvian taxes. For example, as noted, if the motivation for the precautionary principle is to keep policymakers from ignoring uncertain harms, the precautionary principle would be entirely consistent with simply using expectations. I will take the precautionary principle to be making a claim that when the harm is uncertain and irreversible,⁸ environmental abatement should be accelerated relative to the abatement we would take using expected utility alone; one should exercise precaution in the face of the risk of irreversible harms.

One of the features of all of these statements of the precautionary principle is that they purport to apply to all environmental measures. In particular, no statement that I know of distinguishes taxes from other regulatory measures when applying the precautionary principle. While it does not appear that taxes are uppermost in drafters' minds – they seem to instead be thinking of command and control regulations that prohibit certain activities or mandate others – the precautionary principle, in its many forms, does not distinguish taxes.

1.3 *Economic models of the timing of precaution*

The economics of uncertainty, learning, and sunk costs with respect to the environment developed in parallel to the legal development of the precautionary principle. Although there is some earlier work, Arrow and Fisher (1974) and

⁷ This can be seen, for example, in von Schomberg (2006) and Gardiner (2006).

⁸ But not ambiguous. That is, I will assume that we can form priors on the probability distribution of outcomes, so that we need to consider ambiguity aversion. As noted, ambiguity aversion may be a motivation for some versions of the precautionary principle. The implications of ambiguity for Pigouvian taxes has not, to my knowledge been explored.

Henry (1974) are often viewed as the originators of this literature. It has been developed extensively since then. To understand the core arguments in the simplest possible setting, consider a two-period model which is the basis of much of the literature.⁹

An individual or other decision-maker has to determine emissions e_i (or more generally, economic activity which results in emissions) in each of two periods, $i=1, 2$. The individual gets utility u and v from emissions in periods 1 and 2 respectively but emissions also cause damages. Damages depend on the stock of emissions, $\delta e_1 + e_2$, where emissions in period 1 depreciate at a rate $1-\delta$. Damages $\theta(\delta e_1 + e_2)$ occur only in the second period and are uncertain, as reflected in the stochastic function θ . Before the second period, however, the decision maker will receive new information, y , which allows him to revise his estimate of the damages and choose e_2 accordingly. We can write the optimization problem for period 1 as:

$$\max_{e_1 \geq 0} u(e_1) + E_{y_0} \left\{ \max_{e_2 \geq 0} E_{\theta|y_0} \left[v(e_2) - \theta(\delta e_1 + e_2) \right] \right\}. \quad (1)$$

second period choice given new information

Emissions in period 1 are irreversible because e_2 cannot be less than zero. The extent to which period 1 emissions affect period 2 is determined by δ . If $\delta=0$, the pollutant is a flow pollutant – it completely dissipates. If $\delta>0$, the pollutant has stock characteristics – it accumulates in the environment and increases the marginal harm from emissions in later periods.¹⁰ Learning is reflected in the second period choice, which is made after the estimate of θ is updated given the realization y of \tilde{y} . Discounting between periods is omitted for simplicity.¹¹

⁹ Kolstad (1996), Ulph and Ulph (1997), Gollier, Jullien, and Treich (2000), Ingham and Ulph (2005) all use this model.

¹⁰ More formally, $\frac{\partial \theta}{\partial e_1} > 0$, if $\delta > 0$, and $\frac{\partial \theta}{\partial e_1} = 0$, if $\delta = 0$.

¹¹ Ulph and Ulph (1997) and Gollier, Jullien, and Treich (2000) write the utility in the second period as nonseparable in damages: $v[e_2 - \theta(\delta e_1 + e_2)]$. I use an additively separable form because the central case considered here is where the damages fall on third parties. Separability is a natural assumption in this case.

Equation (1) says that we want to choose emissions in period 1 to maximize period 1 utility plus the expected value of period 2 utility given that we will make a choice about period 2 emissions with better information. The internal expected value term in the second term in (1) reflects that second period choice given new information. The external expected value in the second term in (1) reflects current expectations about the second period choice. The central idea in (1) (and what makes it hard to analyze) is that we want to know how to choose period 1 emissions given flexibility in period 2. We cannot simply use the expected value of emissions as of today. Instead, we have to consider the expected value as of today given a future choice based on new information.

We want to know whether first period emissions, e_1 , are lower than with no irreversibility and/or less learning. The effect of irreversibility is relatively straightforward. The prospect of irreversible harm will reduce emissions in the first period. If the irreversibility constraint binds in some states of the world, this increases the expected marginal damages from period 1 emissions, making it desirable to reduce period 1 emissions as compared to the case where there is no such constraint. The size of the effect depends on the likelihood that the constraint binds – that in the future we will want to reduce the stock by emitting a negative amount. This depends on damages and on the depreciation rate. The greater the likelihood of high damages for a given stock and the lower the depreciation rate (higher δ in the notation in (1)), the more likely the irreversibility constraint binds.

Note that if the pollutant is a flow pollutant so that $\delta=0$, first period emissions have no affect on the second period so we can set first period emissions independently of the second period choice. There is no precautionary affect in equation (1) in this case. Advocates for the precautionary principle, however, would still argue that it applies. For example, imagine we are considering an activity might which release a pollutant which will kill large numbers of people and then immediately dissipate. There are no stock effects; $\delta=0$. Nevertheless, many would argue that the precautionary principle would apply: under the precautionary principle we should not let uncertainty about the harm prevent taking action to prevent it. This version of the precautionary principle, however, does not require deviation from first-best Pigouvian taxes.

Assume for now that that $\delta>0$ so that period 1 emissions affect period 2. Learning can either increase or reduce current period emissions and the direction

of the affects appears to depend on the shape of the utility function.¹² While there are not yet any useful general results, scholars have analyzed a number of special cases.

Define π_{y_t} as the updated probability distribution for values of θ given new information y . Epstein (1980) showed that if the marginal value of the second term in (1) with respect to first period emissions is concave with respect to π_{y_t} the prospect of learning reduces first period emissions and if it is convex, learning increases first period emissions. It is not easy, however, to develop an intuition for concavity of marginal second period utility with respect to updated information. Gollier, Jullien, and Treich (2000) show that for hyperbolic absolute risk aversion utility in period 2, learning reduces first period emissions if and only if the measure of relative risk aversion is between zero and 1. Ulph and Ulph (1997) consider the case where both $v(e)$ and θ are quadratic.¹³ In this case, the prospect of learning always reduces first period emissions.

Given the complexity of these results, it is not clear that there is a simple intuition explaining the effect of learning. Nevertheless, we can gain some intuitions by considering a simple case where both the benefit of emissions and damages are quadratic and there are only two levels of damages, high and low. Ingham and Ulph (2005) illustrate this argument with the graph shown in Figure 1. Marginal damages in the second period are either θ'_l or θ'_h . Marginal benefits from second period emissions are given by $v'(e_2)$. Compare the expected marginal damages from emissions when (1) there is no learning to (2) where we expect to learn. When there is no learning, the expected marginal harm is θ'_{avg} . We would choose e_{avg} and expected resulting marginal harm is the distance from the origin to a . If there is learning, we can pick either e_l or e_h depending on whether we learn damages are high or low. The expected marginal harm is the average of b and c . Simple geometry shows that ba is greater than ac , so the expected marginal harm from emissions is lower when there is learning. The reason is, very loosely, that we are better able to choose emissions levels in the future when there is learning. The result in this case is that emissions are *higher* in the first period because their cost is lower.

¹² There is considerable complexity in formally defining when an information set is more informative than another information set. See Epstein (1980) for a discussion.

¹³ The damage function θ is fixed and known in their model. Uncertainty comes about through a random multiplier on damages.

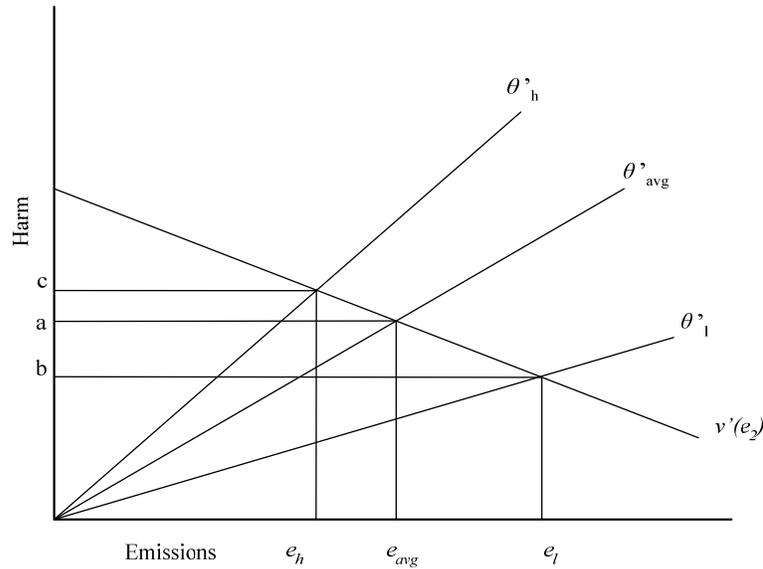


Figure 1: Gains from learning with two levels of future harm

Although the structure assumed in (1) turns out to be complex to analyze, most environmental problems in fact have a yet more complex structure. One important omission, addressed by Kolstad (1996), is that reducing emissions in (1) does not require any expenditures – it just requires consuming less. Reducing emissions, however, often requires expending capital on abatement technology. If harm ends up being low, those expenditures are wasted. For example, if climate change turns out to be not so bad, money spent on carbon capture and storage will have been wasted as this technology has no beneficial effects other than reducing carbon in the atmosphere. We can think of there being offsetting sunk costs: emissions of pollutants in period 1 are sunk because of the irreversibility constraint; abatement resources spent in period 1 are sunk because these resources cannot be immediately redeployed. The two irreversibilities, and a resulting desire to preserve flexibility, go in opposite directions. Which one is stronger is an empirical issue and will depend on the particular pollutant and abatement technology.

A related approach to the problem is to model it as an optimal stopping problem. In these models, time is assumed to be continuous and information arrives regularly. The choice is when to adopt a given policy rather than the level of e_l at a given time. Pindyck (2000) considers a model of this sort, with uncertainty both with respect to emissions (e.g., how the stock evolves for a given flow) and damages and with irreversible damages and abatement expenditures. Damages in his model are a quadratic function of the stock of pollutant and are

uncertain because of an uncertain damage parameter that acts on the stock. There are no available closed form solutions to this model. Balikcioglu, Fackler, and Pindyck (2011) provide numerical solutions to this problem and show that policies are adopted later if uncertainty increases or depreciation is greater (so that the policy is less irreversible).

Finally, because of the complexity of the problem, a number of scholars have used simulations to try to find the direction of the effects. For example, Keller, Bolker, and Bradford (2004) use a computational model of the economy with the possibility of a sudden irreversible harm.¹⁴ In one of their cases, they compare abatement when there is learning to when there is no learning. They find under their parameterization that abatement decreases when there is learning, indicating that the value of flexibility with respect to abatement capital is greater than the value of flexibility regarding the irreversible harm.

2. Implications for taxation and other regulatory systems

The question is what are the implications of this analysis for the regulation of environmental harms? Even in the case where the precautionary principle or the relevant economic analysis would require acceleration or delay of abatement, environmental taxes should be set equal to expected marginal harm. To build up to this conclusion, I begin with a discussion of property rights and tort damages as methods of internalizing environmental harms, and then discuss how these solutions relate to taxes. We might think of this as Coase meets Pigou meets Posner.

2.1 Property rights and torts

The problem described in (1) can apply to any decision maker. Arrow and Fisher (1974) consider the choice to develop a piece of land containing a virgin redwood forest. While they seem to have pollution problems in mind – the redwood forest gives an impression of public value – in the absence of a specified externality, their model is best interpreted as a model of consumer behavior. In the environmental context, however, (1) is often taken to be the social optimization problem to be solved by the government. For example, many of the recent papers examining the issue, such as Ulph and Ulph (1997), do so in the context of climate change, in which case the second period harm falls on third

¹⁴ They assume that there is a possibility that the melting of the Greenland ice sheet causes the Gulf Stream (the thermohaline circulation) to overturn, causing irreversible and dramatic changes to the climate.

parties. If this is the case, the government determines emissions in each period and when there are sunk abatement costs, the choice of abatement expenditures in each period. Equation (1) can then be viewed as a model of a cap and trade system that sets an emissions limit in each period, with the solution telling us what that limit, e_i , should be. Alternatively, (1) can be viewed as a model of the optimal command and control regulation because it tells the government what the actions in each period should be.

If (1) is considered an individual maximization problem in which the individual bears all of the costs and benefits of his choices, the problem is no different than other problems of consumer behavior in that it is not a model of an externality-causing activity. Understanding the solution helps us understand how consumers respond to learning and sunk costs in these situations but an individual solving (1) still maximizes social welfare. There are no externalities (and no other specified market failures), so the individual optimization is the social optimization.

Even if the polluting individual does not bear the harm, the polluter will make the socially optimal choice if property rights are complete so that the individuals who do face the harm can charge the polluter. Coase (1960). Imagine, for example, the harm in the land development case is an increase in water run-off onto a neighbor's land, flooding it and reducing its value. If the developer/polluter had to pay for this use of the neighbor's land, the developer would face a charge of $\theta(\delta e_1 + e_2)$.¹⁵ The developer/polluter will bear the full social consequences from his action, and the individual optimization will again equal social optimization.¹⁶ As Coase emphasized, if property rights are complete (and bargaining does not fail because of transactions costs), decisions will be socially optimal.

If property rights are incomplete, so that the activity creates an externality, the polluter will now consider only the first term in (1) when making his decision

¹⁵ The expression in the text simplifies somewhat as in (1), the information does not resolve uncertainty, so the harm is the marginal expected harm given the new information, $E_{\theta/\pi_0}[\theta'(\delta e_1 + e_2)]$. This remaining uncertainty does not affect the analysis so I omit it from the discussion.

¹⁶ Tort liability can also substitute for the price that a property owner would force the polluter to pay. If liability equals $V(e_1, \pi_0)$, the individual will face the full social costs of emissions. If, alternatively, tort liability results in an injunction, as in some nuisance-type pollution cases, tort liability acts to effectively create property rights.

about first period emissions. The polluter will not consider the harm from first period activity. Emissions will be too high. For example, nobody is able to charge emitters of carbon dioxide for their use of the atmosphere, so emitters only consider the benefits and the resulting emissions are too high.

Tort liability for actual harm $\theta(\delta e_1 + e_2)$ would solve the problem.¹⁷ The individual, expecting this charge, would maximize (1), achieving the social optimum. We can think of tort liability as a substitute for property rights in cases where it is administratively difficult to create property rights.

Suppose that because of concerns about liquidity or bankruptcy, the government required polluters to prepay expected tort liabilities such as by posting a bond, or purchasing insurance. The payment at time 1 would be equal to the expected harm given the information known at time 1. If a polluter prepays the tort liability, this is sufficient to internalize the harm. The polluter pays the insurance premium or the cost of the bond, and nothing more; any actual payments to victims are paid by the insurance company or through liquidation of the bond.

The prepayment would be equal to expected harm. To calculate the expected harm, let e_2^* be the choice of second period emissions given the information \mathcal{Y} available in the second period and subject to an additional charge for the harm that those emissions cause. Note that e_2^* is a function of e_1 and δ because δe_1 affects the marginal harm from emissions in the second period and it is a function of v because it is determined as part of the second period maximization. The prepayment would be the (present value of) expected marginal harm from first period emissions $E_{\mathcal{Y}_0}[\theta'(\delta e_1 + e_2^*)]$. With this prepayment, the result would be the same as with normal tort damages imposed after harm is caused: the polluter would fully take the expected externality into account when deciding on emissions in time 1. We would not need to adjust the tort liability in time 2 for actual harm from period 1 emissions.

¹⁷ I am not distinguishing here between strict liability and negligence. Strict liability imposes a charge equal to harm regardless of the care level taken by the polluter while negligence will impose a charge equal to harm if and only if the care level is suboptimal. I generally use strict liability as the example of tort liability. Taxes equivalent to negligence could also be considered but would be more complex.

2.2 Taxation

Given the discussion above, the optimal tax should be clear: a tax set equal to the expected marginal harm based on current information causes the individual to choose the social optimum. We can view the government imposition of a tax as a special case of complete Coasian markets where the government is the owner of the harmed property. If the government imposes the same price that a property owner would charge, the polluter will choose the social optimum just as in complete property-rights case. Alternatively, we can view the tax as a prepayment of expected tort liability with the government standing in for the victims.

To see this in more detail, start by noting that the standard solution for Pigouvian tax is that the tax should be equal to the present value of the marginal harm from emissions. For a flow-pollutant, it will just be the present value of the harm whenever it occurs. For stock pollutant, an additional unit of pollution in period 1 causes harm in both periods 1 and 2, the optimal tax in period 1 is the sum of the present values of the additional harm.¹⁸

This solution remains optimal when there is uncertainty about future harms, sunk costs, and learning. Consider polluter in the first period, deciding on choice of e_1 . If the polluter bore all of the benefits and harms from emissions, he would get benefits $u(e_1)$ and bear costs equal to the expected marginal harm due to the effects of first period emissions in the second period. If the individual does not bear the harm, a tax equal to the expected marginal harm due to the effects of first period emissions restores the optimum. This is the same as a prepayment of tort liability: $E_{y_0}[\theta'(\delta e_1 + e_2^*)]$.¹⁹

The period 2 tax is simpler. New information y is revealed and θ is correspondingly updated. The polluter need only be charged the marginal harm from emissions in period 2: $\theta'(\delta e_1 + e_2)$. This is just the standard Pigouvian tax

¹⁸ This principle is basic enough that I am not aware of a paper that establishes it as a central proposition, but a number, such as Ko, Lapan, and Sandler (1992) and Sandmo (2000) report the result while considering more complex problems.

¹⁹ Note that for a flow pollutant, the tax is zero because $\theta'=0$ when $\delta=0$. In the setup assumed by (1), harm only occurs in the second period, so flow pollutants do not create harm. If, in a more general model there were harm in the first period, the tax would be the marginal harm in that period.

with the exception that harm depends on the stock of prior emissions, δe_1 . Given this tax, the polluter will make the optimal decision in period 2.

The conclusion is that the government should not raise or lower environmental taxes because of precaution. In particular, first period taxes are not higher so that the government can preserve flexibility during the second period when we know more about the likely harms from emissions. The intuition is that taxes decentralize decisions in the same way that property rights do. We expect individuals operating in markets with functioning property rights to make reasonable choices of investments including the timing of activities that require use of others' property. When there is an externality causing activity, taxes and torts equal to expected harm create the same effects. To the extent that the precautionary principle requires higher abatement than otherwise to preserve flexibility, it does not apply to taxes.

3. Extensions, caveats, and limitations

This section considers extensions and limitations of the analysis in Part 2. I consider three: (1) how irreversibilities and learning affect instrument choice; (2) whether taxes that do not adjust to new information should be set to include a precautionary element; and (3) whether taxes should be set higher or lower than the Pigouvian amount because of their effect on learning and technological development.

3.1 Instrument choice

The analysis above has implications for the choice between market-based instruments and command and control regulations. The core claim is that to determine the optimal Pigouvian tax in the context of stock pollutants with irreversible emissions and learning, we need to know how individuals and firms solve the optimal timing problem. The information requirements for this are similar to those required for command and control regulations. Once we consider Pigouvian taxes in the present setting, their advantage may be smaller than otherwise.

There is a substantial literature comparing command and control systems to pricing systems, (because of their prevalence, usually some sort of cap and trade system).²⁰ The basic claim is that command and control requires more

²⁰ A number of papers are collected in *Moving to Markets in Environmental Regulation* (2007) and *Emissions Trading, Environmental Policy's New Approach* (2000)

information than market-based systems which harness private information. In their most extreme form, command and control regulations require the government to specify particular emissions reductions or the use of a particular technology for individual firms. The government has to know each firm's marginal abatement cost and, moreover, as individual firms develop technologies, the government has to update the regulations to reflect the new marginal costs for individual firms.

With a tax, at least in a simple setting, the government does not need to know the costs of emissions abatement. As Kaplow and Shavell (2002) point out, if the government announces a tax schedule equal to marginal harm at different levels of emissions, firms, knowing their own abatement costs and facing this price will optimize. Moreover, firms can pursue a variety of strategies and are rewarded for finding low-cost methods of mitigation.

Cap and trade systems are slightly more complex but can achieve the same results as a tax with the same information. Cap and trade systems establish a price for the quantity of permits issued through the market for permits. The government, seeing this price, can adjust the quantity to ensure that the price/quantity pair is on the marginal harm curve. For example, if for a given quantity of permits, the trading price of permits is higher than the marginal harm, the government can issue more permits. The government can also automate this by setting a schedule permits with specified prices as described initially by Roberts and Spence (1976). Weisbach (2011) reviews a number of mechanisms for the designing of cap and trade systems to be the same as a Pigouvian tax.²¹

²¹ The results of empirical comparisons between command and control and market-based systems are mixed. Most studies seem to show advantage to market-based systems but the size of advantage is unclear. There are a number of difficulties in making the comparison. The primary problem is that we have to compare an existing regulation to a counterfactual. There is no single choice of command and control or market-based instruments to be the alternative, so even specifying what the counterfactual should be is not straightforward. For example, there are numerous versions of command and control regulations, some which are quite rigid and some which are flexible and resemble market-based systems. If a researcher is to compare how much better, say, the cap and trade system for SO₂ is (enacted in the U.S. in 1990 to control acid rain) than the command and control alternative, the researcher has to specify what that alternative is. Moreover, determining what the world would have looked like given this choice involves speculation. As a result, the precise level of gains (if any) from moving to market-based systems is unclear. Nevertheless, market-based systems are thought to have an informational advantage over command and control regulations.

The possibility of irreversibilities and learning reduces the informational advantages of market-based systems. The reason is that to set a market-price on pollutants (either directly through a tax or indirectly through a cap), we have to know what future emissions will be because the marginal harm from emissions today depends on the future stock.

Consider emissions of a stock pollutant at $t = 0$ that will cause harm at $t = 1, 2$. The optimal tax is the sum of the present value of the marginal harm the emissions cause in all future periods. Because it is a stock pollutant, the harm in period 2 depends on the total emitted in prior periods, $t = 0, 1$. If marginal harm is nonlinear in the stock, to calculate the marginal harm in period 2 of emissions in period 0, we have to know the emissions in period 1. Therefore, when calculating the expected marginal harm from activities involving stock pollutants, decision-makers need to consider how individual actors solve the optimal timing problem. Factors, such as expected learning, that change how polluters solve the timing problem influence the marginal harm from emissions today. Thus, an indirect evaluation of the optimal timing problem can enter the calculation, even though this is only to calculate marginal harm.

In particular, in (1), have to know e_2^* to set first period tax. Future emissions, however, depend on available technology and the choices firms make. The information required to set a Pigouvian tax in this context is not all that different from the information required to impose some forms of command and control regulations. Taxes may retain an advantage in that the regulator only needs to know the variables that enter (1) (or more realistic versions of (1)) in the aggregate rather than at the firm level, but the advantage is smaller than in simpler contexts, such as for flow pollutants.

The information problem makes tort liability seem attractive over either command and control systems or taxation. Tort liability is equal to actual realized harm, so the information costs might be lower. We do not have to estimate e_2^* . Instead, we can wait and observe actual harm. For many environmental issues, however, tort liability may have other problems, such as that by the time the harm arises, the polluter may be judgment proof or that the harm may be sufficiently diffuse that the costs of bringing suit or tracing the harm to polluters overwhelm the potential recovery.²²

²² Shavell (2011) discusses the choice between torts and taxation and concludes that for broad-based pollution problems, such as climate change or emissions into a large body of water,

3.2 Taxes that don't adjust continuously

It is a widespread trope that taxes should be stable. This is captured in aphorism that an old tax is a good tax. While it may or may not be true for other types of taxes, it is not true for Pigouvian taxes. Pigouvian taxes should always be equal to current estimate of marginal harm from activity. If expected marginal harm changes, the tax rate should change. For Pigouvian taxes, artificial stability is bad.²³

One way to see this is to analogize taxes to property. The price of property varies with market conditions. If in (1), θ represented the use of property, it would vary all the time and the government would not normally try to limit price changes. The individual would consider the variance of θ when determining first period emissions. A Pigouvian tax is like government assertion of property rights in the polluted asset – you have to pay the government marginal harm to use the asset. The government's charge for use should vary like other property rights so that the individual will solve (1).

What if the tax does not rapidly adjust to new information about harm, say, because of institutional constraints? We want to know whether the tax should be set higher or lower than its Pigouvian level to take this rigidity into account.²⁴

If taxes are set based on a solution to (1), they will be set in the first period based on expectations about second period information. If we do not adjust taxes in the second period based on new information, however, the second period choice of emissions will be based on a tax that is too high or too low. Second

taxes may be preferred whereas for traditional nuisances, tort liability is preferred. The externality in (1) can be either a broad pollution problem or a nuisance. In subsequent work, he notes that an advantage of tort liability is that the government needs only to measure actual harm, reflecting similar reasoning to that in the text. Shavell (2012).

²³ Ko, Lapan, and Sandler (1992) consider a related problem. They show that first-best Pigouvian taxes should be adjusted continuously and then examine how best to set rigid taxes. They do not particularly address uncertainty and learning, however.

²⁴ Note that most of the literature on the choice between taxes and quantity limits, following Weitzman (1974), relies on non-adjustment to new information as a source of differences in the two systems. The focus here is on the level of taxation not on the choice of instruments. For a discussion of how flexibility and adjustment to new information affect instrument choice, see Kaplow (2011) and Weisbach (2011).

period emissions will be correspondingly too low or too high. In addition, knowing this, first period emissions may also be too high or too low.

To illustrate, suppose in a two period case such as (1) that we set taxes on carbon dioxide to prevent climate change, and then, before the second period, we learn that climate change is worse than we expected. If taxes are not adjusted, they will be too low given the new information and emissions will be too high. Welfare will be lower than it could be. Moreover, a polluter knowing that second period emissions will not be optimal may adjust first period emissions. Similarly, if we learn that the effects of emissions are it not as bad as feared, second period taxes should go down. If they are not adjusted, emissions will be too low given their modest damages, and welfare will again be lower than the optimum.

We want to know whether, if we must have a rigid tax, it should be higher or lower than a flexible Pigouvian tax. We might set rigid Pigouvian taxes higher than flexible taxes if the harm from failing to increase taxes when appropriate is greater than the loss from failing to reduce taxes when appropriate. We might anticipate the failure to adjust taxes and set them initially at a level that minimizes the costs of rigidity.

While anticipation of this sort might be valuable, the direction of adjustment is not clear without a greater specification of the problem. The loss from the tax being higher or lower than optimal depends on both the curvature of the utility from consumption, $v(e_2)$ and on damages, θ . While we may have views about the curvature of the utility function, the shape of the damage function will depend on the particular pollutant and circumstances. A rigid tax may be optimally set higher or lower than a flexible tax depending on the curvature of θ .

3.3 Endogenous technology/information

In the model considered thus far, information arrives exogenously. Scientists or engineers independently conduct experiments which produce the information y used to set second period emissions. While some information may arrive exogenously, much of it will be endogenous to policy. The price on emissions will determine the incentive to innovate.

Many believe that in climate change, the development of technology is by far the most important variable because of the very high welfare costs of pure abatement strategies (i.e. using less) for energy. Fossil fuels are the overwhelmingly dominant source of energy and if emissions eventually have to be near zero to stabilize CO₂ in the atmosphere, these sources will have to be

eliminated. Standards of living correlate highly with energy use. Without replacing that energy, the result would be a severe decline in standards of living. Therefore, reducing the risks from climate change while retaining modern standards of living will require substantial technological developments. These will likely depend on the price placed on carbon.

Solutions to other pollution problems may depend less on technological developments – pure abatement may be a more feasible option in many cases – but technology can make solutions cheaper. The effect of a Pigouvian tax on technological development will be important in many cases. The question is whether and how endogenous information affects the tax in period 1.

In a simple setting with a flow pollutant, we should set the tax equal to marginal harm and not worry about the effects on technology. Once the harm is priced, environmental technology is just like any other technology for markets where there is no externality. Although it is now understood that knowledge spillovers and/or increasing returns to knowledge may require special policies toward technology such as subsidies for research and development, there is nothing special about environmental technologies in this regard. Once a (flow) environmental externality is priced through a tax, general R&D policies that apply to all other areas of the economy without externalities should govern. Any additional R&D policy aimed at an environmental problem would tilt R&D policies away from those with the highest potential.

This approach may not work in the present context where there are stock externalities with learning.²⁵ The problem, like the problem with instrument choice considered above, is that the tax in period 1 depends on e_2^* . If we interpret e_i as economic activity in each period, technology will allow increased economic activity with lower damages, θ . This depends on the technology available in the second period which, in turn, depends on the expected tax. We cannot separate the

²⁵ While there is substantial research on the interaction of environmental policies and technology, I am not aware of work that incorporates irreversibilities of the sort captured in (1). Popp, Newell, and Jaffe (2010) provide a survey of recent work. Hart (2008) considers the timing of carbon taxes with endogenous technology but he uses simple expectations rather than allowing for future flexibility of the type allowed in (1). He concludes that in the central case Pigouvian taxes should not be adjusted for endogenous technology but on transition to a tax regime if the current stock is not optimal, it should be set higher. Because he uses expectations, he does not consider the interaction of tax rate and future behavior, which is central to the analysis here.

marginal harm from emissions from the tax rate when technology depends on the tax rate.

To illustrate, suppose we think future technology will be very good. For example, we might expect to invent a cheap source of carbon-free energy or of eliminating persistent chemicals from the environment. In (1), we can interpret this as having a likely realization of θ that is low, so that e_2^* is high. If, however, we set low tax rates because of this expected development, we may not get the new technology. The development of pollution avoidance technologies might depend on a high price on pollution.

We can rewrite (1) so that second period harm depends on the tax rates in the two periods:

$$\max_{e_1 \geq 0} u(e_1, \tau_1) + E_{y_0} \left\{ \max_{e_2 \geq 0} E_{\theta(y_0, \tau_1, \tau_2)} \left[v(e_2, \tau_2) - \theta(\delta e_1 + e_2) \right] \right\} \quad (2)$$

We cannot set the tax in the first period, τ_1 , without understanding how taxes will affect damages from emissions (or economic activity, if we interpret e more generally). Therefore, in this setting, the solution available in the flow-pollutant setting of just setting the tax equal to marginal harm, is not available.

The problem is difficult because even though we are solving simultaneously for the optimal price and technology in (2), environmental technologies will still likely be subject to general policies regarding technology, such as patent law or R&D subsidies. Even understanding the direction of the effects – is the optimal Pigouvian tax higher or lower because of endogenous technology – would require a complex model.

These considerations point to another advantage of tort liability over taxes. Because tort liability is equal to actual harm, we do not have to estimate e_2^* . This means that we do not have to consider the effects of technology on e_2^* or how those effects interact with general technology policies. If we set tort liability equal to actual harm, the environmental harm is internalized and we can think of the activity as taking place in a complete market just like other activities. General policies toward technology would apply.

4. Conclusion

The question we began with was whether Pigouvian taxes on stock externalities should take the precautionary principle into account. The answer depends on which version of the precautionary principle is considered. The weakest versions simply state that uncertainty about harm should not preclude environmental actions. This version does apply to taxes. The optimal Pigouvian tax considers expected harms. Stronger versions of the precautionary principle would seem to imply that taxes should be higher than the Pigouvian amount (expected value of marginal harm) because of the possibility of learning and of irreversible harm. These versions suggest reducing emissions now to preserve flexibility in the future. These arguments do not apply to environmental taxes: if environmental taxes are set at equal to expected marginal harm, market actors will take appropriate precautions, including if appropriate, abating earlier. Pigouvian taxes externalize these decisions to market actors by imposing a price on pollution.

We also considered a number of extensions and limitations to the analysis. The central difficulty is that for stock externalities, the optimal tax in the first period depends on second period emissions, so we have to estimate second period choices to determine the tax rate. Calculating the tax therefore requires knowledge of abatement decisions which is similar to the knowledge required for setting command and control regulations. Moreover, if technology is endogenous, technology policies and taxes have to be set simultaneous because each depends on the other.

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Readers with comments should address them to:

Professor David A. Weisbach
University of Chicago Law School
1111 East 60th Street
Chicago, IL 60637
d-weisbach@uchicago.edu

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