Should Environmental Taxes Be Precautionary?

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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

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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. More complex models include both irreversible harms and irreversible expenditures on abatement, so that concerns about flexibility run both

[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 (1996a and 1996b), Ulph and Ulph (1997), Gollier, Jullien, and Treich (2000), Pindyck (2000), Pindyck (2002), Gollier and Treich (2003), Ingham and Ulph (2005).

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 or at a higher rate 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 motives. Some versions of the precautionary principle merely require the use of expected values and, therefore, are consistent with such taxes.

[3] Ko, Lapan, and Sandler (1992), Ulph and Ulph (1994), and 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 5 discusses this issue.

Second, it might seem that because there is no tax precautionary principle, the information requirements for taxes would be lower than for other regulatory mechanisms. We do not have to solve the optimal timing problem to set the tax because it is based on expected values. This is not correct. To determine expected marginal harm from an activity, the government needs to understand the extent to which individual actors take precautions. 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 even though taxes, should be set equal to expected marginal harm.

Third, optimal Pigouvian taxes are equal to the current estimate of marginal harm given the 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 regimes.

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.

The paper comes in six sections. Section 1 provides three motivating examples. Section 2 sets forth a two-period model to capture the idea of decision-making when there is an uncertain but irreversible harm where we will learn more about the harm in the future. Section 3 considers the solution to the model in three circumstances: (i) as a problem of consumer behavior; (ii) an externality solved by taxation; and (iii) an externality solved by tort liability or by specifying property rights. It shows that if taxes are based on expected harm, actors will be behave the same was as when the problem is one of consumer behavior. Torts and property rights can achieve the same result, so that Pigouvian taxes, torts, and property rights should be seen as substitutes for one another. Section 4 then examines how the tax solution to the model compares to the precautionary principle. Section 5 considers caveats and extensions to the model. Section 6 concludes.

1. Motivating examples

I begin with three 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. If, however, 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 similar but has a clear harm to a third party. Consider a downstream owner of land who wants to build a dam on a stream or river abutting his property. Building the dam, however, will flood upstream property owners, permanently destroying their property. We do not know the future value of the destroyed property, nor do we know the future value of the benefits from the dam (such as flood control, power, and irrigation). The owner has to decide whether to build the dam now or wait. Although we might classify this problem as one of natural resource use, it has the same structure as environmental problems.

The final 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 all three examples, current decisions inalterably affect the future but the amount of the resulting harm is unknown. In deciding what to do in the now, therefore, we have to consider the future effects. This structure describes some but by no means all pollution or natural resource 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.

2. A Simple Model of the Problem

We want to model the choices in these examples in the simplest possible setting that reflects both that the acivity results in permanent harm and that we will learn more about the size of that harm in the future. Much of the literature has focused on a model in which an actor/polluter has to determine a level of activity and resulting emissions e_i in each of two periods.[4] Emissions in the first period cause damages of an unknown quantity in the second period and cannot be reversed. Before deciding on second period actions, however, the actor learns more about the harm from emissions and can adjust, such as by engaging in less of the activity if damages turn out to be high or by increasing the level of activity if damages turn out to be low.

Let $\tilde{\theta}(\delta e_1 + e_2)$ be stochastic damages, which are a function of the stock of emissions in the second period. Emissions depreciate at rate $1-\delta$, so that δe_1 of first period emissions are left in the second period, and the total stock in the second period is $\delta e_1 + e_2$.[5] First period expectations of the damages are based on the information set $\tilde{y}$. Before the second period the actor will receive new information, y, which allows him to revise his estimate of the damages and choose e_2 accordingly. Discounting between periods is omitted for simplicity.

[4] Kolstad (1996a), Ulph and Ulph (1997), Gollier, Jullien, and Treich (2000), Ingham and Ulph (2005) all use this model.

[5] 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. More formally, $\partial\tilde{\theta}/\partial e_1 > 0,\ \text{if}\ \delta > 0$, and $\partial\tilde{\theta}/\partial e_1 = 0,\ \text{if}\ \delta = 0.$

We can write down this problem as:

$$(1) \qquad \max_{e_1 \geq 0} u(e_1) + E_{\tilde{y}} \left\{ \max_{e_2 \geq 0} \underbrace{E_{\tilde{\theta}|\tilde{y}} \left[v(e_2) - \tilde{\theta}(\delta e_1 + e_2) \right]}_{\text{second period choice given new information}} \right\},$$

where the actor gets utility u and v from emissions in periods 1 and 2.[6] Emissions in the second period cannot be less than zero, so that any remaining stock of emissions from first period activity cannot be reversed. Learning is reflected by the choice of second period activity after new information $\tilde{y}$ is revealed.

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 reflects that second period choice given new information. The external expected value in the second term reflects current expectations about this second period choice. The central idea in (1) 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.

Note that (1) contains an important simplification, which is that there are no sunk abatement costs. Reducing emissions in (1) just requires doing 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. In a more complete model, there would be 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

[6] Ulph and Ulph (1997) and Gollier, Jullien, and Treich (2000) write the utility in the second period as nonseparable in damages: $v\left[e_2 - \tilde{\theta}(\delta e_1 + e_2)\right]$. 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.

irreversibilities, and any resulting desire to preserve flexibility, go in opposite directions. To keep the problem simple, we just consider sunk emissions.[7]

3. Solution

3.1 *As a consumer problem*

Start by considering the solution to (1) where the actor faces all of the costs and benefits from actions. Although such a actor might be taken to be a government planner, it can also be an individual who gets the benefits and bears the costs of his actions. The clear-cutting example used by Arrow and Fisher (1974) might be an example. The owner of the property will receive both the benefits of development and the loss of the virgin forest, so he appears to bear all of the costs and benefits of his actions.

In this situation, the actor chooses emissions in the first period, e_1, to maximize (1). The question is whether the emissions are higher or lower than without irreversibility and/or learning. Irreversibility is reflected in the constraint that $e_2 \geq 0$. The effect of this constraint 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.

Learning is reflected by the flexibility to choose second period emissions given new information y. The effect of learning is ambiguous. It may increase first period emissions because it lowers expected harm from second period emissions. If we expect to know more about the effects of emissions in the future, we can choose the level of emissions in the future more intelligently, so expected harm in the second period as of the first period is lower. It may, on the other hand, reduce first period emissions because lower first period emissions preserve flexibility, giving the information greater value.

[7] Kolstad (1996a and 1996b) addresses the dual-sided problem.

Epstein (1980) provides a complete characterization of the solution. Define $\pi_{\tilde{y}}$ as the updated probability distribution for values of θ given new information y. Epstein (1980) shows that if the marginal value of the second term in (1) with respect to first period emissions is concave with respect to $\pi_{\tilde{y}}$, 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.

As a result, solutions to (1) have focused on special cases. For example, 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.[8] In this case, the prospect of learning increases first period emissions.[9]

Regardless of the details of the solution, if the actor bears all of the costs and benefits of his actions, the choice will be socially optimal. When there are no identifiable externalities, we can think of (1) as an ordinary problem of consumer or producer choice. Actors regularly face these sorts of problems.

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

[9] Other approaches to modeling the problem do not yield simple results either. For example, Pindyck (2000) considers a continuous time model 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). Keller, Bolker, and Bradford (2004) use a computational model of the economy with the possibility of a sudden irreversible harm such as the melting of the Greenland ice sheet. 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.

3.2 *Taxation*

Suppose that the actor in (1) does not bear second period harm so that (1) is a model of an externality such as climate change. The actor will emit too much because he does not consider the effects of his activities. In deciding on first period emissions, he considers only the first term in (1). The standard Pigouvian tax solution to externalities is a tax equal to the marginal harm from the activity. The questions whether this solution applies in the present context.

Consider a charge, such as a fine, imposed in second period equal to the harm $E_{\tilde{\theta}|\tilde{y}}\left[\tilde{\theta}\left(\delta e_1 + e_2\right)\right]$. The actor facing this charge will fully take into account all the costs and benefits of the activity. The actor will receive his own utility in each period, $u(e_1)$ and $v(e_2)$ and in the second period face a fine equal to $E_{\tilde{\theta}|\tilde{y}}\left[\tilde{\theta}\left(\delta e_1 + e_2\right)\right]$. Therefore, the actor will maximize (1) and make the same choices as in the case with no externality.

When we impose a second period charge or a fine, the actor, in period 1, has to determine his actions based on the information available in period 1. In particular, when there is a second period fine equal to actual harm, the polluter must determine how first period emissions change the *expected* value of the fine given current information and knowing that he will learn more and have the flexibility to adjust his behavior in the second period. The actor in the first period chooses emission faced with the marginal expected fine. A first period tax equal to this amount – marginal expected harm from emissions – will, therefore, have same effect as second period fine.[10]

To compute the tax, let e_2^* be the polluter's choice of second period emissions given the information 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 tax is the (present value of) expected marginal

[10] One difference is that a tax equal to the expected value would provide a certain cost for polluting while a fine equal to actual harm would be uncertain. If the actor is risk averse, the resulting behavior may be different. In the model used here, where utility is linear in damages, this should not affect the result. In more general models, we would want to impose a charge equal to the dollar equivalent expected utility costs from the pollution.

harm from first period emissions $E_{\tilde{\theta}|\tilde{y}}\left[\tilde{\theta}'\left(\delta e_1 + e_2^*\right)\right]$. With this tax, the result would be the same with the fine in the second period: the polluter would fully take the expected externality into account when deciding on emissions in time 1.

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: $\theta'\left(\delta e_1 + e_2\right)$. This is just the standard Pigouvian tax 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, therefore, is a tax based on expected marginal harm from emissions causes the actor to make the same choices as an actor who fully internalizes the harm. An actor who fully internalizes the harm has to make choices in the first period based on this expectation so a tax equal to this amount produces the same result.

3.3 P*roperty rights and tort liability*

It is helpful in considering the results discussed above to compare Pigouvian taxes to property rights and tort liability. Even if the actor does not bear the harm, the actor will make the socially optimal choice if property rights are complete so that the individuals who do bear the harm can charge the polluter. Coase (1960). Consider the dam example, where the harm is water run-off onto a neighbor's land, flooding it and reducing its value. If the actor had to pay for this use of the neighbor's land, the actor would face a charge of $E_{\tilde{\theta}|\tilde{y}}\left[\tilde{\theta}\left(\delta e_1 + e_2\right)\right]$, the harm that he has caused. The actor will bear the full social consequences from his action, and the individual optimization will again equal social optimization. As Coase emphasized, if property rights are complete (and bargaining does not fail because of transactions costs), decisions will be socially optimal.

Tort liability for actual harm $E_{\tilde{\theta}|\tilde{y}}\left[\tilde{\theta}\left(\delta e_1 + e_2\right)\right]$, also solves the problem.[11] Tort liability is simply a variant of a fine except that the payment is to the harmed

[11] 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.

party rather than the government (and enforcement is private instead of public). The individual, expecting a charge equal to actual harm will maximize (1), achieving the social optimum. In some situations, such as nuisances, a tort suit can result in an injunction against the harm-causing activity. In this case, tort liability effectively creates a property right: the actor cannot cause the harm without negotiating and obtaining permission from the harmed party.

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 for a unit of emissions would be equal to the marginal expected harm given the information known at time 1, $E_{\tilde{\theta}|\tilde{y}}\left[\tilde{\theta}'\left(\delta e_1 + e_2^*\right)\right]$, which is the same as the Pigouvian tax. If a polluter prepays this amount, he will internalize the harm.

We can, therefore, think of the three instruments, taxes, torts (or fines), and property rights as substitute mechanisms for decentralizing decision-making. The choice among the three instruments will be based on considerations of administrative feasibility, enforcement costs, and similar considerations.[12] For example, in some respects, tort liability seems like the simplest system because we wait until there is actual harm before imposing sanctions. We do not have to compute expected harm. On the other hand, tort liability requires tracing harm to individual tort-feasors. If the harm occurs long after the pollution or is dispersed and due to a large number of actors, tort liability may not be feasible. Similarly, property rights are effective in many contexts but may be difficult to use in other situations, such as when the harm is dispersed. It is likely impossible, for example, to create property rights in the context of climate change and we have to instead rely on administrative surrogates, such as cap and trade systems.

[12] See Kaplow (2011) and Weisbach (2011) for discussions of the administrative considerations in choosing between a property-type regime and taxation. 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, taxes may be preferred whereas for traditional nuisances, tort liability is preferred. 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).

4. The precautionary principle

We can now ask whether the optimal Pigouvian tax is consistent with the precautionary principle. As noted, the precautionary principle is one of the primary legal tools for answering questions about the timing of pollution and abatement activities. 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.[13]

While the precautionary principle is widely used in environmental law, there is, unfortunately, no single meaning of the term, so there may be no single answer to whether it is consistent with optimal Pigouvian taxes. Different versions make different demands on environmental policy. I will present what I view as the central precautionary principle and then alternative interpretations.[14]

4.1 The central precautionary principle

I take as the central claim of the precautionary principle that we should take additional care when there is risk of harm. This means reducing pollution or other activities which have the potential to cause harm more than is required through the use of expected values, such as those used in standard cost-benefit analysis. That is, I take the precautionary principle as saying that we should use something other than cost-benefit analysis and should not merely compare expected marginal benefits to the expected marginal harms.

Many but by no means all invocations of the precautionary principle seem to have something like this in mind, although statements of the precautionary principle are rarely clear on this issue. For example, the United Nations commissioned a body to study the precautionary principle, the World Commission on the Ethics of Scientific Knowledge and Technology (which is

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

[14] Gollier, Jullien and Treich (2000) and Gollier and Treich (2003) attempt to ground the precautionary principle in a model similar to (1). They seem to be considering command and control rather than taxes as a method of internalizing harm. He does not attempt to parse the various legal formulations of the precautionary principle and instead seems to be arguing that the precautionary principle should be implemented as the solution to (1) similar to argument in Sunstein (2006).

part of UNESCO). It defined 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. The statement of the needed precautions contains no reference to costs. This version, therefore, would seem to require precautions well above those required through the use of expected values.[15] Another example 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).

Academics have posed a similar interpretation of the precautionary principle. Richard Stewart formulated a version of the precautionary principle (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) Gollier, Jullien and Treich (2000), Gollier and Treich (2003) and Sunstein (2006) attempt to ground the precautionary principle in option analysis. As quoted in the introduction, Sunstein would require regulators to reduce emissions to preserve flexibility when there are irreversible losses and uncertainty about the timing and likelihood of the loss. Gollier, and co-authors base the precautionary principle on a model similar to (1). They argue that the government ought to mandate precaution in circumstances where the solution to (1) is lower first-period emissions as compared to the case where there is no learning and no irreversibility.

We can say from the analysis above that this version of the precautionary principle does not apply to taxes. Pigouvian taxes should not be raised above an amount calculated using expected values because of precautionary motives. The reason is that Pigouvian taxes decentralize decision-making by forcing actors to face the full costs of their choices. Actors facing the full social costs of their choices will take precaution where appropriate. Once we have imposed a

[15] The Commission, however, 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.

Pigouvian tax, it is as it we have complete property rights and the actions at issue are like other actions chosen in functioning markets. To the extent we interpret the precautionary principle in this manner, there is no tax precautionary principle.

This can be seen in the optimal tax, $E_{\tilde{\theta}|\tilde{y}}\left[\tilde{\theta}^{'}\left(\delta e_1 + e_2^*\right)\right]$. It is equal to the expected harm from emissions in the first period. It is not adjusted upward to ensure additional precaution. Indeed, adjusting the tax upward to additional precaution would lead to sub-optimal activity. Individual actors facing the optimal tax will already take appropriate precautions.

4.2 *Other interpretations*

There are a number of other possible interpretations of the precautionary principle. I highlight three here.

Use expected values. Although one of the central reasons for the precautionary principle seems to be the claim that we should use something other than standard risk analysis using expected values, some versions of the precautionary principle seem to merely require the use of expected values; they do not explicitly require additional precaution. The goal seems to be to prevent opponents of environmental action from using uncertainty as an argument for not acting. For example, the Rio Declaration on Environment and Development (1992), 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. The Wingspread declaration, one of the most well-known statements of the precautionary principle, is consistent with this view. It states that "when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically." Wingspread (1998).

If the precautionary principle is interpreted this way, it is not inconsistent with optimal Pigouvian taxes. Pigouvian taxes are calculated using expected values, so they do not ignore uncertainty or allow uncertainty to be an excuse for not imposing a tax. Indeed, if there is a small probability of a large harm, the expected harm might be large and the resulting tax high.

Procedural versions. Some versions of the precautionary principle are procedural. Polluters may often have better information than the public about the likely harms from an activity. If the public does not know about the harms, it may be difficult to determine the appropriate level of regulation. By assuming the worst in this situation and, therefore, threatening to regulate, the public can force disclosure of the information. Although it is never, to my knowledge, specified, presumably once the private information is disclosed, all that is required is standard cost-benefit analysis (unless, say, the central version of the precautionary principle applies in addition to the procedural version). The Wingspread declaration is an example of the procedural version of the precautionary principle. It states that in the context of applying the precautionary principle, "the proponent of an activity, rather than the public, should bear the burden of proof."

To the extent that the precautionary principle is merely procedural, it is not inconsistent with setting taxes based on expected values. If there is an information problem in which private parties have information about expected harm not currently available to the government, it will similarly affect the computation of taxes and regulations.

Ambiguity aversion. Finally, some versions of the precautionary principle, such as those found in von Schomberg (2006) and Gardiner (2006), appear to be grounded in ambiguity aversion. The argument is that if our knowledge of the risks from an activity is insufficient to form unique priors we should minimize the risk of the worst outcomes. We should, in the face of deep uncertainty, take high levels of precaution. These arguments are based on decision theory, such as Gilboa and Schmeidler (1989), which in turn is based on experiments on human responses to ambiguity, such as Ellsberg (1961). Ellsberg, recall, showed that individuals will pay less for a bet where they do not know the odds. Rawls (1999) can be seen as making a similar claim about how actors would choose when behind the veil of ignorance.

The analysis of optimal taxes under conditions of ambiguity goes beyond the analysis here. The evaluation of (1) assumed that we could form expectations, and it is not clear what the appropriate model would be and what its solution would look like if we cannot form expectations. It is possible that optimal

Pigouvian taxes when there is ambiguity would be higher than otherwise, reflecting precaution, but without further and substantial analysis, we do not know. We do not, for example, know whether the ambiguity aversion seen in Ellsberg-type experiments on individuals is desirable or a mere behavioral regularity, and without sorting out this and other issues, we do not know how taxes should be set in these circumstances.

5. Extensions

5.1 *Instrument choice*

The analysis above has implications for the choice between market-based instruments and command and control regulations. The core claim made here 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, (which, because of their prevalence, is usually some sort of cap and trade system rather than a tax).[16] The basic claim is that command and control requires more information than market-based systems which harness private

[16] A number of papers are collected in Moving to Markets in Environmental Regulation (2007) and Emissions Trading, Environmental Policy's New Approach (2000). 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 SO_2 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.

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.

The possibility of irreversibilities and learning reduces the informational advantages of pricing 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.

The optimal tax on a stock pollutant is the sum of the present value of the marginal harm from emissions in all future periods. If marginal harm is nonlinear in emissions, to calculate the harm from a unit of emissions today, we have to know what emissions will be in the future. This means that we must understand how individuals solve the 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 the 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.

5.2 *Taxes that do not adjust to new information*

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.[17]

To consider the issue, we need to consider a three period problem. In (2), I have added a middle period where we receive new information about the likely harm and can adjust behavior accordingly. The harm occurs in the last period, as

[17] 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.

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).

before. (To keep the notation simple, I assume that all the information is revealed in the second period; no new information is revealed in period 3.)

(2) $$\max_{e_1 \geq 0} u(e_1) + E_{\tilde{y}} \max_{e_2 \geq 0} E_{\tilde{\theta}|\tilde{y}}\, u(e_2) + E_{\tilde{y}} \left\{ \max_{e_3 \geq 0} E_{\tilde{\theta}|\tilde{y}} \left[v(e_3) - \tilde{\theta}\left(\delta^2 e_1 + \delta e_2 + e_3\right)\right]\right\}.$$

Suppose that we set a tax in the first period based on the expected harm and the expected choice of emissions given that harm and subsequent information. Further, suppose that notwithstanding the information revealed in the second period, the tax is not adjusted. First period actions will be optimal because the tax is set based in then-available information. In second period, however, the tax is now too high or too low given the newly-revealed information. From the perspective of the second period, the actor is no longer choosing optimally. There would be gain from adjusting the tax in the second period to reflect the new information.

For example, suppose that we set taxes on carbon dioxide to prevent climate change, and then 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 future emissions will not be optimal may adjust current emissions. Similarly, if we learn that the effects of emissions are not as bad as feared, future 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.

One way to see this is to analogize taxes to property rights. The price of property varies with market conditions. Taxes, as a substitute for fully-specified property rights, should similarly vary. For example, if in (2), θ represented harm to a specific piece of property, as in the dam example, 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 (2).

Although there is a welfare gain from adjusting the tax rate, suppose we do not adjust it, say because the administrative costs are high. 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.

5.3 *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 CO_2 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.[18] 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 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.

[18] 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.

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

$$(3) \qquad \max_{e_1 \geq 0} u\left(e_1, \tau_1\right) + E_{\tilde{y}} \left\{ \max_{e_2 \geq 0} E_{\tilde{\theta}|\{\tilde{y},\tau_1,\tau_2\}} \left[v\left(e_2, \tau_2\right) - \tilde{\theta}\left(\delta e_1 + e_2\right) \right] \right\}.$$

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.

6. 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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