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Working Paper

Joint Use of Liability and Regulation in Environmental Law

ILE Working Paper Series, No. 5

Provided in Cooperation with:

University of Hamburg, Institute of Law and Economics (ILE)

Suggested Citation: Michel, Stephan; Romano, Alessandro; Zannini, Ugo (2017) : Joint Use of Liability and Regulation in Environmental Law, ILE Working Paper Series, No. 5, University of Hamburg, Institute of Law and Economics (ILE), Hamburg

This Version is available at:

<https://hdl.handle.net/10419/157215>

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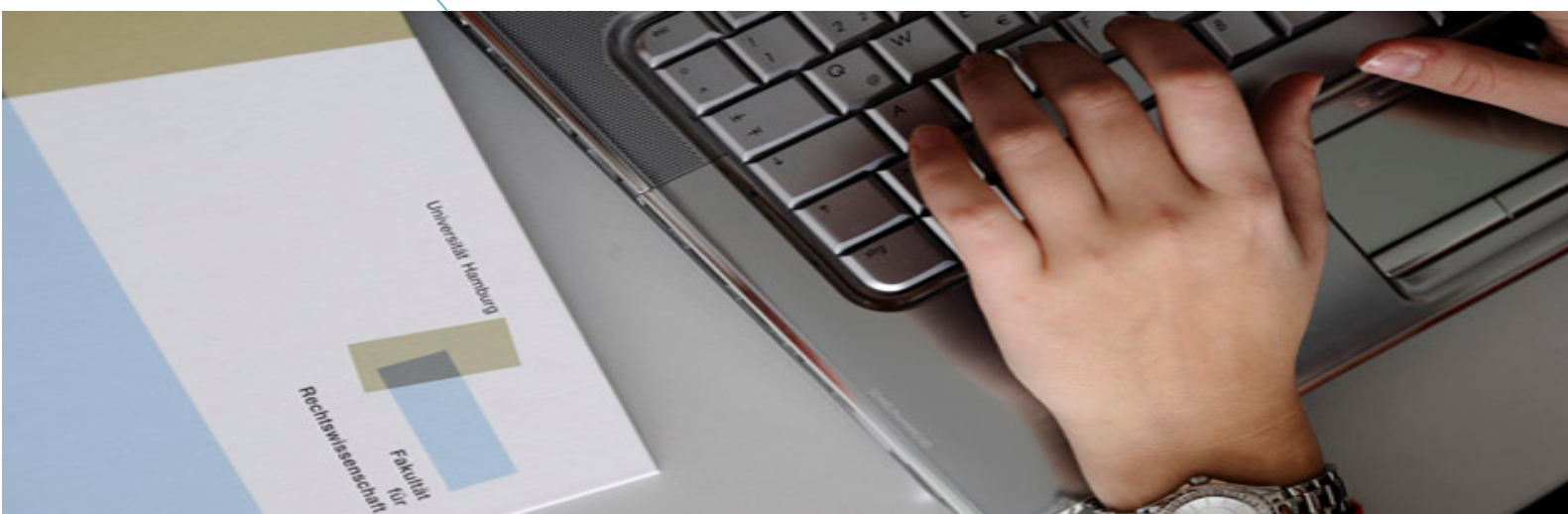
INSTITUTE OF LAW AND ECONOMICS
WORKING PAPER SERIES

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Working Paper 2017 No. 5

April 2017



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They have not been peer-reviewed.

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Joint Use of Liability and Regulation in Environmental Law

Stephan Michel , Alessandro Romano , Ugo Zannini *

April 11, 2017

Abstract

In this paper, we argue that the joint use of ex-ante regulation and ex-post liability rules is efficient when there are uncertainty surrounding causal investigations and regulatory myopia. As these conditions are generally met in environmental cases, we provide an explanation for the frequent coexistence of these two instruments to control activities that create a risk for the environment. Moreover, we suggest that a joint use of liability and regulation should more frequently be optimal at the European (Federal) level than at the Country (State) level.

Keywords: Regulation, Liability, Joint Use, Causal Uncertainty, Regulatory Myopia, Precautionary Principle

JEL Classification Numbers: K13, K32, L50, Q52, Q58

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1 Introduction

One key finding of the tort law and economics literature is that negligence rules induce parties to adopt an optimal level of care (Landes and Posner, 1980). Yet, an enormous amount of resources is invested in crafting and enforcing countless regulations prescribing the care measures that parties must adopt when performing a given activity. When driving, not only we ought to compensate victims if we cause an accident, but we are also required to respect speed limits. Similarly, in many cases when firms engage in an activity they must follow the care standards imposed by ex-ante regulations *and* compensate victims in case of an accident. An obvious question is therefore why do all these costly regulations exist. Or, more precisely, why are activities simultaneously controlled by both ex-ante regulation and ex-post liability rules? In this article we tackle this question, with a special focus on activities that can cause a harm to the environment. In a nutshell, we find that a joint use of ex-ante regulation and ex-post liability rules can be warranted when there are causal uncertainty and regulatory myopia. In particular, we show that a joint use of liability and regulation is more likely to be optimal when causal uncertainty has a higher variance. Therefore, we suggest that a joint use of liability and regulation should more frequently be optimal at the European (Federal) level than at the Country (State) level.

We are not the first to acknowledge the coexistence of liability and regulation, neither we are the first to offer an economic explanation for their joint use (Faure, 2014). Shavell (1984) shows that liability and regulation together might lead to a higher welfare than liability rules alone when there are conviction uncertainty, heterogeneous harm levels, and judgment proofness. However, Schmitz (2000) shows that liability alone is invariably the best solution if damages multipliers are allowed, unless we further assume that injurers are heterogeneous with respect to wealth. In this case, the existence of some judgment proof injurers calls for the joint use of regulation and liability rules. Similarly, De Geest and Dari-Mattiacci (2007) argue that regulation might improve the incentives given by liability rules to judgment proof injurers by inducing them to take a minimum amount of care. Notably, in all these works regulation becomes useless as soon as the injurers' wealth constraint is removed. In other words, these works cling on the limited assets of the injurer to justify the use of regulation. However, the judgement proof problem is not necessarily omnipresent in environmental cases Innes (2004). Therefore, the limited assets of potential injurers can be one possible cause of the joint use of regulation and liability, but certainly not the only one.

To our knowledge, only two works have attempted to demonstrate the complementary nature of regulation and liability without relying directly or indirectly on the judgment proof problem. The closest model to the one developed here is Rouillon (2008). In his model, Rouillon shows that liability alone fails to provide optimal incentives when injurers are heterogeneous with regards to the probability of escaping suit. For this result to hold, it is assumed that judges know the average probability of suit characterizing the universe of injurers, but they cannot assess the probability that each injurer has of being sued (not even ex-post). Last, Bhole and Wagner (2008) prove that regulation and liability might be complementary when some precautions are not observable. As noted by the authors, their findings are only valid in presence of market power and when firms' expected liability costs are relevant for social welfare.

Notwithstanding the importance of these results, we argue that these models do not capture the main distinguishing trait of environmental accidents. In this article, we attempt to explain the joint use of regulation and liability building on the core characteristic of environmental cases, namely causal uncertainty (Gold, 1986; Esty, 1996). Although causal uncertainty has been acknowledged by the law and economics literature on environmental accidents (e.g. Feess et al., 2009), it has generally been perceived as dichotomic in nature. Either an accident is characterized by causal uncertainty or it is not. To the contrary, we argue that the degree of causal uncertainty varies within any single accident. More precisely, we suggest that for every single accident the degree of causal uncertainty is function of the magnitude of its effects at any given time/location and their distance from the accident (both in time and in space). In the proximity of an accident, say an oil spill, it is relatively easy to identify the causal link between the conduct and the harm. The more we depart from the oil spill (both in time and in space), the harder it becomes to identify with a preponderance of evidence the causal link between the accident and the harm. Consequently, ex post liability rules are systematically blind to part of the consequences of many environmental accidents and must be complemented by ex-ante regulation. Interestingly, as we will see in Section 3, this pattern is not universal and for some pollutants – like heavy metals – the quality of the signal might increase over time, at least up to a certain extent. We build on this simple story to explain why in many cases activities that pose

a risk for the environment are simultaneously controlled by ex-ante regulation and ex-post liability rules.

There is, however, another layer of complexity that should be included in the picture. More precisely, it must be noted that the questions asked by courts and the regulator are markedly different. The courts investigate ex-post on the existence of a causal link between the harm and the conduct of the alleged injurer, and hence their analysis is backward looking. When this causal investigation is imperfect we say that there is *causal uncertainty*. On the contrary, the regulator performs a forward looking analysis and tries to forecast the amount of harm associated with a given conduct. When this forward looking estimation is imperfect we say that there is *regulatory myopia*. The different nature of the questions asked by courts and regulators translates in different informative sets required to answer them. In turn, this implies that in some circumstances the quality of the information held by the regulator might be superior to that held by the court, and *vice versa*. Let us clarify this point with an example. Asbestosis is a chronic disease that affects the tissues of the lungs and is caused by exposition to asbestos. These kind of diseases that are almost always associated with the exposure to a given pollutant are generally termed signature diseases (Romano, 2016). If an asbestosis is diagnosed and the victim has been exposed to asbestos the causal connection is almost automatic. Therefore, court's backward analysis from the accident to the kind of pollutant causing the disease is trivial.¹ Instead, estimating with precision how many asbestosis might be caused by a given quantity of asbestos is a much harder task. Thus, in this context the quality of the informative set of the court might be superior to that of the regulator. On the contrary, in other cases it is relatively easier to forecast the magnitude of the expected harm than to backtrack the source of the specific harm. A paradigmatic example is Bisphenol A (BPA), an organic synthetic compound widely used in epoxy resins, lining food and beverage containers. And indeed, there are many studies that (attempt to) estimate the severity of the association between BPA exposure and a number of diseases and that can offer some guidance to regulators (e.g. Lang et al., 2008). At the same time, identifying ex-post the specific source of BPA connected to a given disease is basically impossible, given that BPA is virtually everywhere and causes mostly non-signature diseases. Therefore, for settings involving BPA the informative set of the regulator might be superior to that of the court. We show that the relative quality of the informative sets available to courts and the regulator is a key determinant of the optimal mix of ex-ante regulation and ex-post liability.

The paper is structured as follows. Section 2 sets out our argument in a formal way. We highlight the respective conditions under which a regulation regime, a liability regime or a joint regime are optimal. Section 3 discusses the underlying assumptions and policy implications. A final section concludes.

2 The model

This section introduces imperfect information in an otherwise standard framework for the economic analysis of accident law, and describes how different regimes of liability and/or regulation fare in terms of social welfare.

We assume risk-neutral firms that can cause an accident due to their economic activity. The expected magnitude of the harm from the accident is $h > 0$. By exerting care $x \in [0, 1]$ the firms can influence the probability of an accident $p(x) = 1 - x$. The cost of taking precautions is denoted by $c(x)$, a strictly increasing and strictly convex function with $c(0) = 0$, $\lim_{x \rightarrow 1} c'(x) = \infty$ and $c'(0) = 0$. The firms can be induced to take care by ex-ante regulation and/or ex-post liability rules. Under the assumption of perfect information and no enforcement costs both ex-ante liability and ex-post regulation can induce the firms to adopt optimal precautions.

The welfare loss associated to a single firm is defined by

$$w(x) \equiv c(x) + (1 - x)h, \quad (1)$$

that is the sum of the cost of taking precautions and the harm caused by the accident, which occurs with probability $1 - x$. The social planner minimizes the welfare loss from the firm's activity such that the optimal care level x^* solves

$$c'(x) = h,$$

¹Identifying the specific injurer requires identifying the specific source of asbestos that triggered asbestosis. This task can be very complex if the victim was exposed to many sources of asbestos.

where the marginal cost of taking care equals the marginal benefit from the reduction in the expected harm. The properties of $c(x)$ allow us to define the function $x(y) \equiv c'^{-1}(y) \forall y > 0$ such that

$$x^* = x(h),$$

and x^* increases with h .² Given the functional form of the welfare loss, we can derive $w'(x) < 0, \forall x < x^*$ and $w''(x) > 0$.

Under the assumption of perfect information, the social planner can induce the firms to adopt x^* via ex-ante regulation or ex-post liability. This standard result no longer holds once the assumption of perfect information is relaxed.

2.1 Causal Uncertainty and Regulatory Myopia

In this section, we introduce imperfect information on two dimensions that we label *causal uncertainty* and *regulatory myopia*, respectively. The former affects the causal investigation of the courts, whereas the latter regards the crafting of regulations.

More precisely, in presence of causal uncertainty the court only receives an imperfect signal on the existence of a causal link between the conduct of the injurer and the accident. Under causal uncertainty we assume that only a fraction $0 < \alpha < 1$ of the harm can be discovered ex-post by the court. At the same time, we assume that the regulator is myopic, i.e. a standard x_r can only be based on scientific evidence proving that a given pollutant is harmful, and this information is costly to acquire for the regulator. Moreover, the firm has private information about α , hence regulation cannot be perfectly tailored on each firm but must be based on the distribution of causal uncertainty. The distribution of causal uncertainty is assumed to be public knowledge.³

In particular, we define x_r as the standard based on the ex-ante knowledge of $\alpha_r h$, where α_r is the amount of harm that the regulator can ascribe to a particular economic activity with $\alpha_r \in [0, 1]$. The research cost function, $\tau(\alpha_r)$ captures the relation between α_r and a given level of investment in research. We assume $\tau(0) = 0$, $\tau(1) = R < \infty$, $\tau' > 0$, $\tau'' \geq 0$, and impose $\tau'(0) < h^2/c''(0)$.

Importantly, we assume that α is heterogeneous across firms. For the sake of simplicity, we only consider two firms and a two-points distribution for α , but the qualitative results also hold with continuous heterogeneity across a continuum of firms. Firm i is characterized by α_i , with $i = L, H$ and $\alpha_L < \alpha_H$. The model also applies to a situation with one firm and two possible states of nature, either high (α_L) or low (α_H) causal uncertainty.

In this setting, the social planner determines the optimal mix of regulation and liability under the constraints that affect courts and the regulator, namely causal uncertainty and regulatory myopia.

Liability regime

Let us begin by supposing that only liability is in place. In presence of causal uncertainty, once an accident occurs the court can only verify $\alpha_i h < h$, thus liability will not induce the injurer to internalize the full cost of his activity. More precisely, the firm anticipates that it will not be held liable for $(1 - \alpha_i)h$. Formally, firm i 's problem reads

$$\min_{x_i \in [0, x^*]} [c(x_i) + (1 - \alpha_i)\alpha_i h], \quad (2)$$

and the marginal condition is

$$c'(x_i) = \alpha_i h.$$

Using $x(y) = c'^{-1}(y)$, the above expression defines the solution

$$x_i = x(\alpha_i h) < x^*.$$

²As $c'(x) - h$ is increasing on $x \in [0, 1]$ from $-h$ to ∞ , with slope $c''(x) > 0$ independent of h , then $h \in (0, \infty)$ identifies a unique $x^* \in (0, 1)$. Using the Inverse Function Theorem, we can show that x^* increases with h : $x^{*'} \equiv \frac{\partial x(h)}{\partial h} = \frac{\partial c'^{-1}(h)}{\partial h} = [c''(x^*)]^{-1} > 0$.

³In general, firms will have more information than third parties about the risks associated to the specific characteristics of their production process. This is especially true if the expected harm depends also on specific and highly variable characteristics of the production process of the firm and of the area where the firm operates (e.g. weather conditions).

Evidently, in presence of causal uncertainty the firm adopts a sub-optimal level of care. Moreover, $x_L < x_H$ because the firm has less incentives to invest in precautions when causal uncertainty increases, or

$$x'_i \equiv \frac{\partial x_i}{\partial \alpha_i} = \frac{h}{c''(x_i)} > 0.$$

Using (1), the implementation of the liability regime (LR) determines the welfare loss

$$W_{LR} = w(x_L) + w(x_H). \quad (3)$$

In general, $\alpha < 1$ prevents the LR from reaching the first best and a smaller α results in a larger welfare loss. In other words, liability rules are less effective when there is more causal uncertainty.

Regulation

Let us now suppose that only regulation is in place. In this framework, the benefit from research is a more accurate estimate of the expected harm associated with the economic activity of the firm, which translates into the possibility of crafting regulations that induce firms to adopt care levels that are closer to the social optimum.

In this case, the regulatory standard can be based on $\alpha_r h$ by investing $\tau(\alpha_r)$ in research. Because the regulator knows $c(x)$ and $p(x)$, she also knows that for any α_r a firm will choose the precaution level

$$x_r = x(\alpha_r h) \leq x^*,$$

by solving the firm's problem (2). As we assume that the regulatory standard can be perfectly enforced, the regulator chooses the value of α_r that minimizes the welfare loss,

$$W_{RR}(\alpha_r) = 2w[x(\alpha_r h)] + \tau(\alpha_r) = 2w(x_r) + \tau(\alpha_r). \quad (4)$$

In general, if $W_{RR}(\alpha_r)$ is concave the minimization problem has only corner solutions, i.e. $\alpha_r \in \{0, 1\}$. To focus on the more interesting interior solutions, we require convexity for W_{RR} by assuming $c'''(x) > 0$ and $\tau''(\alpha) \geq 0$.⁴ Those assumptions together are sufficient to ensure convexity.⁵

Call α_{RR} the value that minimizes (4) by solving

$$-2w'(x_r)x'_r = \tau'(\alpha_r). \quad (5)$$

The RHS measures the marginal research cost to justify the standard based on α_r . The LHS measures the marginal benefit on the welfare losses, $-2w'(x_r) > 0$, by increasing the standard, $x'_r > 0$. Call W_{RR}^* the social loss in $\alpha_{RR} \in (0, 1)$.⁶ By definition, regulation is preferred to liability if and only if

$$W_{RR}^* < W_{LR}.$$

The next part discusses the relative advantages of the two regimes. We will, with a slight abuse of notation, use w^* , w_j , and w'_j as shortening for $w(x^*)$, $w(x_j)$, and $w'(x_j)$, with $j = i, r$.

Understanding the role of causal uncertainty and research cost

Figures 1 and 2 examine the role of causal uncertainty and research costs in determining the optimal choice between liability and regulation. The graphs show on the x-axis the fraction of the expected harm that the regulator can ascribe to the substance, i.e. α_r , and on the y-axis the social loss. Hence, from (3) W_{LR} is constant as it is determined by α_L and α_H , while $W_{RR}(\alpha_r)$ is strictly convex.

As a starting point, it is useful to consider the functions at the extremes of the domain in figure 1. Absent any investment in research i.e. $\alpha_r = 0$ with $\tau(0) = 0$ and $x_r = 0$, liability improves on a situation without

⁴ $c'''(x) > 0$ implies that the precautionary cost function is more convex for higher values of precautions. $\tau''(\alpha) \geq 0$ implies that the research cost function is linear or convex. As they are applied to cost functions, these restrictions appear plausible.

⁵The second order derivative of $W_{RR}(\alpha_r)$, omitting the arguments of the functions, reads $2\frac{h^2}{c''}\left(1 + \frac{h-c'}{c'''}\right) + \tau''$.

⁶With $\alpha_r = 0$ and $\alpha_r = 1$, expression (5) reads $2h^2/c''(0) > \tau'(0)$ and $0 < \tau'(1)$, respectively. Thus, the minimum exists in $(0, 1)$ and is unique.

regulatory standard, i.e. $w_i < w_r = h$ which implies $W_{LR} < W_{RR}(0)$. At the other extreme, i.e. $\alpha_r = 1$ with $\tau(1) = R$ and $x_r = x^*$, the regulator makes the maximum investment in research in order to identify the complete expected harm. If R is sufficiently small and/or causal uncertainty is very severe such that $W_{RR}(1) < W_{LR}$, then liability can never be the optimal regime. Figure 1 represents this situation through an increase in causal uncertainty: the distribution of α moves to the left and W_{LR} shifts to W'_{LR} . The new level of causal uncertainty makes regulation the optimal regime because $W_{RR}(1) < W'_{LR}$.

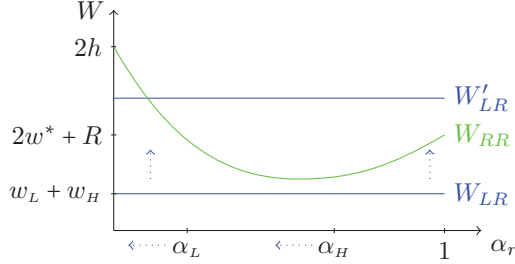


Figure 1: Liability vs. Regulation: welfare loss and the role of causal uncertainty.

This figure shows the welfare losses under regulation (W_{RR}) and liability (W_{LR}) for different levels of information (α_r) the regulator has acquired. The losses from liability are unaffected by the behaviour of the regulator, while the U-shape of the welfare loss from regulation depends on the trade-off between marginal costs of acquiring information about potential harm and the marginal benefits from the reduction of firms' welfare-loss functions, see equation (5). An increase in causal uncertainty reduces the part of the harm that a court can attribute to each type of firm and therefore the flat curve of the liability losses is shifted upwards.

Together with causal uncertainty, research costs play a decisive role in the choice of an optimal regime. Figure 2 shows how the shape of the research cost function impacts social welfare. The panels configure two patterns of $\tau(\alpha_r)$, while keeping the maximum cost R and the degree of causal uncertainty constant. Panel (a) describes a situation where research costs grow at constant rate. Instead, in panel (b) research costs grow slowly at the beginning, with a strong increase when α_r is close to 1. In the second case, the marginal gains from regulation remain positive for higher values of α_r compared to in the first case. With the research cost function in panel (b), it is more likely that regulation is superior to liability. Note that $W_{RR}(0)$ and $W_{RR}(1)$ are not affected from changing the shape of $\tau(\alpha_r)$.

Before introducing the joint use of regulation and liability, let us conclude this part with an observation. The social planner strictly prefers liability over regulation when the regulatory standard is based on $\alpha_r \leq \alpha_L$. In this case regulation gives to all the firms less incentives to take care than liability, while requiring investment in research. This can also be seen in figure 2 with $W_{LR} < W_{RR}(\alpha_r) \forall \alpha_r \leq \alpha_L$.

Joint use of Liability and Regulation

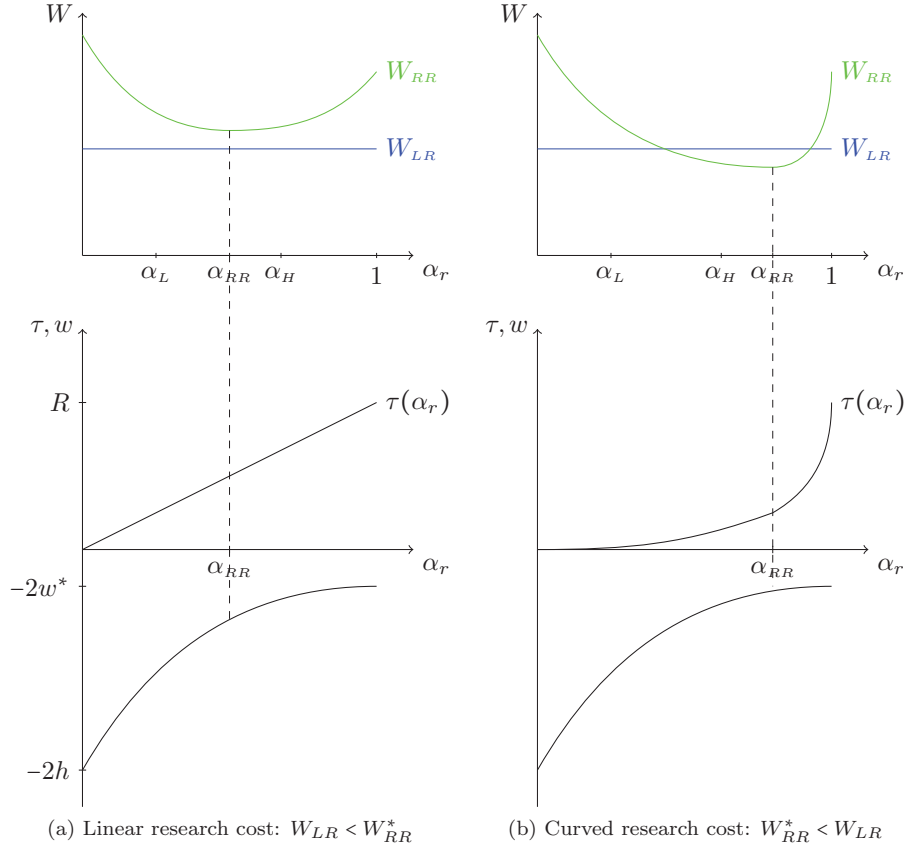
Often, economic activities are governed by a combination of liability and regulation. In many of these cases, following the standards imposed by regulation does not exonerate firms from facing liability (Schwartz, 2000). Therefore, the firms that face high expected liability have incentives to take more precautions than required by regulation, whereas firms that face a smaller liability threat merely comply with the regulatory standard.

In this model, the *raison d'être* of the joint regime of liability and regulation (JR) is the following. Suppose that $\alpha_L < \alpha_r < \alpha_H$. In this case, regulation gives to firm L less incentives to take care than liability because $x_L < x_r$. At the same time, regulation is less effective on firm H because $x_r < x_H$. The liability threat will incentivize firm H to increase the care level from x_r to x_H . By imposing liability in addition to the regulatory standard, the social planner can thus improve welfare.

When $\alpha_r \geq \alpha_H$ the joint regime simply corresponds to regulation alone, as liability has no additional effect on either firm. Instead, when $\alpha_r \leq \alpha_L$ a joint regime provides firms with the same incentives as liability alone, while generating research costs. Thus, in this case the joint regime is dominated by liability. As a consequence, and without loss of generality, we narrow the domain of the welfare loss under JR,

$$W_{JR}(\alpha_r) = w(x_r) + w(x_H) + \tau(\alpha_r), \quad (6)$$

Figure 2: Liability vs. Regulation: welfare loss and the role of research cost.



This figure shows how research costs affect the outcome reached using liability or regulation. In panel (a) the research cost function $\tau(\alpha_r)$ is linear. In α_{RR} , regulation minimizes the welfare loss because the research cost function and the welfare benefits, $-2w(x_r)$, have the same slope, see equation (5). Because research costs rapidly increase, liability works better than regulation, i.e. $W_{LR} < W_{RR}^*$. In panel (b) α_{RR} higher than in panel (a) because research costs are sufficiently low at the beginning. In this case regulation exploits higher benefits, and regulation is superior to liability, $W_{RR}^* < W_{LR}$.

to $[\alpha_L, \alpha_H]$.⁷ In (6), regulation and liability work on firm L and firm H , respectively. Indeed, the only difference between $W_{JR}(\alpha_r)$ in (6) and $W_{RR}(\alpha_r)$ in (4) is the welfare loss caused by firm H , with $w(x_H) < w(x_r)$. Hence, in the relevant domain JR always produces a lower welfare loss than RR. In turn, this implies that regulation can only be optimal for $\alpha_r \geq \alpha_H$ or, equivalently, if $\alpha_{RR} \geq \alpha_H$.

We can summarize the findings on the relations among the three regimes and their regions of optimality in the following lemma.

Lemma 1. *The liability regime is optimal for $\alpha_r \in (0, \alpha_L]$. The joint regime dominates regulation for $\alpha_r \in (\alpha_L, \alpha_H)$ and it is equivalent to regulation for $\alpha_r \in [\alpha_H, 1]$. Therefore, the joint regime can be optimal in (α_L, α_H) , whereas regulation can be optimal in $[\alpha_H, 1]$.*

Proof. Any $0 < \alpha_r \leq \alpha_L$ implies $W_{LR} = w(x_L) + w(x_H) < W_{JR}(\alpha_r) = w(x_L) + w(x_H) + \tau(\alpha_r) < W_{RR}(\alpha_r) = 2w(x_r) + \tau(\alpha_r)$, thus liability reaches the lowest welfare loss. Any $\alpha_r \in (\alpha_L, \alpha_H)$ implies $W_{JR}(\alpha_r) = w(x_r) + w(x_H) + \tau(\alpha_r) < W_{RR}(\alpha_r) = 2w(x_r) + \tau(\alpha_r)$, hence the joint regime reaches the lower welfare loss. Any $\alpha_r \in [\alpha_H, 1]$ implies $W_{JR}(\alpha_r) = W_{RR}(\alpha_r) = 2w(x_r) + \tau(\alpha_r)$. In the end, the only domain in which the joint regime can be optimal is (α_L, α_H) . Moreover, if $\alpha_{RR} \in (0, \alpha_H)$, then regulation is dominated by either liability or a joint regime. Therefore, $\alpha_{RR} \in [\alpha_H, 1]$ is a necessary (but not sufficient) condition for regulation to be the optimal regime. \square

Lemma 1 states that: (i) a very low regulatory standard not providing any firm with additional incentives to take precautions is never optimal because of the research costs borne without any benefit; (ii) a joint regime always improves upon regulation when the regulatory standard only affects the care level of some firms, but not all; (iii) regulation is better than liability if and only if the gains from applying the standard on all firms are sufficiently large.

Call $\alpha_{JR} \in (\alpha_L, \alpha_H)$ the value that solves the first order condition of (6), that is

$$-w'(x_r)x'_r = \tau'(a_r), \quad (7)$$

and define $W_{JR}^* = W_{JR}(\alpha_{JR})$ the associated welfare loss. Minimization of the welfare loss under JR requires that the marginal gain on firm L (left-hand side of the equation) equals the marginal research cost (right-hand side). The next lemma specifies the necessary condition for the joint regime to be superior to liability.

Lemma 2. *The necessary marginal conditions for the joint use of regulation and liability to be superior to liability are*

$$-w'(x_L)x'_L > \tau'(\alpha_L), \quad (\text{L2.1})$$

$$-w'(x_H)x'_H < \tau'(\alpha_H). \quad (\text{L2.2})$$

The conditions are most likely met when, everything else equal, α_H increases and α_L decreases, and when R is neither very high or very low.

The necessary condition on the level of welfare losses is

$$w(x_{JR}) + \tau(a_{JR}) < w(x_L) \quad (\text{L2.3})$$

where $x_{JR} = x(\alpha_{JR}h)$. This condition is most likely met when, everything else equal, α_L decreases, R decreases, and h increases.

Proof. First, suppose that (L2.1) does not hold, then $W_{JR}(\alpha_r)$ is not decreasing in $\alpha_r = \alpha_L$. Since additional precautions for $\alpha_r \in (\alpha_L, \alpha_H)$ have a decreasing marginal effect on welfare, whereas marginal research costs are not decreasing, this implies that $W_{JR}(\alpha_r)$ is increasing. Given that $W_{JR}(\alpha_L) > W_{LR}$, $W_{JR}(\alpha_r) > W_{LR}$ holds and the joint regime is not optimal. As α_L decreases, the LHS of (L2.1) becomes larger and the RHS of (L2.1) becomes smaller.

Second, assume that (L2.2) does not hold, then $W_{JR}(\alpha_r)$ is not increasing in $\alpha_r = \alpha_H$. Given $-w'(x_H)x'_H \geq \tau'(\alpha_H)$, then $W_{JR}(\alpha_r)$ is decreasing on (α_L, α_H) because marginal welfare gains must be higher than marginal

⁷The fact that JR is equivalent to RR in $\alpha_r = \alpha_H$, i.e. $W_{JR}(\alpha_H) = W_{RR}(\alpha_H)$, and is dominated by LR in $\alpha_r = \alpha_L$, i.e. $W_{LR} < W_{JR}(\alpha_L) = W_{LR} + \tau(\alpha_L)$, does not impose any restriction on the domain.

research cost. Furthermore, $W_{RR}(\alpha_r)$ must be decreasing in $\alpha_r = \alpha_H$ because $-2w'(x_H)x'_H > \tau'(\alpha_H)$ holds in this case. Therefore, at least $W_{RR}(\alpha_H) < W_{JR}(\alpha_r)$. As α_H increases, the LHS of (L2.2) becomes smaller and the RHS of (L2.2) becomes larger.

Expressions (L2.1) and (L2.2) together guarantee that $\alpha_{JR} \in (\alpha_L, \alpha_H)$ solving (7) exists and is unique. Condition (L2.3) guarantees that $W_{JR}^* < W_{LR}$, since $w(x_H)$ is the same for both regimes. Hence, a lower α_L would increase the welfare loss under liability, without affecting α_{JR} and the welfare loss under the joint regime.

Moreover, given τ'' , a lower R reduces τ and possibly τ' for each value of α_r . A lower research cost in (α_L, α_H) makes a joint regime more attractive compared to a liability regime. Note that R also affects the marginal conditions. A very low R reduces the RHS of (L2.2), while a very high R increases the RHS of (L2.1), both of which make the marginal conditions less likely.

Last, it is useful to discuss whether a higher h makes the joint regime more advantageous. The effect of h on $w(x_{JR}) + \tau(a_{JR})$ is

$$w'x'_h + (w'x' + \tau')\frac{\partial\alpha_{JR}}{\partial h} = w'x'_h,$$

where x'_h indicates the derivative with respect to h . Consequently, the effect of h on the welfare loss between JR and LR can be reduced to the properties of $\frac{\partial w(x(\alpha h))}{\partial h}$. For $x(\alpha h) < x(h)$ the welfare loss increases with h iff

$$\frac{\partial w(x(\alpha h))}{\partial h} = 1 - x(\alpha h) + \frac{c'(x(\alpha h)) - h}{c''(x(\alpha h))}\alpha > 0.$$

For $\alpha \rightarrow 0$ and $\alpha \rightarrow 1$ the expression converges to 1 and $1 - x(h) > 0$, respectively. Moreover, the above expression is always positive and decreasing in α , because its derivative with respect to α is

$$-x' + \frac{c' - h}{c''} - \frac{(c'')^2 - (c' - h)c'''}{[c'']^2}\alpha x' < 0.$$

Hence, given a rise in h , $w(x(\alpha h))$ increases more than for lower α . In our case, an increase of h has a stronger effect on $w(x_L)$ than on $w(x_{JR})$, that are respectively the lower boundaries of liability and a joint regime. As a consequence, an increase in h is less costly in terms of welfare for the joint regime than for a liability regime. \square

The marginal conditions in Lemma 2 require that the welfare loss under a JR has a minimum in the domain (α_L, α_H) . To ensure that this is the case, the first condition requires that additional research is increasing welfare at the beginning of the domain, whereas the second condition requires that additional research actually reduces welfare at the end of the domain.

Figure 3 depicts a situation in which the joint use of regulation and liability is the optimal regime. In panel (a), we first show the comparison between regulation and liability. The degree of causal uncertainty and the steep research cost determine that liability is superior to regulation. The same situation in panel (b), however, shows that a joint regime is superior to liability. For the sake of clarity, we have graphed W_{JR} on the whole domain.

So far, we have highlighted that liability is always optimal if $\alpha_r \in (0, \alpha_L]$ and the conditions under which a joint regime is optimal in (α_L, α_H) . This section can be concluded with a lemma stating the necessary conditions for regulation to be optimal in its domain $\alpha_r \in (\alpha_H, 1]$

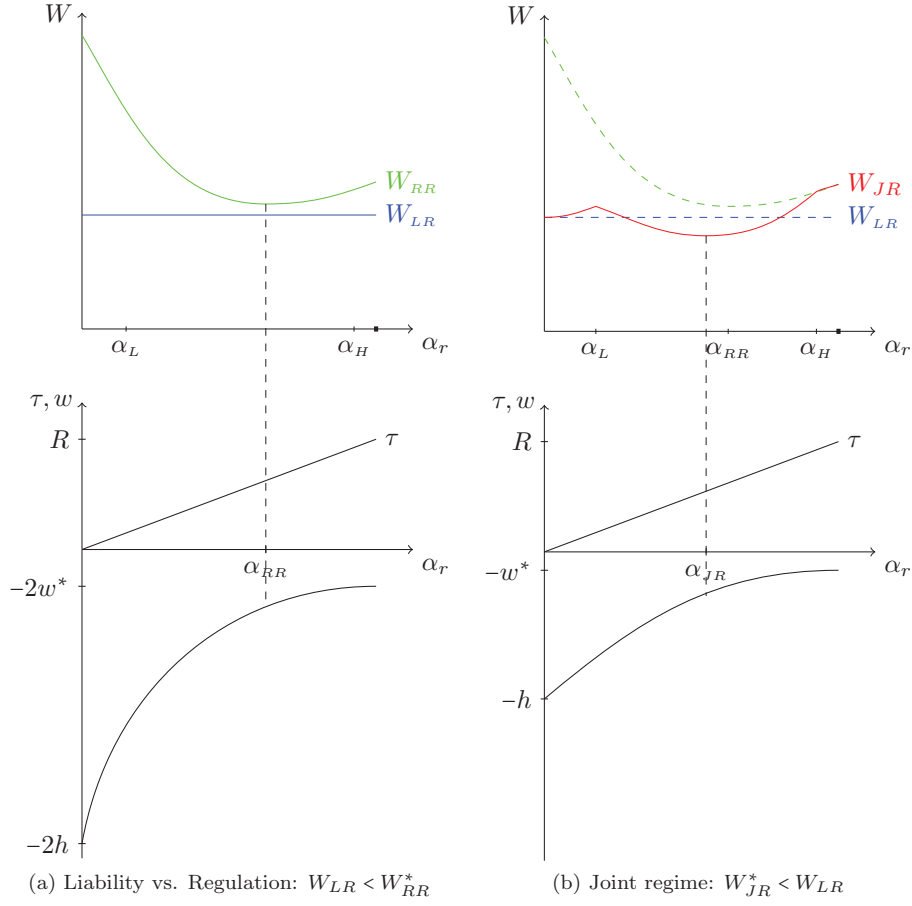
Lemma 3. *The necessary conditions for regulation to be superior to liability in the domain $[\alpha_r \geq \alpha_H]$ are*

$$-2w'(x_H)x'_H \geq \tau'(\alpha_H), \quad (\text{L3.1})$$

$$2w(x_{RR}) + \tau(\alpha_{RR}) < w(x_L) + w(x_H) \quad (\text{L3.2})$$

The marginal condition (L3.1) is more likely to hold for lower α_H and R . Ceteris paribus, the level condition (L3.2) is more likely to hold for lower α_L , α_H , R as well as for higher h . In particular, liability is never optimal for $R \leq \sum_i [w(x_i) - w(x^)]$.*

Figure 3: An Optimal Joint Use of Liability and Regulation.



This figure shows a situation where the combined action of causal uncertainty and regulatory myopia determines the optimality of the joint regime. In panel (a) liability is superior to regulation. In panel (b), given the same causal uncertainty and cost structure of panel (a), the joint regime is superior to liability, where α_{JR} solves equation (7), the welfare loss from the standard on firm L , i.e. $w(x_{JR}) + \tau(\alpha_{JR})$ is lower than the loss from liability, i.e. $w(x_L)$.

Proof. It is useful to first discuss the necessary marginal condition, which implies that $\alpha_{RR} \geq \alpha_H$. If (L3.1) does not hold, then $W_{RR}(\alpha_r)$ is increasing in $\alpha_r = \alpha_H$. In turn, this implies that $\alpha_{RR} < \alpha_H$, but we have already established in lemma 1 that regulation can never be optimal in $[0, \alpha_H)$. Therefore, condition (L3.1) is a necessary condition.

The condition is more easily met with lower α_H , as it reduces the RHS and increases the LHS. Moreover, a lower R reduces τ' for each α_r , hence favors condition (L3.1) by lowering the RHS.

The level condition L3.2 is necessary by definition. Lower α_L and α_H increase the welfare loss under liability, while not affecting regulation. At the same time, a lower R that does not affect W_{JR} also makes the condition more likely to hold. Given a lower $\tau(\alpha_r)$ for any α_r , W_{RR} is reduced, *ceteris paribus*. In particular, $R \leq \sum_i [w(x_i) - w(x^*)]$ implies $W_{RR}(1) \leq W_{LR}$, hence $W_{RR}(\alpha_r) < W_{LR}$ for some $\alpha_r < 1$.

The effect of h on condition (L3.2) is similar to the that on condition (L2.3). Indeed, the implicit function theorem at the optimum ensures that only $\frac{\partial w(x(\alpha h))}{\partial h} > 0$ matters, without the terms multiplied by $\frac{\partial \alpha_{RR}}{\partial h}$. Hence, an increase in h is advantageous for regulation because the welfare loss increases are larger for lower α , and we have $\alpha_L < \alpha_H < \alpha_{RR}$ with $w(x_L) < w(x_H) < w(x_{RR})$. \square

The marginal condition in Lemma 3 requires that additional research actually increases welfare at α_H . In other words, regulation can only be optimal if the welfare effects of additional research are positive for the domain where liability rules do not induce additional care. This situation will be more likely if additional research in this area is relatively inexpensive and if causal uncertainty is severe for all firms.

Both these factors also make the level condition more likely because lower research costs directly enter the welfare effects of regulation, while more severe causal uncertainty for all firms increases the welfare losses under a liability regime.

Section 2.2 connects the results of the Lemmas in form of a set of propositions highlighting under which circumstances each of the regimes will be optimal.

2.2 Optimal regime

The goal of this section is to clearly identify how liability and regulation should be used when facing causal uncertainty and regulatory myopia. In particular, we investigate the conditions under which a joint use of the two instruments becomes desirable. We will discuss the conditions favoring regulation, liability and a joint regime in turn.

Proposition 1. *The likelihood that liability alone is the optimal regime increases with the level of research costs and with the steepness of their incremental change. The likelihood that liability alone is the optimal regime decreases with the expected magnitude of the harm and the degree of ex-post causal uncertainty.*

Proof. Combining lemmas 2 and 3 we can claim that: (i) both a higher R and a lower h increase the probability that the joint regime and regulation are superior to liability; (ii) conditions (L2.1) and (L3.1) are less likely met for higher α_L and α_H – note that (L2.2) is not met when (L3.1) does not hold; (iii) a steep research cost function, i.e. a high τ' , at the beginning of the firms' distribution of causal uncertainty makes condition (L2.1) less likely to hold. \square

The results of proposition 1 are in line with intuitive expectations. When research becomes (marginally) more costly, liability alone becomes more attractive. However, an increase in causal uncertainty makes liability less likely to be the optimal regime.

Proposition 2. *The likelihood that regulation alone is the optimal regime increases with the expected magnitude of the harm and the degree of ex-post causal uncertainty. Regulation also benefits from a research cost function that increases very slowly. The likelihood that regulation alone is the optimal regime decreases with the level of research costs.*

Proof. The statement results from lemmas 2 and 3. We refer to the latter for the comparative statistics about the optimality of regulation over liability, and discuss here the comparative statistics from both lemmas for the optimality over the joint regime.

A higher h and a lower α_L benefit both regulation and the joint regime. A low α_H benefits regulation, while the joint regime benefits from a high α_H . Hence regulation benefits from an increase across the whole

distribution of causal uncertainty. Moreover, there is an upper bound on R after which the marginal condition (L2.1) is not met, while a higher R is always beneficial for regulation. \square

The results of proposition 2 can be seen as the mirror image of proposition 1. Thus, when research becomes more costly, regulation becomes less attractive. Increasing causal uncertainty will make it more likely that regulation is the optimal regime. Furthermore, increasing total harm makes regulation more attractive. This effect can be explained by the behavior of research costs, which are not tied to total harm, but rather to the percentage of total harm to be explained. It appears reasonable to assume that the research costs necessary to investigate the consequences of a pollutant are not perfectly correlated with the total harm that the pollutant might cause.

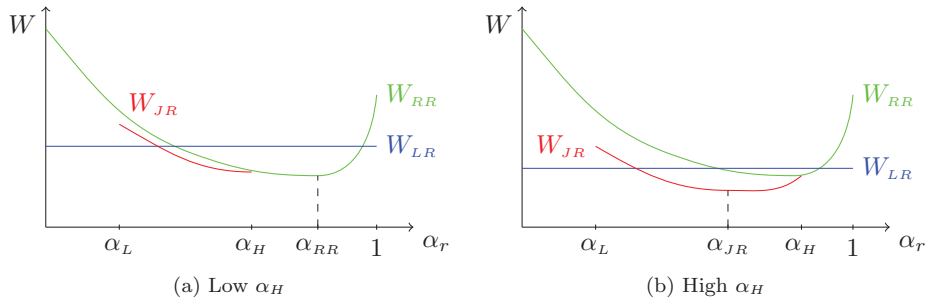
Proposition 3. *The likelihood that the joint use of regulation and liability is the optimal regime increases with the expected magnitude of the harm and the degree of dispersion of causal uncertainty. The joint regime benefits from moderate values of research costs that increase mildly on the bottom and are steeper on the top of the distribution of causal uncertainty.*

Proof. The statement results from lemmas 2 and 3. We refer to the former for the comparative statistics about the comparison between the joint regime and liability, and to the proof of Proposition 2 for the comparative statistics, from both lemmas, for the comparison between the joint regime and regulation. \square

The optimality of the joint regime requires a solution $\alpha_{JR} \in (\alpha_L, \alpha_H)$, i.e. the research cost increases moderately in the region where regulation is affecting the care levels of a sub-sample of firms. In other words, a JR can be optimal when the regulatory standard in a joint regime is high enough to affect the level of care of firms with a low expected liability, but at the same time low enough to not influence the choice of firms with a high expected liability. This situation is more likely when there is a wide distribution of causal uncertainty. Especially when dealing with pollutants, the location and type of pollutant used by some firms will make it more difficult for the courts to establish causality. If this is the case for only some of the firms dealing with the same pollutant, we can expect to see a wide distribution of expected liability even in the same market. This assumption is discussed in more detail in the next section.

However, even if there is a wide distribution of causal uncertainty the level of research costs might undermine the efficiency of a JR. On the one hand, low levels of research costs lead to an optimal level of regulation only in the range of $[\alpha_H, 1]$. In other words, when research leading to very strict regulation is available at a low cost, RR is superior. On the other hand, a very high level of research costs renders all kinds of regulation inferior to liability. That is, when the fixed costs of research are sufficiently high, even a mild-shaped research cost function will always lead to an inferior result in terms of welfare compared to a LR. Note that this effect can be mitigated by an increase in total harm, which reduces the relative cost of research per unit of harm.

Figure 4: The effect of α_H on the optimal regime



Here, we can also see an illustration of the effect of a wide distribution of firms' expected liabilities on the optimality of a joint regime. This figure highlights our key result on the role played by α_H , namely that its rise favors the joint regime over regulation alone. In panel (a), with a low α_H , regulation is the optimal regime. In panel (b), the reduction of the causal uncertainty in the upper concentration of firms, i.e. a rise of α_H , lowers the welfare loss under liability, although regulation is still preferred to it. At the same time, the welfare loss under the joint regime lowers with liability now has an interior minimum and a joint regime is optimal in panel (b).

Table 1 summarizes the main results of our analysis. In general, a large harm and a high degree of causal uncertainty work in favor of regulation (either alone or in a joint regime). Instead, higher research costs make liability more attractive. For a joint regime to be optimal the total research costs should neither be too high nor too low. Also, a wide variance in the level of causal uncertainty across firms increases the chance that a joint regime is optimal.

Table 1: The impact of exogenous variables on the likelihood of optimal regime

Regime	Variables				
	h	α_L	α_H	R	$\Delta\alpha$
Liability	-	+	+	+	-
Regulation	+	-	-	-	-
Joint Use	+	-	+	?	+

3 Discussion & Policy Implications

In Section 2 we show that a joint use of liability and regulation might be warranted in presence of causal uncertainty and regulatory myopia. The former is backward looking and haunts liability rules when courts do not have perfect information on the causal link between the conduct of the injurer and the harm. The latter, forward looking, arises when the regulator cannot predict with accuracy the expected harm associated with a conduct. Our model is grounded on the assumption that the degree of causal uncertainty varies among firms using the same pollutant *and* across pollutants. Support to this hypothesis is offered in Sections 3.1 and 3.2. Further, we show that the optimal mix of regulation and liability is determined by the relative quality of the forward looking judgement of the regulator and the backward looking judgement of the court. Therefore, to translate the results of the model in concrete policy implications it must be understood when the causal enquiry of the court is more accurate than the estimation of the harm made by the regulator. To this end, we develop a matrix to identify for which pollutants the information held by the courts is likely to be superior, and vice versa. In section 3.3 we connect the quadrants of this matrix to the propositions of the model.

3.1 Harm in time and space

As we argue in more details in section 3.2, the quality of the signal received by the courts depends also on the distribution of the harm in time and in space.⁸ In Section 2 we discuss the case of two firms causing a harm that can be traced with different levels of accuracy. If it is true that the distribution of the harm in time and in space affects the quality of the causal investigation of the courts, the case we describe is frequent even for accidents involving the same pollutant. This is because the distribution of the harm is often strictly dependant on highly variable factors. For example, the behavior of an oil spill is influenced by the density and the direction of the wind, the sea currents and the temperature of the water (Keramitsoglou et al., 2003). Therefore, even two spills of the exact same quantity and taking place in the exact same location can have different consequences depending on the weather conditions on the given (and following) day. Another example is thermal inversion, that is when a layer of warm air lies over a layer of cooler air that lies near the ground. Thermal inversion prevents pollutants from dispersing and therefore can exacerbate to the extreme the negative consequences associated to their presence (Helfand et al., 2001).

Let us recall that a joint use of regulation and liability is more likely to be optimal when there is a high variance in the ex-post causal uncertainty characterizing the various firms (Proposition 3). Or, to put it differently, a JR is more often optimal when the difference between the high and the low values of α is large. It follows that geographic areas with more heterogeneous characteristics across locations and throughout the year *ceteris paribus* should rely more often on a joint use of liability and regulation. Moreover, the gap between the high and the low values of α is affected by the tracking technologies available and the

⁸In the model we focus only on the time dimension, but most of the considerations apply also to the space dimension.

existing regulations. An important corollary is that regulation should complement liability more often at the European than at the national level. In fact, given the very heterogeneous weather and geographical characteristics of the European countries and their different regulations and tracking technologies, the difference between the high and the low values of α will generally be larger at the European than at the national level. A similar logic can be applied to regulation at the State and Federal level in United States. More generally, the normative implication to be derived is that it is more likely that a joint use of regulation and liability is optimal for larger and heterogeneous areas.

Proposition 3 also offers guidance to make comparisons across pollutants. For instance, some pollutants are more easily carried around by the wind and therefore the consequences caused when they are released in the atmosphere are strictly tied to the weather conditions. On the contrary, other pollutants are heavier and less affected by the winds, thus the harm they cause is less sensitive to weather conditions. Everything else being equal, the first kind of pollutants should be characterized by a greater variance in the α (especially in areas where the weather conditions are often changing and/or are heterogeneous), and therefore should be more often subjected to a JR. More generally, a joint regime of regulation and liability is more often efficient for pollutants causing a harm that can have a highly variable distribution in time and in space.

Moreover, the behavior of the harm in time and space depends on the nature of the pollutants. And indeed, some pollutants are more resistant to environmental degradation and therefore the consequences of an accident associated to them are more long-lasting. Important classes of persistent organic pollutants (POP) include many families of chlorinated aromatics and different organochlorine pesticides (Jones and De Voogt, 1999), whereas the typical example of long-lived climate pollutant is carbon dioxide (CO_2). On the contrary, other pollutants remain in the atmosphere for a much shorter period. Notable short-lived climate pollutants are fluorinated gasses, black carbon and methane. Importantly, the simple fact that some pollutants have a much longer life does not automatically imply that they are more harmful. For instance, some short-lived climate pollutants are “powerful climate forces and harmful air pollutants that have an outsized impact on climate change in the near term, compared to longer-lived GHGs [greenhouse gasses], such as carbon dioxide” (California Environmental Protection Agency: Air Resources Board, 2016). In other words, irrespective of the total harm they cause, some pollutants have effects that are more concentrated in time, whereas others have a more long-lasting impact. To further clarify this point, let us assume that there are two pollutants, A and B, causing the same amount of harm. Moreover, let us assume that the pollutant A is short-lived and all his effects disappear after $t = 3$. Instead, let us assume that pollutant B is long lived and his effect last until $t = 7$. Figure 5 represents a stylized description of the behavior in time of the harm caused by A and B.

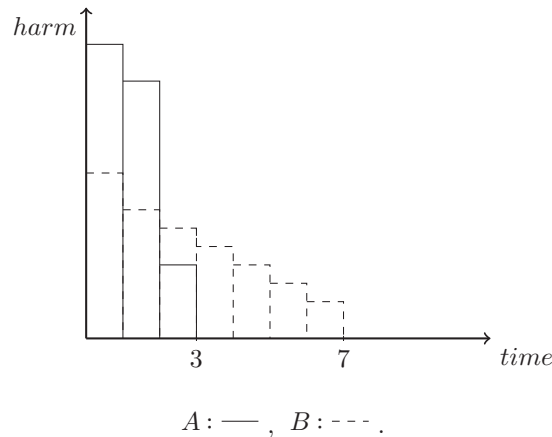


Figure 5: Short- and long-lived pollutants.

This figure shows two pollutants, who both in total cause the same amount of harm. However, pollutant A is short-lived and only harmful for 3 periods, whereas pollutant B causes harm for 7 periods.

3.2 The Quality of the Signal Received by the Court

Having introduced the time and, qualitatively, the spatial dimension in the picture, let us connect it to the model presented in Section 2. For the sake of simplicity, in the model we considered α a parameter. Yet, because the degree of causal uncertainty varies within any given accident, α is more appropriately described as a function of time, spatial distance and specific characteristics of the pollutant.

The gist of the argument is that the distribution of the harm in time and in space depends on the specific pollutant and on environmental conditions and it affects the quality of the signal at different points in time. This is merely an exercise in common sense as we are stating that *ceteris paribus*: (i) the more time passes since the accident the harder it becomes to establish a causal nexus, (ii) larger harms are easier to notice than smaller harms and (iii) the more information is available on the pollutant the easier the causal investigation will be. Last, (iv) the more the harm is pollutant-specific and the less sources of that pollutant there are the easier it is to identify the injurer.

For most pollutants, the larger fraction of the harm is in the proximity of the accident, hence we assume that the quality of the signal received by the court generally decreases when we depart – in time – from the accident. And indeed, the more time passes from the accident the more confounding factors emerge making causal investigation harder. In this framework, the efficiency of liability rules is strictly tied to the behavior of pollutants. To clarify this point, we assume that there are two accidents causing exactly the same amount of harm. Let us further assume that the first accident involves the pollutant A that causes a harm extending for T_A , whereas the harm caused by B extends for T_B , with $T_B > T_A$. Pollutant B, for example, could be nuclear wastes as they remain in the environment causing damages for an extremely long time. Last, let us assume that scientific knowledge only allows to trace A and B for a time that is equal to T_A and that after T_A α becomes too small to hold the alleged injurer liable. How liability rules would perform in these circumstances is captured by Figure 6.

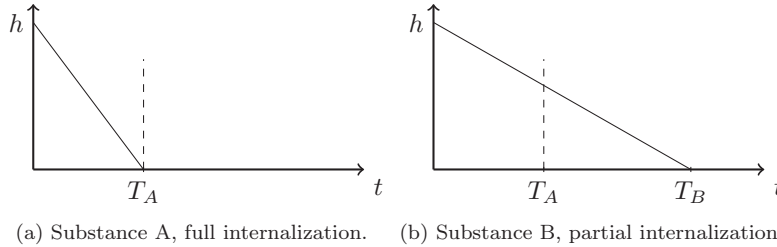


Figure 6: Liability and harm internalization

This figure highlights how a long-lived pollutant might affect harm internalization. In panel (a), we show a substance where the full harm is internalized due to the short-lived nature of the pollutant. Panel (b) is an example of a more long-lived pollutant, where only parts of the harm are internalized by the injurer.

For pollutant A liability rules induce the injurer to internalize the whole harm, whereas in the case of pollutant B liability rules would be blind to part of the harm. Therefore, regulation should complement liability rules to control the use of pollutant B, while it would be a waste of resources to regulate the pollutant A. To put it differently, the positive implications of this framework can be tested by observing whether pollutants with wider distribution in time and space are more strictly regulated than pollutants causing a harm concentrated in time and in space.

While it is true that for most pollutant the harm decreases over time, there are some notable exceptions. For example, substances like organic mercury and dichlorodiphenyltrichloroethane (DDT) produce a phenomenon known as biomagnification (Carson, 1962; Gray, 2002). Biomagnification is the transfer of a chemical from food to an organism that generally results in a higher concentration of the chemical within the organism than in the source (Gray, 2002). In a nutshell, the idea is that the organism keeps feeding on a food that contains a given chemical and, because the intake of chemical is larger than what is eliminated, the chemical starts accumulating in the organism. If the chemical is potentially harmful – as is the case of

organic mercury – the harm grows over time as the chemical accumulates. While there is certainly overlapping in many instances, biomagnification is not simply another name for lagged harm. In particular, lagged harm manifests itself later in time, whereas the first traces of harm caused by biomagnification can appear shortly after the accident, yet they are smaller than the future consequences of the accident. We visualize a case of biomagnification in Figure 7.

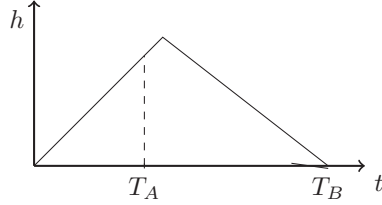


Figure 7: Liability and biomagnification

This figure shows the extreme case of a substance that produces a phenomenon called biomagnification. For those substances, harm is actually increasing over time for an initial period, until it at some point starts to decrease.

The most infamous case of biomagnification is probably the accumulation of methylmercury and other forms of mercury in Minamata Bay, Japan, caused by industrial wastewater (Harada, 1995). The Shin Nippon Chisso Fertilizer Company started its production of acetaldehyde in Minamata in 1932, yet only 24 years later the first cases of Minamata disease were diagnosed (Balogh et al., 2015). In the Minamata accident, due to the biomagnification, (marginal) harm *increased* over time. More recently, biomagnification has been associated with the expansion of the market of genetically engineered seeds (GES). The development of this multi-billion market has been driven by the demand for herbicide-resistant crops. In fact, for 80% of the existing GES crops, the process of genetic engineering is performed with the sole intent of making crops that can resist to herbicides (Shrader-Frechette, 2005). However, this practice can cause biomagnification of pesticides along the food chain which might produce long term consequences (Shrader-Frechette, 2005). Crafting appropriate regulations for substances characterized by biomagnification requires a special attention to the dynamic of the harm over time. In the example presented in Section 1, the harm caused by the oil spill decreases over time and therefore the quality of the signal received by the court is strictly decreasing in time. Instead, in these cases of biomagnification the harm increases over time, and thus also the quality of the signal received by the court, might increase over time. This effect can lead to a change of how courts perceive the harm caused. While for accidents involving most of the pollutants it is harder to prove (in front of a court) the part of the harm that is further away in time from the accident, in case of biomagnification it might be harder to prove the initial part of the harm.

3.3 The determinants of k

The diffusion in space and time of the harm affects the quality of the signal received by the court, but is not the only determinant of α . We introduce two additional and fundamental characteristics of pollutants and of the harm they cause.

- 1 The number of other pollutants causing the same kind of harm,
- 2 The number of sources of the pollutant.

Generalizing, combining [1] and [2] we can derive a matrix that offers some guidance on the effect of pollutant-specific characteristics.

In the North-West quadrant there are pollutants for which few sources exist and that cause a form of harm that is easily associated to them (e.g. signature diseases). These cases are generally connected to Proposition 1, as liability rules should be relatively effective. Regulation can be observed when the magnitude of the harm associated to a given pollutant is so large that firms might end up being judgement proof and/or the use of the pollutant is simply unreasonable. Thalidomide serves as an example for the this quadrant, because few other substances cause the childbirth defects typical of Thalidomide, e.g. malformation of the limbs (Phocomelia)

Table 2: Examples for combinations of sources and uniqueness

	Harm unique to Pollutant	Harm common to other pollutants
Few sources of pollutant	Thalidomide	Nuclear wastes
Many sources of pollutant	Asbestos	BPA; Plastic Pellets

(Bernstein, 1997). Moreover, in Germany Thalidomide was only commercialized by Chemie Grünenthal, and hence it was easy to trace the source of the harm. In fact in this case ex-post measures were extremely effective and in Germany the trial ended with a 30.000.000\$ compensation paid by Chemie Grünenthal to roughly 2800 victims. Importantly, the compensation was awarded through criminal action, and not in a personal injury cases (Curran, 1971). This fact suggests that also the more stringent requirements imposed by criminal law were met. Had the harm caused by Thalidomide not been so catastrophic ex-post measures would have sufficed to induce injurers to internalize the harm caused.

The other two quadrants indicate middle point situations in which our model suggests that a joint use of liability and regulation might be efficient (Proposition 3). The long-term radiation from nuclear accidents can be seen as an example for the North-East quadrant. While people affected by nuclear radiation typically only face one source, Schwartz (2006) argues that cancers originating from radiation are very difficult to distinguish from cancer caused by natural background sources. Incidentally, in most legal systems activities related with the production of nuclear energy are governed by a mix of regulation and liability. For instance, in the United States the Price-Anderson Nuclear Industries Indemnity Act, governing liability-related issues for all non-military nuclear facilities, complements a wide range of regulations.

Asbestos is a good example for the South-West quadrant. In fact, asbestosis and mesothelioma are signature diseases that are almost always associated with Asbestos exposure. However, a recent study by Frank and Joshi (2014) highlights that large quantities of asbestos are still used around the globe and thus it can be difficult to link the harm directly to a given source. We remark that courts have generally been able to identify the Asbestos as the cause of harm, whereas identifying the specific source of exposure has traditionally been more problematic.

Last, let us turn to the South-East quadrant. These cases are generally connected to Proposition 2. BPA is a widespread plastic which can be related to a multitude of medical conditions (see Lang et al., 2008). Biomonitoring studies found that 90% of the (Canadian) population is exposed in a way or another to BPA (Bushnik et al., 2010). In this case, it is very hard to establish causation, and therefore we expect that – as scientific evidence on the consequences of exposure to BPA accumulate – its use will mostly be controlled via regulation. Many countries and American States are moving in this directions and are introducing regulations related to the use of BPA. For instance, the government of Canada has introduced a ban on polycarbonate plastic baby bottles containing Bisphenol A, and the government of California requires warning labels for exposure to BPA of canned and bottled foods and beverages (Edge and Eyles, 2013; Government of California, 2016).

Plastic pellets (also sometimes referred to as nurdles) from all kinds of plastic are another example for the South-East quadrant. Plastic pellets, which are typically only the size of a lentil, are an intermediate product necessary for the production of plastic goods. They are produced by many different suppliers globally, contributing to a global plastic production of 311 million metric tons in 2014 (PlasticsEurope, 2015). The harmful effect of plastic pellets is related to spills in the production or transportation process. In a study dealing with plastic pellet spills in the United Kingdom, it has been estimated that between 5 and 53 billion pellets are lost every year in the UK only (Cole and Sherrington, 2016). Spilled pellets often end up in the sea, even when the spillage happened on land. And indeed, it is estimated that 80% of marine litter is a result of land-based sources (Andrady, 2011). Once the plastic pellets have entered the marine environment, they attract other harmful chemicals already in the ocean, as for example DDT (Mato et al., 2001). These other pollutants attach themselves to the pellets and this toxic combination might cause a wide array of negative consequences. For instance, it might end up in the stomachs of fishes and other marine animals or reach the beaches. A further way in which plastic pellets can enter the ocean is through the degradation of plastic bags, bottles and containers. Through this process, also BPA can enter the ocean as plastic pellets, linking the two pollutants. Recent contributions discussing how to deal with the growing problem of marine litter from a legal and political perspective have called for an increased regulation of plastic pellets, for

example through extended producer responsibility (Eriksen, 2013; Monroe, 2013). Instead, given the many steps from the initial plastic pellet to the harmful effect and the great number of sources of pellets, it is clear that liability will be difficult to establish.

To summarize, for courts the causal investigation is relatively easier in cases involving harm that is pollutant-specific and pollutants that are connected to only one source (north-west quadrant). At the other extreme, causal investigation is harder when the harm can be caused by a multitude of factors and there exist many sources of the pollutants (e.g. BPA or plastic pellets, south-east quadrant). Holding constant the distribution in time *and the magnitude of the harm*, we expect to have more stringent regulation for pollutants in the south-east quadrant than in the north-west quadrant. And indeed, for pollutants in the north-west quadrant liability rules can provide injurers with better incentives because the quality of the signal received by the court is relatively higher.

Therefore, in our framework the relative quality of the information held by the court *vis-à-vis* that held by the regulator determines the optimal mix of liability and regulation. On the one hand, the quality of these two informative sets is likely to be partially correlated. In fact, a deeper understanding of the characteristics of a pollutant is likely to improve both the prospective judgement of the regulator and the backward looking analysis of the court. On the other hand, for many pollutants there might be a marked difference in the reliability of the information held by courts and regulators.

Having discussed the effects of time, space and pollutant-specific characteristics, we can use our results to discuss an important element of environmental policy, namely the precautionary principle.

3.4 The Precautionary Principle

Despite its importance in environmental policies, economists are struggling to find a normative justification for the existence of the precautionary principle. We claim that the emergence of the PP is coherent with our framework, especially for pollutants in quadrant 4.

As noted by Aldred (2012), the traditional explanations advanced by mainstream economics are unsatisfying.⁹ A more promising path has been paved by Aldred (2012, 2013). Building on Rawlsian lexicographic preferences, Aldred shows that a rational regulator would adopt the PP when there is Knightian uncertainty and losses are unacceptable. In the context of environmental protection, this translates into a simple idea: the losses stemming from environmental disasters are of a different kind from the possible gains deriving from industrial production. Therefore, a precautionary principle is justified because not causing unacceptable harm to the environment is lexically prior to any possible potential gain.

Exploring this debate lies outside the scope of this paper, but it is worth to note that by implying incommensurability between gains and losses Aldred's argument goes against the standard - yet controversial - axiom that it is possible to attach a monetary value to everything. While abandoning this axiom seems a reasonable choice in some contexts, we attempt to offer a complementary explanation for the existence of the precautionary principle that does not require incommensurability. In fact, our model shows that *ceteris paribus* (i.e. for the same research cost functions, harm etc.) a rational regulator would regulate less those pollutants for which a larger part of the consequences is unknown. If those pollutants fall in the fourth quadrant, i.e. they cause a common form of harm and they are ubiquitous, then also liability rules are ineffective. In these instances, a precautionary principle seems warranted. Let us assume that there exist two pollutants C and D, that both cause a (total) harm equal to 100, that the regulator can invest 10 to investigate the harm caused by each pollutant and that there are no liability rules. Let us also assume that following this investment in research the regulator is able to identify 50% of the harm (i.e. $\alpha_r = 0.5$) for pollutant C and 10% of the harm (i.e. $\alpha_r = 0.1$) for pollutant D. We show that pollutant C will be more strictly regulated than pollutant D, despite the future impact of D is largely unknown. Now, let us further assume that liability rules are introduced and that pollutant C belongs to the first quadrant, whereas pollutant D belongs to the fourth. Pollutant D should be more strictly regulated than pollutant C because for it liability rules are less effective. Yet, a rational regulator would do exactly the opposite and regulate pollutant D less. Introducing the precautionary principle might help countering this simultaneous failure of ex-ante regulation and ex-post liability rules, given that the regulator is aware of the (relative) future uncertainty of a pollutant. From this perspective, it becomes easy to explain the decision of the Government of Canada to ban baby bottles

⁹Aldred mainly analyzes the Option Value Argument.

containing BPA. According to the Canadian Protection Act (Government of Canada, 1999), the Canadian government must consider science based evidence *and* employ precaution (Edge and Eyles, 2013). As BPA is situated in the South-East quadrant, liability rules would most likely be highly ineffective in deterring injurers from engaging in harmful behavior. Thus, it is reasonable to give higher weight to the precautionary concerns.

4 Conclusions

In this article we offer a possible explanation for the frequent joint use of ex-ante regulatory tools and ex-post liability rules in the area of environmental law. Instead of clinging on the judgement proof problem, we argue that when there are regulatory myopia (i.e the forward looking predictions of the regulator are imperfect) and causal uncertainty (i.e. the backward looking causal analysis of the courts is imperfect) a joint use of liability and regulation can be optimal. In particular, we find that the relative quality of the information held by the regulator *vis-à-vis* that held by the courts determines the optimal mix of regulation and liability. From this perspective, we find that three factors are especially relevant: (i) the distribution of the harm in time and in space, (ii) whether the kind of harm is pollutant-specific or it can be the resultant of many different causes, and (iii) whether there are many sources of the pollutant. From a policy perspective, this article offers a justification for joint use of regulation and liability in the area of environmental law from an efficiency perspective. For cases where substantial regulatory myopia combine with substantial causal uncertainty, we argue that the emergence of a precautionary principle can be justified. In general, the main limitation of our approach is the problem of assigning the optimal mix of both regimes in a world without perfectly informed social planners. However, the aim of this article is to provide a justification for the joint use of regulation and liability and not a prescription of the exact mix. This framework applies to every possible context characterized by regulatory myopia and causal uncertainty. Therefore, it can be transferred to many other areas of the law to explain the use of a particular regime more frequently than the others. For instance, a similar logic can be adapted to explain the frequent joint use of regulation and liability in health law. While a detailed discussion of these applications is outside the scope of this article, they represent an interesting venue for future research.

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