Environmental risk and extended liability: The case of green technologies

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Abstract

We analyze the effect of extending environmental risk to banks. We assume that the firm needs external funds to invest in green technology and reduce the risk of environmental damage. Prevention may affect the distribution of both environmental losses and operating revenues. We show that, under moral hazard, the firm does not always invest less in prevention than the optimal social level. We also show that extending liability may improve both the level of prevention and the level of compensation. However, extended liability always leads to an increased probability of bankruptcy for the firm. We also obtain that partial extended liability improves social welfare, while full extended liability does not.

Key words: Environmental risk, limited liability, extended liability, investment in prevention, moral hazard
JEL Classification: G33; K32; D82; D21

1 Introduction

Environmental risks display several specific dimensions in addition to those presented by more "standard" risks. First, an environmental risk is often related to very high levels of disaster but to low probabilities of accident (e.g., nuclear power plants). Second, the agent responsible for an accident is not the sole victim and the accident's impact may persist over several years. Fighting against environmental risks has now become an international priority. Governments agree that this must be done through a precise definition of respon-

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sibility and accurate attribution of the liabilities to all actors involved directly or indirectly in risky activities [1] .

Extending liability to partners of the firm has two principal aims: it should lead to better prevention *ex ante* and to better compensation *ex post.* The United States Congress adopted CERCLA (*Comprehensive Environmental Response, Compensation and Liability Act*, 1980-1985) which extends liability to banks financing firms guilty of environmental damage, provided such banks are sufficiently involved in the activities of the former. The intent of this legislation was to increase funds set aside for compensation, knowing that firms are often protected by the limited liability rule. Furthermore, implicating banks would motivate them to use instruments such as suitable financial contracts to give firms more incentives to invest in prevention.

Some European countries have also created compensation funds [2] , similar to the Superfund related to CERCLA in the United States, to provide for quick clean-up and compensation. Furthermore, the European Commission's DG XI - Environment, Nuclear Safety and Civil Protection, is currently working on "The role of the financial sector in achieving sustainable development". The European community's *Fifth Environmental Action Programme* [3] (European Community, 1993) states that "financial institutions which assume the risk of companies and plants can exercise considerable influence - in some cases control - over investment and management decisions which could be brought into play for the benefit of the environment". Hence, focusing on the impact banks have on the activities of their clients is becoming an important practice when dealing with corporations whose operations yield environmental risks.

Boyer and Laffont (1997) show that, under full information, extending all the liability to the bank is a first-best strategy in inducing firms to adopt adequate measures of prevention. The socially optimal level of prevention is attained and victims are well compensated if damage does occur. Reality, however, lags woefully behind such optimal conditions, and banks often have only partial information about the preventive measures adopted by the firms they finance. Thus, financial institutions cannot easily link the terms of the financial contract with the desired level of prevention when making loans. In the current context, Boyer and Laffont show that partial liability may be a

[1] This claim was first discussed at the 1972 Conference of Stockholm and has been ratified by the Convention of Lugano (Council of Europe, 1993). The 1992 Conference of Rio de Janeiro (Earth Summit, 1992) also played a large part in this ratification.

[2] For instance, FIPOL has been created in France and the *Umwelthaftungsgesetz* in Germany. Such public funds also exist in England and in Italy (see Bianchi (1994) for more information on European compensation funds).

[3] See also the *Progress Report in Implementation of the 5th Action Programme* (European Community, 1996), and the *Report to the European Commission by DELPHI International LTD in Association with Ecologic GMBH* (European Commission, 1997).

solution in obtaining the second-best level of prevention under some specific conditions.

Besides, by also assuming that prevention is not observable, Pitchford (1995) shows that even attributing partial liability to the bank is not a good solution: It tends to lessen prevention when compared to the level obtained without extended liability. There appears to be a trade-off between a high level of prevention and a high level of compensation, and the author concludes that the society has to choose between more prevention and larger compensation funds. In other words, extending liability does not solve both problems simultaneously.

One main result of the analyses just cited above concerns the optimal private level of prevention: It is always lower than the optimal social level, which is a standard result of the agency problem. But other analyses show that limited liability firms may adopt or even exceed the social level of prevention. Indeed, Beard (1990) and Lipowsky-Posey (1993) obtained this result by assuming than the funds used for prevention will no longer be available for compensation and clean-up in case of environmental damage. In other words, prevention is financed out of the firm's wealth which is subject to confiscation after an episode of damage. This leads to a decrease in the marginal cost of prevention when comparing the private case with the social case: Through the opportunity of bankruptcy, the firm externalizes part of the marginal cost, which is finally borne by the victims. Thus, private prevention may reach higher levels than social prevention depending on whether marginal costs or marginal benefits decline more rapidly.

In all these studies it is implicitly assumed that no external funds are needed to sustain risk-reducing activities[4]. But in the real world, preventing harm from environmentally risky activities often calls for borrowing to finance substantial investments. "Green" technologies, for instance, may be very expensive. The big difference between the works of Pitchford and Boyer and Laffont and a model allowing for investment in prevention is that, in the former, current expenses are paid during the course of the activity, whatever the *ex post* solvency of the firm. However, in fact, funds borrowed in order to invest either in production or prevention are only reimbursed if the firm is not bankrupted. Moreover, when calculating the net value of the firm, investment but not current expenses should be taken into account. When limited liability works, the firm internalizes the cost of financial investment only over those states of nature for which it is solvent.

In this paper we go a step beyond the previous analyses by allowing a firm to be financed by equity and by credit in order to invest simultaneously

[4] In Pitchford (1995) and in Boyer and Laffont (1997) external funds are borrowed from a bank only for the production activity, whereas Beard (1990), Lipowsky-Posey (1993) and van't Veld et al. (1997) do not allow for external credit. To our knowledge, the sole paper that treats the case of environmental risk, credit, and prevention is that of Craig and Thiel (1990).

in prevention and in production. This particularity adds an effect to that of Beard (1990) and Lipowsky-Posey (1993) to explain why private firms may have the incentive to invest more in prevention than the social optimal level. We show that some firms will invest more in prevention than the social optimal level when the marginal effect of preventive investment on projects is higher than the marginal effect of productive investment. In other words, the relative efficiency between preventive and productive activities is accounted for in deriving our main results. We also study what impact extending liability to the bank will have on social welfare by looking at its effects on the levels of prevention and compensation, the face value of debt and, finally, the firm's solvency. We show that our results are robust to the introduction of both endogenous investment and contingent debt. Finally, we obtain that full extended liability is never optimal.

The monetary amount invested in prevention by the firm is not observable by the bank: The latter observes the total investment in the project but does not know how the firm reallocates it between prevention and production. Furthermore, we assume that the bank cannot observe without cost the amount of the firm's net revenue, namely the operating revenue minus the level of damage if any has occurred, because the former is never observable without cost. Under this last hypothesis, it is known that the financial contract signed by both parties can be a standard debt contract, even if both forms of moral hazard are present (Dionne and Viala, 1992, 1994). When the accident is verifiable, the optimal financial contract is contingent debt in presence of *ex post* moral hazard (Caillaud et al., 2000).

The main characteristic of the model is that prevention calls for an investment at the beginning of the risky activity that is financed by equity and debt. Prevention also induces some current expenses during the activity. Moreover, prevention affects not only the distribution of environmental losses but also the distribution of operating revenues through its negative effect on the investment available for production.

In the model, the sequence of decisions is as follows: The firm and the bank first agree on a level of debt and on the corresponding face value of debt. The firm then splits the available funds between production and prevention. At the end of the period, operating revenues and the level of damage are realized. Payments are made.

As a consequence of our analysis, more prevention is not incompatible with a higher level of compensation for damages, especially when liability is extended to the bank. In that way, CERCLA legislation does not wander from its two main objectives. Unfortunately, extended liability increases the likelihood of bankruptcy for the firm, even in cases where the firm has an interest in improving prevention. Before now, this fact had never been pointed out in the literature, despite its importance.

The paper is organized as follows. Section 2 presents the model, while Section 3 investigates the debate around "private level of prevention *vs.* social level of prevention". The results about the impact of extended liability on social welfare are presented in Section 4. Section 5 introduces endogenous investment, while Section 6 considers contingent debt. Section 7 concludes the paper and discusses the implications of the results. Proofs are presented in the appendices. Due to space constraint, appendices I' to M are available from the authors at www.hec.ca/gestiondesrisques/98-12.pdf.

2 The Model

Consider an economy with a firm, a bank and a regulatory agency - each of them being risk neutral. For the firm, limited liability applies[5]. It wants to invest in a risky project but does not have sufficient equity to start up activities. Additional funds must be borrowed from the bank. We assume that the project in question calls for a minimum level of productive investment. This activity will be important for the derivation of our main results. The operating revenues entailed in the production and sale of the goods are random. In such a context, we assume that each additional unit of productive investment yields a greater value of expected operating revenues.

Besides random operating revenues, this project's technology carries a risk of environmental damage. The firm can adopt some measures of prevention. But, as argued in the introduction, prevention requires investment at the beginning of the project and may incur current expenses during the production process. Let e denote the financial investment in prevention at the beginning of the activity and I the total amount of investment. By definition, I equals productive investment (p) plus preventive investment (e). I is financed by borrowed funds B plus equity E contributed by the firm to the project[6]: $I = p + e = B + E$, with $e \in [\underline{e}, \overline{e}]$, $\underline{e} \geq 0$, $\overline{e} = I - \underline{p}$ and $\underline{p} > 0$. The scalar $\underline{p}$ is the minimal level of productive investment needed to run the activity. So we have:

$$e \leq I - \underline{p}, \tag{1}$$

which implies that $p \in [I - \overline{e}, I - \underline{e}]$. Total investment I is kept constant in the first sections (see Section 5 for the consideration of endogenous investment).

When the total investment I is held fixed, an increase in e has a negative effect on the expected operating revenues, since the amount of money allocated to prevention is not used for production: p must decrease, which affects not only the firm's level of production but also its marginal productivity. Thus, only substitution of prevention for production (or the reverse) is allowed when

[5] On limited liability see Sappington (1983)

[6] We consider an owner-manager of the firm so that the problem raised by the conflict of interest between managers and shareholders is not captured in our model. For the latter point the reader is referred to Harris and Raviv (1992).

I is held fixed. Moreover, for a given I we assume that the capital structure is fixed.

The distribution of operating revenues can now be expressed with respect to preventive investment. Formally, by having $G(\pi/e)$ (respectively $g(\pi/e)$) denote the distribution (the density function) of the random operating revenue $\tilde{\pi}$ on the bounded interval $[\underline{\pi}, \overline{\pi}]$, an increase in preventive investment e leads to a deterioration of the distribution $G(\pi/.)$ in the sense of the Monotone Likelihood Ratio Property [7] (MLRP): $\frac{\partial}{\partial \pi}\left(\frac{g_e(\pi/e)}{g(\pi/e)}\right) < 0$. This implies first order stochastic dominance: $G_e(\pi/e) > 0$. It is more likely to observe a higher level of operating revenue with a lower level of preventive investment [8].

Assumption 1 The random operating revenue $\tilde{\pi}$ is such that, for any e in $[\underline{e}, \overline{e}]$ and for a fixed level of total investment I we have $g(\pi/e) > 0$, $G_e(\pi/e) > 0$ and $G_{ee}(\pi/e) \leq 0$ $\forall \pi \in]\underline{\pi}, \overline{\pi}[$. Moreover, $G_e(\underline{\pi}/e) = G_e(\overline{\pi}/e) = 0$.

This model differs from the others considered in the literature for the following reasons. It states that the relation between the operating revenues and prevention is negative, while Pitchford (1995) and Boyer and Laffont (1997) assume that prevention has no impact on gross payoffs and Brander and Spencer (1989) assume that it does have a positive impact on operating revenues. We shall see that the possibility for firms to choose between precautionary expenditure and productive expenditure will be an important explanatory factor in our results. Particularly, it will permit us to add a significant effect to that derived by Beard (1990) and Lipowsky-Posey (1993).

Now, let us state precisely the characteristics of the environmental risk. The environmental risk denoted $\tilde{l}$ is affected by prevention in the sense of MLRP: It is more likely to observe a low level of damage with a high level of prevention. Formally:

Assumption 2 The environmental risk $\tilde{l}$ is such that, for any e in $[\underline{e}, \overline{e}]$, we have $f(l/e) > 0$, $F_e(l/e) > 0$ and $F_{ee}(l/e) \leq 0$ $\forall l \in]0, L[$. Moreover $F_e(0/e) = F_e(L/e) = 0$.

Assumption 2 is implied by MLRP. If G_{ee} equals zero, Assumption 2 is sufficient to obtain a global solution. Like $G(\pi/e)$, $F(l/e)$ is not a conditional distribution in a statistical sense. In this context, it is reasonable to assume that $\tilde{\pi}$ and $\tilde{l}$ are independent random variables even if their distribution depends on the same parameter e.

Assumption 3 $\tilde{\pi}$ and $\tilde{l}$ are independently distributed. Their joint distribution $H(\pi, l, e)$ is such that: $H(\pi, l, e) = G(\pi/e).F(l/e)$.

[7] We assume that both G and g are twice differentiable. See Spaeter (2001) for examples of such distributions that also satisfy CDFC.

[8] With I fixed and $e = I - p$ we have explicitly $G_p(\pi/p) = -G_e(\pi/e)$.

The fact that both F and G depend on the level of prevention will lead to a trade-off between reducing the risk of environmental damage through improved prevention and raising the expected operating revenues through increased productive investment. New insights for the understanding of the firms's behaviour will appear.

Environmental damage may push the firm into insolvency, meaning its revenues will not be sufficient for compensation and for clean-up. This fact can be expressed as follows:

$$\overline{\pi} < L \tag{2}$$

The financial contract which is signed to seal the bank loan B is assumed to be a standard debt contract[9] . The face value D is such that the firm is always solvent if no damage occurs:

$$\underline{\pi} - D \geq 0 \tag{3}$$

This last assumption is not necessary, but is made in order to isolate the impact of the environmental risk on the firm's behaviour. Lastly, the insurance sector is absent from this model[10] . However, this model can be reinterpreted for the case of a firm with partial insurance against the risk of environmental damage. This is particularly true when debt is contingent on environmental damages, as considered in Section 6.

Now, let us write the objective function and the constraints. Under limited liability the entrepreneur can never lose more than the value of the firm's assets, whatever the environmental damage and operating revenues. Furthermore, because of (2) and (3), there exists for each level of π an amount of loss l^*, strictly positive and less than L, for which the firm's net revenue is equal to zero for a given level of debt:

$$\exists l^* \in \,]0, L[\ / \ \pi - D - l^* = 0, \tag{4}$$

so that (4) defines l^* as $l^* = l^*(D, \pi)$.

From (4), the firm's net revenue, expressed as $r(l, \pi)$, is such that:

[9] In the literature on costly states verification, it has been shown that such a contract is optimal. See Gale and Hellwig (1985) for the one-period model and Chang (1990) and Coestier (2000) for a dynamic approach. See Dionne and Viala (1992, 1994) for a model with both *ex ante* and *ex post* moral hazard. For a review of the literature, the reader is referred to Freixas and Rochet (1997).

[10] For an analysis of both the bank and the insurance sectors see Caillaud et al. (2000). Katzman (1988) provides an analysis of the insurability of pollution liabilities.

$$r(l,\pi)=\begin{cases}\pi-D-l>0,\ \forall l<l^{*}\\ 0,\ \forall l\geq l^{*}\end{cases}.$$

By having $\phi(e)$ (with $\phi'(e)\geq 0$ and $\phi''(e)\geq 0$) denote the current expenses in prevention (such as costs related to clean-up of filters set on chimneys or to inspection by specialized employees), the expected net profit of the firm is

$$R\left(e;D,E\right)=\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{l^{*}(\pi,D)}(\pi-D-l)f(l/e)g(\pi/e)dld\pi-v(E)-\phi(e),\tag{5}$$

where $v(E)$ is the opportunity cost of contributing E. Before dealing with the bank's behaviour, let us define precisely the probability of bankruptcy. The firm is declared insolvent if a loss l greater than l^{*} occurs. Since l^{*} depends on π, bankruptcy depends on the realized couple (π,l). In other words, for a given π, the probability of bankruptcy is $(1-F(l^{*}(\pi,D)/e))$. Accordingly, for a given D, the probability of bankruptcy over the interval $[\underline{\pi},\overline{\pi}]$ equals:

$$1-\int_{\underline{\pi}}^{\overline{\pi}}F(l^{*}(\pi,D)/e)g(\pi/e)d\pi=1-\overline{F}(D/e).\tag{6}$$

The bank observes $I=p+e$ but does not know how the firm splits the funds between production and prevention: Neither p nor e is observable. Furthermore, though the bank knows the distributions of π and l, it cannot observe without cost the realized operating revenue net of loss, namely $\pi-l$. To get this information, it has to audit at a fixed cost A. This justifies the use of a debt contract, where it is optimal for the bank to audit every time the firm declares bankruptcy. In the last section, we will assume that l is verifiable by the court so that contingent debt can be introduced.

As a last but important assumption, the firm will compensate victims of a catastrophe before reimbursing the bank[11]. In other words, the latter gets back only the firms's residual value, which is zero if the loss exceeds the operating revenue.

Furthermore, the bank may be financially responsible *ex post* if the firm is insolvent. We allow for zero, partial or full extended liability. The bank

[11] Assuming that, in case of bankruptcy, priority of compensation is given to the victims over any secured creditor, such as banks, is consistent with reality. Indeed, since CERCLA, in the United States and also in some provinces of Canada, several examples are provided where courts have decided that clean-up and compensation costs should be recovered before banks are reimbursed for their loan. For a review of some court decisions and an accurate discussion of the lender's responsibility, the reader is referred to Staton (1993). In Europe, this property is also explicitly taken into account in the environmental liability system.

takes this eventuality into account when calculating the face value D and the amount B of funds it agrees to lend. Thus, the zero economic profit constraint of the risk-neutral bank is such that the funds it lends to the firm must yield, on average, as much as the opportunity cost corresponding to the risk-free interest rate:

$$B(1+i) = D\overline{F}(D/e)+\int_{\underline{\pi}}^{\overline{\pi}}\int_{l^*(\pi,D)}^{\pi+c}(\pi-l)\,f(l/e)g(\pi/e)dld\pi-(1-\overline{F}(D/e))A, \tag{7}$$

where $\overline{F}(D/e)$ is defined by (6), i is the risk-free interest rate, A is the fixed audit cost and c is the level of the bank's liability if any damage occurs, with $c \in [0, L-\pi]$. No liability is extended to the bank when $c = 0$, while full extended liability holds for $c = L-\pi$. Extended liability is partial for any c in $]0, L-\pi[$. In case of bankruptcy, when c equals zero the bank receives the firms's residual value after victims have been compensated. If the loss exceeds the realized operating revenues π, this value is nil and the bank receives nothing and pays nothing. If c is positive, then the bank has to compensate the victims up to the amount c if the loss is greater than π. In what follows, we assume that the bank is always able to pay for the damage whatever its responsibility. This hypothesis permits us to preclude some chain-moral-hazard problems. Finally, the optimization program for the firm is: $Max_e(5)$ subject to (7) and to (1).

3 Social *versus* private optimal level of effort

Assume there exists a regulator who observes the level of prevention without cost. Taking into account the zero-profit constraint of the bank, the social welfare equals

$$W^S = \int_{\underline{\pi}}^{\overline{\pi}}\int_0^L(\pi-l)f(l/e)g(\pi/e)dld\pi-v(E)-\phi(e)-B(1+i). \tag{8}$$

Result 1 *The optimal social level of prevention e^S satisfies the following first-order condition*

$$\int_{\underline{\pi}}^{\overline{\pi}} G_e(\pi/e^S)d\pi+\phi'(e^S) = \int_0^L F_e(l/e^S)dl, \tag{9}$$

where the left-hand-side (right-hand-side) term is the social expected marginal cost (benefit) of prevention.

Notice that the expected marginal cost contains an additional term when compared to the models in the literature. This first term corresponds to the variation in the productive activity associated with an increase in care expenditure, since I is fixed in this section. The second term is the current marginal cost of care as in the literature.

Knowing that $\phi'(e) > 0$, both terms in equality (9) are positive because of Assumptions 1 and 2. In equilibrium, the optimal level of prevention e^S is such that the marginal negative effect on expected operating revenues caused by investment in prevention plus the marginal cost of current expenses must be compensated by the marginal improvement in the distribution of loss.

Equation (9) can be rewritten as:

$$\int_{\underline{\pi}}^{\overline{\pi}} G_e(\pi/e^S)F(L/e^S)d\pi + \phi'(e^S) = \int_{\underline{\pi}}^{\overline{\pi}} \int_0^L g(\pi/e^S)F_e(l/e^S)dld\pi \tag{10}$$

It is worth noticing that in (10) the expectations of the marginal cost and of the marginal benefit are calculated over all states of nature related to the loss. This remark no longer holds when looking at the optimal private level of prevention[12]. Let e^P denote this private level.

Result 2 *The optimal private level of prevention e^P satisfies the following first-order condition*

$$\int_{\underline{\pi}}^{\overline{\pi}} G_e(\pi/e^P)F(l^*(\pi, D)/e^P)d\pi + \phi'(e^P) = \int_{\underline{\pi}}^{\overline{\pi}} \int_0^{l^*(\pi,D)} g(\pi/e^P)F_e(l/e^P)dld\pi, \tag{11}$$

where the left-hand-side (right-hand-side) term is the private expected marginal cost (benefit) of prevention.

Observe that both sides in (11) are evaluated only over the states of nature for which the firm is solvent[13], namely on $[0, l^*]$. On the side of the marginal benefit this feature characterizes the partial internalization of the social costs of environmental damage by the firm: The private marginal benefit of prevention is less than the social one. Because of the limited liability rule, the firm internalizes the cost of an accident only up to $l^*(\pi, D)$. As argued in the literature, one may expect that the private level of prevention e^P will always be lower than the social one e^S, knowing that the "quantity" of prevention is the entrepreneur's privileged information. This is not necessarily true here.

[12] To obtain Results 1 and 2, we have implicitly assumed that the second-order conditions are satisfied. This assumption will hold throughout the paper. The sufficient conditions are discussed in Appendix K.

[13] Except for the current marginal expenses $\phi'(e)$ that are paid before the realization of the state of nature and, consequently, whatever the *ex post* solvability of the firm.

Indeed, in order to run some risk-reducing activities financial investment is needed, so the firm must reduce the productive activity. Moreover when the firm evaluates its expected net revenue it makes sure that, in case of insolvency, it will lose no more than this net revenue. The firm is not concerned with how the bank will recover the funds it has lent or with how victims will be compensated. Consequently, both the expected private marginal cost and marginal benefit are lower than the social ones. So we cannot conclude anything about the difference $e^S - e^P$ without introducing more restrictions.

Proposition 1
i) Under moral hazard, a limited liability firm which must invest simultaneously in preventive and productive activities may choose a level of prevention greater than the optimal social one.
ii) A necessary and sufficient condition for having $e^P > e^S$ is that:

$$\int_{\underline{\pi}}^{\overline{\pi}} H_e(\pi, l^*(\pi, D), e^S) d\pi + \phi'(e^S) < \int_{0}^{l^*(\overline{\pi}, D)} F_e(l/e^S) dl \tag{12}$$

iii) Condition (12) may not be satisfied when the capital is rationed by the bank.

The left-hand-side term in (12) displays the private expected net marginal cost of prevention evaluated at $e = e^S$. When looking at the impact of prevention on the risk of bankruptcy, it is relevant to consider the net revenue $(\pi - D - l)$ rather than the operating revenues π: This explains the presence of the joint distribution H. The right-hand-side term in (12) is the private expected marginal benefit of prevention evaluated at the highest possible level of gross revenue $\overline{\pi}$ and at $e = e^S$.

Proposition 1 means that a private firm will invest more in preventive activities (e^P) than the regulator (e^S) if the private marginal benefit of prevention is higher than the private marginal cost when both are evaluated at e^S. From (12) we observe that the marginal private cost function for current expenses on effort ($\phi'(e)$) is the same as for the public cost function in (10). However, the other two terms are lower for each level of effort for a private firm than for the regulator because of limited liability: Each term in (12) is evaluated only when the private firm is solvent, that is only on $[0, l^*]$ instead of $[0, L]$ as in (10). Moreover, since the private firm must borrow money from the bank in order to finance part of its productive and preventive investments the two terms are dependent on the level of preventive activities. For a given I, when borrowed money is invested in preventive activities, this investment reduces available funds for productive activities. Consequently, the marginal productivity of both activities are affected when marginal decisions on preventive activities are made. In conclusion, the inequality in (12) will be satisfied for firms that have a higher marginal benefit of investing in preventive activities than the corresponding marginal benefit in productive activities. This result is different from those obtained by Pitchford (1995) and Boyer and Laffont (1997) where only current expenses (or the disutility of effort) are considered [14]. It is also different from the conclusions of Lipowsky-Posey (1993) and Beard (1990), as they did not take productive activity into account [15]. However, just as in their model, the firm externalizes part of the marginal benefit of prevention since it will not pay for a residual amount of damage exceeding its net revenue. But here it also externalizes part of the marginal cost of prevention since it spends the money borrowed from the bank and will reimburse only if it is not bankrupted. The trade-off between both effects is not taken into account by the regulator when evaluating the social level of prevention, because he is not concerned with the firm's net profits.

Another important remark deals with Point iii) of Proposition 1. Constraint (1) may be binding at the optimum. In such a situation, the optimal private level of prevention e^P equals $I-\underline{p}$. A greater level of prevention would lead to increased well-being for the firm (and for people exposed to the risk), but the entrepreneur cannot reach this higher level since the funds required are not available to him. Such a situation can be observed especially when the firm has already contributed all its capital to the project and when the bank is unwilling to lend more. Accordingly, moral hazard and limited liability should not be considered as the sole principal causes of under-investment in prevention. Banks' behaviour may also play an important part.

4 Extended liability and social welfare

In this section, we emphasize the impact of extended liability on social welfare. In order to get the total effect, we need first to isolate intermediate results on: (i) how increasing the face value of debt affects prevention; (ii)

[14] Observe that for $G_e(\pi/e) \equiv 0$ the first order conditions yield the results of Pitchford (1995) and of Boyer and Laffont (1997). So e^P is always lower than e^S. It is clear that the difference between these two contributions and those of Beard (1990) and Lipowsky-Posey (1993) is not due to whether expenditures are monetary or not but to the possibility that they may not be paid under bankruptcy when they are monetary. See the next footnote.

[15] It is important to emphasize how the major difference between our work and that of Beard (1990) and Lipowsky-Posey (1993) is due to the fact that our model introduces a reduction in productive activity when preventive activity is increased. From (12') in Appendix J, we observe that the result is yielded in part by the presence of the first term on the left hand side which corresponds to the variation in the productive activity discussed in the previous footnote. When $G_e(\pi/e) \equiv 0$, (12') is reduced to the model of Beard (1990) and Lipowsky-Posey (1993). The significant difference here is that (12) can be satisfied when $\phi'(e) \equiv 0 \; \forall e$. In other words, this section's ambiguous result on the variation in preventive activity is obtained because the entrepreneur has two activities (production and prevention) that require investment.

how extending liability to the bank affects debt; (iii) how extending liability to the bank affects prevention; and, iv) how extending liability to the bank affects the probability of bankruptcy for the firm. These points are treated in paragraph 4.1. Paragraph 4.2 deals with the welfare analysis of extended liability. From now on, we are exclusively interested in the private level e^P so that we can use the convention $e^P \equiv e$ without ambiguity. We only consider the case where (1) is not binding.

4.1 Intermediate results

We have to compute $\frac{de}{dc} = \frac{de}{dD} \cdot \frac{dD}{dc}$ and $\frac{dp}{dc} = \frac{dp}{dD} \cdot \frac{dD}{dc}$.

4.1.1 Variation in the face value of debt: Its impact on prevention

In the literature, it is shown that an increase in the face value of debt always generates a decrease in the level of prevention. The explanation is as follows: When D increases, the expected marginal benefit of prevention is calculated over a smaller range of states of nature and, consequently, is smaller. On the other hand, the marginal cost is not affected when only current expenses due to prevention are considered. Thus, the new optimal level of prevention must be lower than the initial one.

In the environment we focus on, the effect of D on the marginal benefit still holds, but it may be balanced by a non-zero effect on the marginal cost when productive activity is affected.

Lemma 1

i) The effect of a variation of D on the optimal level of prevention is as follows

$$\frac{de}{dD} = \frac{\frac{\partial}{\partial D}\left[mb(D,e) - mc(D,e)\right]}{|R_{ee}|}, \tag{13}$$

where R_{ee} is the second derivative of $R(e; D, E)$ with respect to e, and $mb(e)$ and $mc(e)$ are the expected marginal benefit and the expected marginal cost of prevention appearing in the first order condition (11).
ii) A sufficient condition for having $de/dD > 0$ is that:

$$\varepsilon_{G,e} > \varepsilon_{F,e} \cdot \frac{\eta_{G,e}}{\eta_{F,e}}, \ for\ each\ \pi$$

where $\varepsilon_{.,e}$ denotes the elasticity with respect to e and $\eta_{F,e}$ ($\eta_{G,e}$) the hazard rate related to F at l^* (to G at π).

In both cases ($de/dD < 0$ or > 0), an increase in D has a negative effect on the firm's net revenues. But this negative impact does not lead to a systematic decrease in preventive investment. Indeed, if the marginal cost decreases more rapidly than the marginal benefit with respect to D, then the firm is better off investing more in prevention in order to equalize the marginal cost to the marginal benefit.

Point ii) of Lemma 1 displays a sufficient condition related to the distributions of the operating revenues and losses to obtain a positive relation between e and D. Furthermore, firms with a high probability of bankruptcy may have an interest in doing more prevention following an increase in D. Indeed, the probability of bankruptcy $(1 - \overline{F}(D/e))$ can be rewritten as follows:

$$1-\overline{F}(D/e) = 1-\int_{\underline{\pi}}^{\overline{\pi}} f(l^*(\pi,D)/e)G(\pi/e)\frac{\eta_{G(\pi/e),e}}{\eta_{F(l^*(\pi,D)/e),e}}d\pi$$

Hence, for a given ratio $\varepsilon_{G,e}/\varepsilon_{F,e}$, firms with low ratios $\eta_{G,e}/\eta_{F,e}$ or high probability of bankruptcy are more likely to obtain a positive relation between e and D. In other words, firms with a higher probability of bankruptcy would tend to meet the sufficient condition displayed by point ii) of Lemma 1.

4.1.2 The effect of extended liability on the face value D

We now evaluate the impact of extended liability on the optimal face value D of debt for a given level B of borrowed funds. In other words we calculate dD/dc where c reflects the level of liability extended to the bank:

Lemma 2 *Extending liability to the bank always leads to an increase in the face value of debt D. In this way, the bank provides social insurance to the potential victims of environmental damage and the corresponding insurance premium is paid by the firm.*

The bank transfers its liability to the firm through the debt value. This increase in debt can be interpreted as an insurance premium paid by the firm to the bank when the former is solvent. Hence extending liability to the bank makes it possible to increase the funds available for compensating victims in case of damage. It is worth noticing that a direct consequence of Lemma 2 is that the expected wealth of the bank is not affected: The increase in D is such that the expected net profits remain equal to zero.

4.1.3 The effect of extended liability on prevention

But how will the firm react to this extended liability, knowing that it entails a higher face value of debt? We have by definition : $\frac{de}{dc} = \frac{de}{dD}.\frac{dD}{dc}$. Thanks to Lemmas 1 and 2, we are able to discuss the total effect of c on the level of prevention e:

Lemma 3 *When an increase in the face value of debt leads to an increase (a decrease) in prevention, extended liability increases (reduces) the private optimal level of prevention.*

A sufficient condition for obtaining an increase in prevention is displayed by point ii) in Lemma 1. High levels of compensation obtained thanks to a high level of extended liability are not always incompatible with high levels of prevention. Accordingly, the CERCLA legislation extending liability to any operator (such as banks) that are sufficiently involved in the pollutant activity may be a better way to cope with the *ex ante* well-being of society (through prevention) and also with the *ex post* wealth of the potential victims of a damage (through compensation and clean-up). Nevertheless, if extended liability seems to be a valuable tool in some situations, it also produces two perverse effects that have not been stressed in the literature until now and that are presented hereafter.

4.1.4 The effect of extended liability on the financial condition of the firm

Before proceeding to the analysis of how extended liability affects social welfare, let us introduce two additional intermediary results concerning the effect of extended liability and prevention on the firm's probability of bankruptcy. They will be useful in our conclusions about the variation of social welfare.

Lemma 4 *For given preventive and productive activities, extending liability to the bank always leads to an increase in the probability of bankruptcy for the firm.*

This effect is obtained because extended liability raises the face value of debt [16] for a given level of total investment. Moreover, when considering the reaction of the firm in terms of risk-reducing activities, this negative effect is always strengthened:

Lemma 5 *Whatever the optimal decision of the firm whether to increase or decrease its level of preventive investment following an increase in the face value of debt, the probability of bankruptcy is higher.*

The feature displayed by Lemma 5 can be observed by noticing that the derivative of the probability of bankruptcy $(1 - \overline{F}(D/e))$ with respect to e equals the numerator of de/dD given by (13) in Lemma 1. Hence, in the standard case where an increase in D induces a decrease in e, higher prevention leads to a decrease of $(1-\overline{F}(D/e))$, prevention permitting improvement in the financial conditions of the firm. But since the firm prefers to invest less in risk-reducing activities following an increase in D, it ends up being less solvent.

[16] Formally we have (with $l^*_D = -1$):

$$\frac{\partial}{\partial c}\left[1 - \overline{F}(D/e)\right] = \frac{dD}{dc}.\int_{\underline{\pi}}^{\overline{\pi}} f(l^*(\pi, D)/e)g(\pi/e)d\pi > 0$$

In the more striking case where D and e vary in the same direction, higher prevention leads to an increased probability of bankruptcy: The bad effect of prevention on operating revenues distribution G counterbalances the good effect on loss distribution F. Thus the increase in e induced by an increase in D also causes an increase in the probability of bankruptcy.

These conclusions drive the idea that investing in prevention may deteriorate the firm's financial conditions (when the total investment available is limited), even though it serves to reduce environmental risks. This negative effect has to be counterbalanced when evaluating the optimal level of extended liability from society's point of view.

4.2 The impact of extended liability on social welfare

When the firm privately chooses the level of preventive investment, the social welfare is:

$$W = \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} (\pi - D - l) f(l/e) g(\pi/e) dl d\pi - \int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} l f(l/e) g(\pi/e) dl d\pi \quad (14)$$
$$+ \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c)\left(1 - F(\pi + c/e)\right) g(\pi/e) d\pi - v(E)$$

Recall that the expected wealth of the bank equals zero whatever c happens to be and that, when l is between $l^*(\pi, D)$ and $\pi + c$, net transfers between the firm, the victims and the bank are nil: The victims are fully compensated, while the remaining revenues of the firm, if any, are given to the bank.

We show in Appendix F that:

$$\frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} \left(1 - F(\pi + c/e)\right) g(\pi/e) d\pi \quad (15)$$
$$- \frac{dD}{dc} \left[\frac{de}{dD} \frac{\partial}{\partial e} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e)) g(\pi/e) dl d\pi \right) + \overline{F}(D/e) \right]$$

Three effects appear. The first term, namely $\int_{\underline{\pi}}^{\overline{\pi}} \left(1 - F(\pi + c/e)\right) g(\pi/e) d\pi$, corresponds to the direct effect that extending liability to the bank will have on the welfare of the victims: If c increases, then victims are better off since more compensations are paid. The expression multiplied by $\frac{de}{dD}$ in the second term represents the effect preventive investment has on the probability of not being completely compensated. Since an increase in prevention improves the distribution of loss but also deteriorates expected gross profits, the total effect is undetermined. The last expression $-\frac{dD}{dc}\overline{F}(D/e)$ is negative and represents the negative effect of extended liability on the firm's solvency. Thus the overall effect of c on W is ambiguous. However, it is interesting to observe that [17]:

$$\lim_{c \to L-\pi} \frac{dW}{dc} = -\frac{dD}{dc}\overline{F}(D/e) < 0$$

and

$$\lim_{c \to 0} \frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi/e))\, g(\pi/e) d\pi > 0$$

Since W is continuous in c, we conclude that neither no-extended liability nor full-extended liability is optimal:

Proposition 2 *Extending partial liability to the bank is welfare improving while total extended liability is never optimal.*

This is in contradiction with CERCLA, since, up to now, lenders have been considered either free of liability or fully liable before a court of law. Partial extended liability is a better solution for society, as partial insurance is welfare improving in the standard principal-agent model. This result extends Pitchford's analysis by showing that a net social gain can be achieved with partial extended liability. In conclusion, we have shown that CERCLA may be compatible with high prevention *ex ante* and high compensation levels *ex post*. But it always reduces firms' solvency when total investment is limited. Finally, total extended liability is never optimal. We now extend the above analysis by permitting endogenous investment for a given level of equity.

5 Model with endogenous investment

This analysis is important because it permits evaluation of how the results of Section 4 are due to the fact that I is fixed. We shall show that the major explanation for our conclusions (concerning relative variations in the marginal benefits of both preventive and productive activities) is robust enough to withstand the introduction of endogenous investment.

From now on, the levels of preventive investment e and of productive investment p are decision variables for the firm: $I = e + p$. For a given level of equity E the level of borrowing B is chosen by the firm to finance the variations of I. So I becomes endogenous: $I = E + B$.

[17] For the second limit, we use the expression of dD/dc given in Appendix E (Equation (33)).

Since productive investment is a decision variable here, it must explicitly appear in the distribution of profits. We have:

Assumption 4 The distribution of the random revenue $\tilde{\pi}$ is such that we have $g(\pi/p) > 0$, $G_p(\pi/p) < 0$ and $G_{pp}(\pi/p) \geq 0$ $\forall \pi \in]\underline{\pi}, \overline{\pi}[$. Moreover $G_p(\underline{\pi}/p) = G_p(\overline{\pi}/p) = 0$.

The risk of environmental damage satisfies Assumption 2. Equations (2), (3) and (4) defined in Section 2 still hold. Furthermore we have $D = D(B, E)$ and $B = B(e, p)$. Lastly, the probability of bankruptcy is now: $1-\overline{F}(D/e, p) = 1 - \int_{\underline{\pi}}^{\overline{\pi}} F(l^*(\pi, D)/e)g(\pi/p)d\pi$.

The firm maximizes its net profits defined by [18]

$$R\,(e, p; B, E, D) = \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} (\pi - D - l) f(l/e) g(\pi/p) dl d\pi - v(E), \tag{16}$$

subject to the bank's zero-profit constraint

$$B(1+i) = D\overline{F}(D/e, p) + \int_{\underline{\pi}}^{\overline{\pi}} \int_{l^*(\pi,D)}^{\pi+c} (\pi - l) f(l/e) g(\pi/p) dl d\pi - (1 - \overline{F}(D/e, p))A. \tag{17}$$

What is important here is that preventive and productive activities are no longer systematically substitutes. It is possible for the firm to increase both investments by increasing the total amount of funds to be borrowed. From now on, we have to deal with two first-order conditions. Appendix G presents the derivation of these conditions (Equations (34) and (35)). Notice that the choice of e and p determines the level of borrowing B and thus, the face value of debt D. This is reflected in the right-hand-side terms of the two first-order conditions (34) and (35).

To compare social and private decisions, we have to focus on the regulator's problem. He maximizes the expected social welfare defined by:

$$W^S = \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{L} (\pi - l) f(l/e) g(\pi/p) dl d\pi - v(E) - B(1+i) \tag{18}$$

The first-order conditions related to the optimal social levels of e^S and p^S

[18] Since the results of the previous section are not affected by the current expenses function $\phi(e)$, we do not consider it here.

are

$$e^S \; : \; \int_0^L F_e(l/e^S)dl = B_e.(1+i) \tag{19}$$

and

$$p^S \; : \; -\int_{\underline{\pi}}^{\overline{\pi}} G_p(\pi/p^S)d\pi = B_p.(1+i) \tag{20}$$

The steps to obtain (19) and (20) are similar to those used for Result 1 (See Appendix A), except that B varies with e and p because I is endogenous.

5.2 Social vs. private levels of preventive and productive investments

We now derive the conditions under which the firm will invest more in prevention than the optimal social level.

Proposition 3 *Under moral hazard, a limited liability firm which is free to decide its total amount of investment will choose to invest more in prevention than the optimal social level if and only if:*

$$-\frac{\int_{\underline{\pi}}^{\overline{\pi}} \int_0^{l^*(\pi,D)} F_e(l/e^S)g(\pi/p)dld\pi}{\int_{\underline{\pi}}^{\overline{\pi}} F(l^*(\pi,D)/e)G_p(\pi/p^P)d\pi} > \frac{\overline{F}(D/e^S,p)}{\overline{F}(D/e,p^P)} \tag{21}$$

By symmetry we can show that production may also be higher than the social level. To interpret Equation (21) notice that its left-hand-side term is the ratio between the expected marginal benefit of prevention and that of production. Thus Equation (21) means that the firm will choose to invest more in prevention than the regulator if the relative expected marginal benefit of doing so is higher than the relative expected marginal cost of the two activities.

We conclude that the firm deals with prevention and production in the same manner it would deal with two different standard "productive" activities: It invests at the margin in the more profitable one.

5.3 Extended liability and social welfare

From now on, we use the following notations: $e^P \equiv e$ and $p^P \equiv p$. Because the total amount of investment is endogenous, the firm may be able to increase prevention and production by borrowing more. Nevertheless, the comparative statics of this section show that the firm always substitutes one type of investment for the other when liability is extended to the bank, because extended liability increases the cost of borrowing.

5.3.1 Intermediate results

As in Section 4 we need some intermediate results. Indeed we have to compute $\frac{de}{dc}$ and $\frac{dp}{dc}$.

The impact of a variation in the face value of debt on e and on p

The results are summarized in Lemma 5' presented in Appendix I. Two opposite effects appear in de/dD and dp/dD but e and p always vary in opposite directions. Following an increase in the face value of debt, the firm chooses either to increase e and to decrease p or the reverse. What is important here is that, contrary to Section 4 where B was fixed, the total effect of this substitution on the level of borrowing may be positive or negative, depending on the sensitivity of marginal benefits to the variations of p and of e.[19]

The effect of extended liability

To obtain the effect of c on e and p we must know the sign of dD/dc. We have to differentiate the bank's zero-profit constraint (17). Recalling that $B = e + p - E$, total differentiation with respect to D and to c yields:

$$\frac{dD}{dc} = \frac{\int_{\underline{\pi}}^{\overline{\pi}} cf(\pi + c/e)g(\pi/p)d\pi}{\overline{F}(D/e, p) - \overline{f}(D/e, p)A} \tag{22}$$

The numerator is positive. The denominator is also positive[20]. Thus extending liability to the bank always leads to an increase in the face value of the debt, as in the case with I fixed.

Thanks to this result and to Lemma 5' we can come to this conclusion about prevention:

Lemma 6 *When an increase in the face value of debt leads to an increase (a decrease) in prevention, extended liability increases (reduces) the optimal private level of prevention.*

Another important result deals with the probability of being solvent, namely $\overline{F}(D/e, p)$. The numerator of de/dD and dp/dD is the difference between the marginal effect of preventive investment and the marginal effect of productive investment on this probability[21]. We obtain that the firm compensates for the

[19] This is reflected in the equations through the presence of the second derivatives of the distributions. Recall that $B = e + p - E$ so that $\frac{dB}{dD} = \frac{de}{dD} + \frac{dp}{dD}$.

[20] The proof is similar to that discussed in footnote 25 in Appendix E.

[21] Recall that $\overline{F}(D/e, p) = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(l^*(\pi, D)/e))\, g(\pi/p)d\pi$.

increase in the level of debt by decreasing its chances to reimburse D. Finally, this result associated with Lemma 6 yields the following conclusion:

Lemma 7 *Extended liability always deteriorates the firm's solvency, even when the total amount of investment is endogenous.*

These results are similar to those obtained with exogenous investment. So, in this context, extending liability to the bank may not change the final conclusions about the impact on social welfare. The following paragraph confirms this conjecture.

5.3.2 The impact of extended liability on social welfare

When the firm privately chooses the level of preventive investment and of productive investment, the social welfare function is equal to:

$$W = \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} (\pi - D - l) f(l/e) g(\pi/p) dl d\pi - \int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} l f(l/e) g(\pi/p) dl d\pi$$
$$+ \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c)(1 - F(\pi + c/e)) g(\pi/p) d\pi - v(E). \tag{23}$$

From Appendix L, we verify that:

$$\frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e)) g(\pi/p) d\pi \tag{24}$$
$$- \frac{dD}{dc} \left[\frac{de}{dD} \frac{\partial}{\partial e} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e)) g(\pi/p) dl d\pi \right) \right.$$
$$\left. + \frac{dp}{dD} \frac{\partial}{\partial p} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e)) g(\pi/p) dl d\pi \right) + \overline{F}(D/e, p) \right]$$

The steps of the calculus for (24) are similar to those presented in Appendix F, except that p is now a decision variable. As a result, (24) is similar to (15), except that e and p are perfect substitutes in (15) because I was fixed, while both e and p are choice variables in this section. The first term in (24) corresponds to the direct effect that extending liability to the bank will have on the welfare of the victims. The terms multiplied respectively by $\frac{de}{dD}$ and by $\frac{dp}{dD}$ represent what effect preventive and productive investment will have on the probability of not being completely compensated. Both effects are positive. But we know that e and p always vary in opposite directions, so that the total effect is undetermined. The last term $-\frac{dD}{dc}\overline{F}(D/e, p)$ is negative and represents the negative effect of extended liability on the firm's solvency. As in Section

4, we have:

$$\lim_{c \to L-\pi} \frac{dW}{dc} = -\frac{dD}{dc}\overline{F}(D/e,p) < 0$$

and

$$\lim_{c \to 0} \frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi/e))\, g(\pi/p) d\pi > 0$$

Partial extended liability remains a dominant strategy.

We have shown that introducing endogenous investment and permitting the firm to increase investment in prevention and in production simultaneously do not induce radical differences in the results obtained when I is fixed. The firm still makes a trade-off between prevention and production because extending liability increases the cost of borrowing for the firm. Furthermore, only partial extended liability improves social welfare and the firm's solvency is still deteriorated. All these conclusions have been obtained with a standard debt contract. Thus one may ask if other types of financial contracts may mitigate the negative effect of extended liability on the firm. For instance, one natural extension is to introduce financial contracts contingent on the level of the environmental damage. In such a situation, the bank could provide insurance to the firm and not just to the victims. This possibility is investigated in the next section.

6 Model with contingent debt and endogenous investment [22]

In this section, the level of damage is not only observable as in the previous section, but it is also verifiable by a court. So we can assume that the firm signs a contingent debt contract. This means that the level of face value it has to pay will vary with the states of nature related to the environmental accident. In order to simplify the calculus, we assume the environmental loss takes only two possible values, namely that in the no-accident state and that in the accident state. Let l denote the level of damage if one occurs, with $\underline{\pi} < l < \overline{\pi}$, and $1 - q(e)$ as its probability of occurrence. Thus $q(e)$ is the probability that no accident will occur and it depends on the level of preventive investment e, such that $q'(e) > 0$ and $q''(e) \leq 0$. Profits are still distributed over $[\underline{\pi}, \overline{\pi}]$ with distribution $G(\pi/p)$. In the no-accident state of nature, let D^0 denote the face value of debt with $D^0 < \underline{\pi}$, so that the firm cannot be pushed into bankruptcy

[22] For the purpose of concision we do not present all the proofs, except when they are necessary for the discussion. They are available in Appendix M.

when no accident occurs[23]. Let D^l denote the level of face value the firm has to pay if the damage l is observed, with $\underline{\pi} < D^l + l < \overline{\pi}$. The bank provides insurance to the firm if $D^0 > D^l$.[24] We still assume that $D^0 < D^l + l$ so that the net revenue of the firm in the no accident state remains higher than its net revenue in the accident state. We also have $B \equiv B(e,p)$, $D^0 \equiv D^0(B,E)$ and $D^l \equiv D^l(B,E)$. Lastly, in such a model, bankruptcy is generated by a too low level of profit in the accident state of nature. Consequently there exists a level of profit π^* in $]\underline{\pi}, \overline{\pi}[$ that satisfies the following condition:

$$\pi^* - D^l - l = 0 \tag{25}$$

6.1 Preventive vs. productive investment

The firm chooses e and p to maximize its private net revenues defined by

$$\begin{aligned} & R\left(e,p;B,E,D^0,D^l\right) \qquad (26) \\ &= q(e)\int_{\underline{\pi}}^{\overline{\pi}} (\pi - D^0) g(\pi/p) d\pi + (1-q(e)) \int_{\pi^*}^{\overline{\pi}} (\pi - D^l - l) g(\pi/p) d\pi - v(E), \end{aligned}$$

subject to the bank's zero-profit constraint

$$\begin{aligned} B(1+i) = {} & q(e)D^0 \qquad (27) \\ & + (1-q(e)) \left[(1 - G(\pi^*/p)) D^l + \int_{l-c}^{\pi^*} (\pi - l) g(\pi/p) d\pi - G(\pi^*/p) A \right] \end{aligned}$$

where c, the level of liability extended to the bank, is now such that no liability is extended to the bank if $c = 0$, full extended liability holds if $c = l - \underline{\pi}$ and partial extended liability is observed for any level c in $]0, l - \underline{\pi}[$.

The first-order conditions related to the private optimal levels of e and p are derived in Appendix M (Equations (40) and (41)). We obtain that the firm still may invest more in prevention than the optimal social level. It keeps investing in the more profitable activity at the margin. See Appendix N for a parametrized example where $e^P > e^S$.

6.2 Impact of extended liability on social welfare

We show here that contingent debt does not change the results for the impact of c on social welfare. The structure of the intermediary results is

[23] This hypothesis is made to be consistent with the previous models where D was lower than $\underline{\pi}$. Nevertheless, we have also computed the model with a risk of bankruptcy in the no-accident state of nature. Results are similar to those we present in this section.

[24] See Caillaud et al. (2000) for the proof of the optimality of such a contract in the presence of *ex post* moral hazard.

identical to that in Sections 4 and 5. We do not present the equations here but we provide a discussion about the main effects.

The total effect of a variation of both levels of debt D^0 and D^l on e and on p remains ambiguous and e and p still vary in opposite directions. Following an increase in both face values of debt, the firm chooses either to increase e and decrease p or the reverse. But what is interesting here is that an increase in D^0 always leads to less prevention and to more productive investment: In the no-accident state the firm is always solvent so that it pays D^0 whatever the level of profits. As a standard result, it decreases prevention if borrowing becomes more expensive. The results are reversed in the accident state of nature. The firm invests more in prevention following an increase of D^l in order to compensate for the increase of its probability of bankruptcy. To summarize, we have $\frac{de}{dD^0} < 0$, $\frac{dp}{dD^0} > 0$, $\frac{de}{dD^l} > 0$ and $\frac{dp}{dD^l} < 0$.

Concerning the level of extended liability, we still obtain that an increase in c always leads to an increase in D^0 and in D^l such that the impact of c on e remains ambiguous. Nevertheless, we verify that increasing liability to the bank always leads to an increase in the firm's probability of bankruptcy, even if contingent debt provides some kind of insurance to the firm. This result is explained by the positive relation between both face values of debt and the level of extended liability and by the fact that the firm still substitutes, at optimum, one activity for the other. The interpretations of such results are identical to those presented in the previous sections.

Finally, even if the impact that c has on e remains ambiguous, it is possible to improve social welfare with partial extended liability. The social welfare function can be written as:

$$\begin{aligned} W = &q(e) \int_{\underline{\pi}}^{\overline{\pi}} (\pi - D^0) g(\pi/p) d\pi + (1 - q(e)) \int_{\pi^*}^{\overline{\pi}} (\pi - D^l - l) g(\pi/p) d\pi \\ &-(1 - q(e)) \int_{\underline{\pi}}^{l-c} (l - (\pi + c)) g(\pi/p) d\pi - v(E) \end{aligned} \tag{28}$$

Recall that the expected economic profit of the bank is nil. Total differentiation of (28) with respect to c leads to:

$$\begin{aligned} \frac{dW}{dc} = &G(l - c/p)(1 - q(e)) \\ &+ \frac{dD^0}{dc} \left[-q(e) + \frac{de}{dD^0} (J) + \frac{dp}{dD^0} (K) \right] \\ &+ \frac{dD^l}{dc} \left[-(1 - q(e))(1 - G(\pi^*/p)) + \frac{de}{dD^l} (J) + \frac{dp}{dD^l} (K) \right] \end{aligned} \tag{29}$$

with $J = q'(e) \int_{\underline{\pi}}^{l-c} (l - (\pi + c)) g(\pi/p) d\pi$ and $K = (1 - q(e)) \int_{\underline{\pi}}^{l-c} G_p(\pi/p) d\pi$. The first term in (29) is positive and reflects the improved welfare of the victims due to greater compensation in case of environmental damage. The second term is negative since extending liability to the bank leads to an increase in D^0 and, thus, deteriorates the expected wealth of the firm in the no-accident state. But when a loss occurs (third term) the negative effect of an increase in D^l may be counterbalanced by the increase in the preventive investment decided by the firm, so that the sign of the third term is a priori undetermined. Nevertheless, considering the limits of (29) when c tends respectively towards zero and $l - \underline{\pi}$ permits us to conclude:

$$\lim_{c \to 0} \frac{dW}{dc} = G(l/p)(1 - q(e)) > 0$$

and

$$\lim_{c \to l - \underline{\pi}} \frac{dW}{dc} = -q(e)\frac{dD^0}{dc} - (1 - q(e))\frac{dD^l}{dc} < 0$$

The first limit is obtained using the fact that $\lim_{c \to 0} \frac{dD^0}{dc} = \lim_{c \to 0} \frac{dD^l}{dc} = 0$, just as for $\lim_{c \to 0} \frac{dD}{dc}$ in the previous models. The second limit is due to the fact that J and K defined above tend towards zero when c tends towards $l - \underline{\pi}$. Finally, we observe that the results do not depend on $q(e)$.

Proposition 4 *Even if a state-contingent debt contract is signed, full extended liability is never optimal. Partial extended liability remains a better strategy to improve social welfare whatever the accident probability.*

7 Conclusion and discussion

We have considered a firm protected by the limited liability rule. It needs to borrow from a bank in order to invest simultaneously in production and in prevention. The total amount of investment is financed by equity and debt, where the latter is reimbursed by the firm only if it remains solvent after an environmental catastrophe. Due to the need of preventive investment in order to sustain risk-reducing activities, the firm may have an interest, under moral hazard, in privately choosing a level of prevention higher than the social one. The enterprise internalizes both the marginal cost and the marginal benefit on a smaller range of states of nature because in the bankruptcy states it gets nothing and it pays nothing more than its net value. The originality of our contribution is that the firm has to manage two activities, namely production and prevention, each of which requires some financial investment. First, we have considered the total amount of investment as fixed for the firm, so that production and prevention are, by definition, perfect substitutes. In this context, we have shown that the firm is better off with a higher level of prevention when an increase in prevention generates more benefits in terms of risk-reduction than it costs in terms of expected operating revenues.

We have also focused on what impact extending liability to the bank will have on prevention. It was shown that the bank transfers its expected extended liability to the firm through an increase in the face value of debt. In such a manner, the bank provides insurance to the victims and the firm pays the premium. Because it may be profitable for the firm to invest more in prevention following an increase of the face value of debt, we have concluded that extended liability can lead to better prevention and also to more funds for victims' compensation. However, extended liability always leads to an increase in the probability of bankruptcy for the firm because debt becomes more expensive. So, the total effect that extending liability to the bank will have on social welfare is not immediate. But we have shown that partial extended liability improves welfare, while full extended liability, as applied by CERCLA, is never optimal.

In a second model, we considered endogenous investment in order to evaluate how dependent our results may be on the restriction that holds total investment fixed. We obtained the same conclusions, but for different reasons. As a result, preventive and productive activities are substitutes following an extension of liability to the bank, because borrowing additional funds becomes more expensive for the firm. In such a situation, partial extended liability remains a dominant strategy for the regulator. In a last model, we have assumed that the level of environmental damage was verifiable by a court, so that we were able to consider contingent debt. Still there, our conclusions about the effect of extended liability remain valid.

To highlight the implications of our results from a practical point of view, let us take a look at the legislation. In the United States, CERCLA states that any owner or operator of a facility involved in environmental damage may be held liable for clean-up and compensation. Hence, in some court decisions banks have been prosecuted in order to recover these costs, while others have been exempted, depending on their degree of implication in the activity of the polluting firm. This extended liability has also been the feature of some court decisions in Canada. To date, CERCLA has led either to full responsibility or to no responsibility at all. Such legislation and its subsequent jurisprudence have made it possible to recover costs assumed by the Superfund for quick clean-up and compensation and it has induced a modification in the behaviour of lenders. One alternative solution proposes partial extended liability in some cases and our results support that conclusion. Consequently CERCLA's utility must be qualified, especially because extended liability always deteriorates the firm's solvency.

One extension of our work will be to study other financial contracts, especially in a multi-period model, which would allow the bank to be more active in the bank/firm relation. By considering renegotiation for instance, we might be able to reduce the negative effect on the firm's financial conditions. Another possibility would be to use capital markets in order to finance extended liability instead of imposing this cost on the firm. In doing so, the bank would be able to reduce the negative effects on productive investment.

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Appendix A. Proof of Result 1.

Differentiation with respect to (w.r.t.) e of the expected social wealth (8) leads to:

$$\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{L}(\pi-l)f_e(l/e^S)g(\pi/e^S)dld\pi+\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{L}(\pi-l)f(l/e^S)g_e(\pi/e^S)dld\pi-\phi'(e^S)=0$$

Integration by part w.r.t. l for the first term and w.r.t. π for the second term yields:

$$\begin{aligned}0=&\int_{\underline{\pi}}^{\overline{\pi}}\left\{\Big[(\pi-l)F_e(l/e^S)\Big]_0^L+\int_0^L F_e(l/e^S)dl\right\}g(\pi/e^S)d\pi\\&+\int_0^L\left\{\Big[(\pi-l)G_e(\pi/e^S)\Big]_{\underline{\pi}}^{\overline{\pi}}-\int_{\underline{\pi}}^{\overline{\pi}}G_e(\pi/e^S)d\pi\right\}f(l/e^S)dl\\&-\phi'(e^S)\end{aligned}$$

From Assumptions 1, 2 and 3 we get:

$$e^S \text{ satisfies } \int_{\underline{\pi}}^{\overline{\pi}}G_e(\pi/e^S)d\pi+\phi'(e^S)=\int_0^L F_e(l/e^S)dl$$

Result 1 is demonstrated.

Appendix B. Proof of Result 2.

The expected net profit of the firm is given by (5). Differentiation w.r.t. e leads to the following private first-order condition for an interior solution e^P:

$$-\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{l^*(\pi,D)}(\pi-D-l)f(l/e^P)g_e(\pi/e^P)dld\pi+\phi'(e^P)$$
$$=\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{l^*(\pi,D)}(\pi-D-l)f_e(l/e^P)g(\pi/e^P)dld\pi \tag{30}$$

By integrating by part both terms w.r.t. l and by using (4), Assumptions 1, 2 and 3, we have:

$$-\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{l^*(\pi,D)}F(l/e^P)g_e(\pi/e^P)dld\pi+\phi'(e^P)=\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{l^*(\pi,D)}F_e(l/e^P)g(\pi/e^P)dld\pi$$

Integration by part w.r.t. π of the left-hand-side finally yields (with $l^*_\pi = 1$):

$$\int_{\underline{\pi}}^{\overline{\pi}}F(l^*(\pi,D)/e^P)G_e(\pi/e^P)d\pi+\phi'(e^P)=\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{l^*(\pi,D)}F_e(l/e^P)g(\pi/e^P)dld\pi \tag{31}$$

Result 2 is demonstrated.

Appendix C. Proof of Proposition 1.

Point i) is derived from the comparison of (9) and (11). Point ii) is obtained by assuming that R_e evaluated at e^S is strictly positive:

$$\int_{\underline{\pi}}^{\overline{\pi}}F(l^*(\pi,D)/e^S)G_e(\pi/e^S)d\pi+\phi'(e^S)<\int_{\underline{\pi}}^{\overline{\pi}}\int_{0}^{l^*(\pi,D)}F_e(l/e^S)g(\pi/e^S)dld\pi$$

$$\Leftrightarrow \int_{\underline{\pi}}^{\overline{\pi}}F(l^*(\pi,D)/e^S)G_e(\pi/e^S)d\pi+\phi'(e^S)<\int_{0}^{l^*(\overline{\pi},D)}F_e(l/e)dl-\int_{\underline{\pi}}^{\overline{\pi}}F_e(l^*(\pi,D)/e)G(\pi/e)d\pi$$

$$\Leftrightarrow \int_{\underline{\pi}}^{\overline{\pi}}\left[F(l^*(\pi,D)/e^S)G_e(\pi/e^S)+F_e(l^*(\pi,D)/e)G(\pi/e)\right]d\pi+\phi'(e^S)<\int_{0}^{l^*(\overline{\pi},D)}F_e(l/e)dl$$

$$\Leftrightarrow \int_{\underline{\pi}}^{\overline{\pi}}H_e(\pi,l^*(\pi,D),e)d\pi+\phi'(e^S)<\int_{0}^{l^*(\overline{\pi},D)}F_e(l/e)dl,$$

Point iii) is obvious. Proposition 1 is demonstrated.

Appendix D. Proof of Lemma 1.

Keeping in mind that $l^*_D = -1$, total differentiation of the private first-order condition expressed by (31) w.r.t. e and D leads to:

$$\frac{de}{dD} = -\frac{-\int_{\underline{\pi}}^{\overline{\pi}} F_e(l^*(\pi, D)/e)g(\pi/e)d\pi + \int_{\underline{\pi}}^{\overline{\pi}} f(l^*(\pi, D)/e)G_e(\pi/e)d\pi}{R_{ee}} \tag{32}$$

From the second-order conditions R_{ee} is negative. Hence :

$$\frac{de}{dD} = \frac{-\int_{\underline{\pi}}^{\overline{\pi}} F_e(l^*(\pi, D)/e)g(\pi/e)d\pi + \int_{\underline{\pi}}^{\overline{\pi}} f(l^*(\pi, D)/e)G_e(\pi/e)d\pi}{|R_{ee}|}$$

The first (second) term of the numerator is the derivative w.r.t. D of the optimal expected marginal benefit of prevention, denoted as $mb(D, e)$, (of minus the optimal expected marginal cost, denoted as $mc(D, e)$). Point i) is demonstrated.

Point ii) is obtained by developing $\frac{\partial}{\partial D}\left[mb(D, e) - mc(D, e)\right]$ and by applying the required transformations to obtain the elasticities and the hazard rate $\eta_{F(l^*(\pi,D)/e),e} = f(l^*(\pi, D)/e)/F(l^*(\pi, D)/e)$ and $\eta_{G(\pi/e),e} = g(\pi/e)/G(\pi/e)$.

Appendix E. Proof of Lemma 2.

Total differentiation with respect to D and to c of the bank's zero-profit constraint (7) leads to

$$\frac{dD}{dc} = \frac{\int_{\underline{\pi}}^{\overline{\pi}} cf(\pi + c/e)g(\pi/e)d\pi}{\overline{F}(D/e) - \overline{f}(D/e)A}. \tag{33}$$

The numerator and the denominator are positive [25]. Lemma 2 is demonstrated.

Appendix F. Computation of Equation (15).

When the firm privately chooses the level of preventive investment the social welfare is given by (14). Thus:

$$\frac{dW}{dc} = W_c + \frac{dD}{dc}\left(W_e\frac{de}{dD} + W_D\right)$$

[25] Indeed it can be shown that this denominator equals that of the multiplicator associated with the bank's zero-profit constraint in the Lagrangian problem related to the choice of the optimal face value of debt (see for instance Froot et al. (1993) and Dionne and Viala (1992)).

$$\Leftrightarrow \frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) f(\pi + c/e) g(\pi/e) d\pi$$

$$- \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) f(\pi + c/e) g(\pi/e) d\pi + \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, g(\pi/e) d\pi$$

$$+ \frac{dD}{dc} \left[\frac{de}{dD} \left(- \int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} [l f_e(l/e) g(\pi/e) + l f(l/e) g_e(\pi/e)]\, dl d\pi \right.\right.$$

$$\left. - \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) F_e(\pi + c/e) g(\pi/e) d\pi + \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c)\, (1 - F(\pi + c/e))\, g_e(\pi/e) d\pi \right)$$

$$\left. - \overline{F}(D/e) \right]$$

Thanks to integrations by part and to simplifications we obtain:

$$\frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, g(\pi/e) d\pi$$

$$+ \frac{dD}{dc} \left[\frac{de}{dD} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} F_e(l/e) g(\pi/e) dl d\pi - \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e)) G_e(\pi/e) d\pi \right) \right.$$

$$\left. - \overline{F}(D/e) \right]$$

It is easy to show that the term multiplied by de/dD is equal to minus the derivative of $\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e)) g(\pi/e) dl d\pi$ w.r.t. e, so that (15) is demonstrated.

Appendix G. Computations of the first-order conditions (34) and (35).

The expected private net profits of the firm is defined by (16). Differentiation w.r.t. e and integration by part w.r.t. l of the left-hand-side yields Equation (34):

$$\int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} (\pi - D - l) f_e(l/e^P) g(\pi/p) dl d\pi = D_B.B_e. \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} f(l/e^P) g(\pi/p) dl d\pi$$

$$\Leftrightarrow \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} F_e(l/e^P) g(\pi/p) dl d\pi = D_B.B_e.\overline{F}(D/e^P, p) \tag{34}$$

Differentiation of (16) w.r.t. p and integration by part w.r.t. π and to l of the left-hand-side yields Equation (35):

$$\begin{aligned}
&\int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} (\pi - D - l) f(l/e) g_p(\pi/p^P) dl d\pi \\
&= D_B.B_p. \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} f(l/e) g(\pi/p^P) dl d\pi \\
&\Leftrightarrow \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} F(l/e) g_p(\pi/p^P) dl d\pi = D_B.B_p.\overline{F}(D/e, p^P) \\
&\Leftrightarrow - \int_{\underline{\pi}}^{\overline{\pi}} F(l^*(\pi, D)/e).G_p(\pi/p^P) d\pi = D_B.B_p.\overline{F}(D/e, p^P)
\end{aligned} \tag{35}$$

Appendix H. Proof of Proposition 3.

The optimal private level of prevention is higher than the social one if the difference between the left-hand-side term and the right-hand-side term in (34) is positive at $e = e^S$:

$$e^P > e^S \text{ iff } \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} F_e(l/e^S) g(\pi/p) dl d\pi > D_B.B_e.\overline{F}(D/e^S, p)$$

Thanks to Equation (35) this result is equivalent to:

$$e^P > e^S \text{ iff } - \frac{\int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} F_e(l/e^S) g(\pi/p) dl d\pi}{\int_{\underline{\pi}}^{\overline{\pi}} F(l^*(\pi, D)/e) G_p(\pi/p^P) d\pi} > \frac{D_B.B_e.\overline{F}(D/e^S, p)}{D_B.B_p.\overline{F}(D/e, p^P)} \tag{36}$$

Recall that e and p are monetary values. Thus for E fixed, a \$1 increase of e leads to a \$1 increase of B. The same reasoning holds for p. Consequently we have $B_e = B_p = 1$. Thus $D_B.B_e$ equals $D_B.B_p$ and finally we obtain Condition (21). In the same manner, the condition on p^P is:

$$p^P > p^S \text{ iff } - \frac{\int_{\underline{\pi}}^{\overline{\pi}} F(l^*(\pi, D)/e) G_p(\pi/p^S) d\pi}{\int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} F_e(l/e^P) g(\pi/p) dl d\pi} > \frac{D_B.B_p.\overline{F}(D/e, p^S)}{D_B.B_e.\overline{F}(D/e^P, p)} \tag{37}$$

Furthermore $D_B.B_p$ equals $D_B.B_e$ and we finally obtain the condition on the productive investment.

Appendix I. Lemma 5' and its proof.

Lemma 5'
i) The effect of a variation of D on the optimal level of prevention and on the optimal level of production is as follows:

$$\frac{de}{dD}=\frac{\int_{\underline{\pi}}^{\overline{\pi}} F_e(l^*(\pi,D)/e)g(\pi/p)d\pi+\int_{\underline{\pi}}^{\overline{\pi}} f(l^*(\pi,D)/e)G_p(\pi/p)d\pi}{\int_{\underline{\pi}}^{\overline{\pi}}\int_0^{l^*(\pi,D)} F_{ee}(l/e)g(\pi/p)dld\pi+\int_{\underline{\pi}}^{\overline{\pi}} F_e(l^*(\pi,D)/e)G_p(\pi/p)d\pi} \tag{38}$$

and

$$\frac{dp}{dD}=\frac{\int_{\underline{\pi}}^{\overline{\pi}} F_e(l^*(\pi,D)/e)g(\pi/p)d\pi+\int_{\underline{\pi}}^{\overline{\pi}} f(l^*(\pi,D)/e)G_p(\pi/p)d\pi}{-\int_{\underline{\pi}}^{\overline{\pi}} F_e(l^*(\pi,D)/e)G_p(\pi/p)d\pi+\int_{\underline{\pi}}^{\overline{\pi}} F(l^*(\pi,D)/e)G_{pp}(\pi/p)d\pi} \tag{39}$$

ii) Despite the fact that total investment is a decision variable for the firm, it always substitutes one activity for the other following an increase in the face value of debt.

Just as in the previous model, by using (36) and (37) we can show that e^P and p^P satisfy the following condition:

$$e^P,p^P \quad / \quad -\frac{\int_{\underline{\pi}}^{\overline{\pi}}\int_0^{l^*(\pi,D)} F_e(l/e^P)g(\pi/p^P)dld\pi}{\int_{\underline{\pi}}^{\overline{\pi}} F(l^*(\pi,D)/e^P)G_p(\pi/p^P)d\pi}=1$$

Total differentiations of this condition yield Equations (38) and (39) and Point i) is demonstrated. For Point ii), notice that the denominator of (38) is negative and that of (39) is positive, while both equations display the same numerator with an undetermined sign. So we cannot conclude what impact D has on e and on p, but we know that both effects are always opposed. Point ii) is demonstrated.

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ADDITIONAL PROOFS FOR THE READERS

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Appendix I'. Social first-order conditions when I is endogenous.

Recall that the social wealth equals:

$$W^S = \int_{\underline{\pi}}^{\overline{\pi}} \int_0^L (\pi - l) f(l/e) g(\pi/p) dl d\pi - v(E) - B(1+i)$$

Differentiation with respect to (w.r.t.) e leads to:

$$\int_{\underline{\pi}}^{\overline{\pi}} \int_0^L (\pi - l) f_e(l/e^S) g(\pi/p) dl d\pi = B_e(1+i)$$

Integration by part w.r.t. l of the first term yields Equation (19):

$$\int_{\underline{\pi}}^{\overline{\pi}} \left\{ \left[(\pi - l) F_e(l/e^S)\right]_0^L + \int_0^L F_e(l/e^S) dl \right\} g(\pi/p) d\pi = B_e(1+i)$$
$$\Leftrightarrow \int_0^L F_e(l/e^S) dl = B_e(1+i)$$

Differentiation of (19) w.r.t. p and integration by part w.r.t. π of the first term yields Equation (20):

$$\int_{\underline{\pi}}^{\overline{\pi}} \int_0^L (\pi - l) f(l/e) g_p(\pi/p^S) dl d\pi = B_p(1+i)$$
$$\Leftrightarrow \int_0^L \left\{ \left[(\pi - l) G_p(\pi/p^S)\right]_{\underline{\pi}}^{\overline{\pi}} - \int_0^L G_p(\pi/p^S) d\pi \right\} f(l/e) dl = B_p(1+i)$$
$$\Leftrightarrow - \int_0^L G_p(\pi/p^S) d\pi = B_p(1+i)$$

Appendix J. The case where $\phi(e)$ may not be paid when the firm is bankrupted.

Under this possibility, l^* is now defined as:

$$\exists l^* \in]0, L[\,/\, \pi - D - \phi(e) - l^* = 0, \qquad (4')$$

which implies that $l^* = l^*(\pi, D, e)$.

The expected revenue of the entrepreneur becomes

$$R(e; D, E) = \int_{\underline{\pi}}^{\overline{\pi}} \int_0^{l^*(\pi, D, e)} (\pi - D - \phi(e) - l) f(l/e) g(\pi/e) dl d\pi - v(E), \qquad (5')$$

and the bank's zero profit constraint is

$$B(1+i) = D\overline{F}(D, e/e) + \int_{\underline{\pi}}^{\overline{\pi}} \int_{l^*(\pi,D,e)}^{\pi+c} (\pi - l) f(l/e) g(\pi/e) \, dl d\pi$$
$$- \left(1 - \overline{F}(D, e/e)\right).A \tag{7'}$$

where the bank is implicitly reimbursed after the victims have been compensated but before the other creditors.

The social welfare function and the first-order condition for e^s (9) are not modified but the first-order condition for private level of care becomes:

$$\int_{\underline{\pi}}^{\overline{\pi}} G_e\left(\pi/e^P\right) F\left(l^*\left(\pi, D, e^P\right)/e^P\right) d\pi + \phi'\left(e^P\right) \overline{F}\left(D, e^P/e^P\right)$$
$$= \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D,e)} g\left(\pi/e^P\right) F_e\left(l/e^P\right) dl d\pi \tag{11'}$$

So (12) in the text becomes:

$$\int_{\underline{\pi}}^{\overline{\pi}} H_e\left(\pi, l^*\pi, D, e^S, e^S\right) + \phi'\left(e^S\right).\overline{F}\left(D, e^S/e^S\right) < \int_{0}^{l^*\left(\overline{\pi},D,e^S\right)} F_e\left(l/e^S\right) dl \tag{12'}$$

Appendix K. The private second-order conditions.

Differentiation w.r.t. e of (11) leads to:

$$R_{ee}(e; D, E) = \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} g(\pi/e) F_{ee}(l/e) dl d\pi + \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} g_e(\pi/e) F_e(l/e) dl d\pi$$
$$- \int_{\underline{\pi}}^{\overline{\pi}} G_{ee}(\pi/e) F(l^*(\pi, D)/e) d\pi - \int_{\underline{\pi}}^{\overline{\pi}} G_e(\pi/e) F_e(l^*(\pi, D)/e) d\pi - \phi''(e)$$

Recall that $\pi - D - l^* = 0$. Integration by part w.r.t. π of the second right-hand-side term and simplification yield:

$$R_{ee}(e; D, E) = \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} F_{ee}(l/e) g(\pi/e) dl d\pi - \int_{\underline{\pi}}^{\overline{\pi}} F(l^*(\pi, D)/e) G_{ee}(\pi/e) d\pi$$
$$-2 \int_{\underline{\pi}}^{\overline{\pi}} F_e(l^*(\pi, D)/e) G_e(\pi/e) d\pi - \phi''(e)$$

Because of the assumptions made in the paper, all terms are negative except the second one, which may be positive or equal to zero following Assumption 1. We assume in the paper that the sum of all these terms is negative.

Appendix L. Computation of Equation (24).

Recall that social welfare, when the firm privately chooses the level of preventive investment and of productive investment, is:

$$W = \int_{\underline{\pi}}^{\overline{\pi}} \int_{0}^{l^*(\pi,D)} (\pi - D - l) f(l/e) g(\pi/p) dl d\pi - \int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} l f(l/e) g(\pi/p) dl d\pi$$
$$+ \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) \left(1 - F(\pi + c/e)\right) g(\pi/p) d\pi - v(E)$$

We have to calculate

$$\frac{dW}{dc} = W_c + \frac{dD}{dc}\left(W_e \frac{de}{dD} + W_p \frac{dp}{dD} + W_D\right).$$

Thus:

$$\frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) f(\pi + c/e) g(\pi/p) d\pi$$
$$- \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) f(\pi + c/e) g(\pi/p) d\pi + \int_{\underline{\pi}}^{\overline{\pi}} \left(1 - F(\pi + c/e)\right) g(\pi/p) d\pi$$
$$+ \frac{dD}{dc}\left[\frac{de}{dD}\left(- \int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} l f_e(l/e) g(\pi/p) dl d\pi - \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) F_e(\pi + c/e) g(\pi/p) d\pi\right)\right.$$
$$+ \frac{dp}{dD}\left(- \int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} l f(l/e) g_p(\pi/p) dl d\pi + \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) \left(1 - F(\pi + c/e)\right) g_p(\pi/p) d\pi\right)$$
$$\left. - \overline{F}(D/e, p)\right]$$

$$\Leftrightarrow \frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, g(\pi/p) d\pi$$
$$+ \frac{dD}{dc} \left[\frac{de}{dD} \left(\int_{\underline{\pi}}^{\overline{\pi}} \left(- [lF_e(l/e)]_{\pi+c}^{L} + \int_{\pi+c}^{L} F_e(l/e) dl \right) g(\pi/p) d\pi - \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c) F_e(\pi + c/e) g(\pi/p) d\pi \right) \right.$$
$$+ \frac{dp}{dD} \left(\int_{\underline{\pi}}^{\overline{\pi}} \left(- [lF(l/e)]_{\pi+c}^{L} + \int_{\pi+c}^{L} F(l/e) dl \right) g_p(\pi/p) d\pi + \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c)\, (1 - F(\pi + c/e))\, g_p(\pi/p) d\pi \right)$$
$$\left. - \overline{F}(D/e, p) \right]$$

$$\Leftrightarrow \frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, g(\pi/p) d\pi$$
$$+ \frac{dD}{dc} \left[\frac{de}{dD} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} F_e(l/e) dl g(\pi/p) d\pi \right) \right.$$
$$+ \frac{dp}{dD} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} F(l/e) g_p(\pi/p) dl d\pi + \int_{\underline{\pi}}^{\overline{\pi}} (\pi + c - L) g_p(\pi/p) d\pi \right)$$
$$\left. - \overline{F}(D/e, p) \right]$$

$$\Leftrightarrow \frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, g(\pi/p) d\pi$$
$$+ \frac{dD}{dc} \left[\frac{de}{dD} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} F_e(l/e) dl g(\pi/p) d\pi \right) \right.$$
$$+ \frac{dp}{dD} \left(\left[\int_{\pi+c}^{L} F(l/e) dl . G_p(\pi/p) \right]_{\underline{\pi}}^{\overline{\pi}} + \int_{\underline{\pi}}^{\overline{\pi}} F(\pi + c/e) G_p(\pi/p) d\pi \right.$$
$$\left. + [(\pi + c - L) G_p(\pi/p)]_{\underline{\pi}}^{\overline{\pi}} - \int_{\underline{\pi}}^{\overline{\pi}} G_p(\pi/p) d\pi \right)$$
$$\left. - \overline{F}(D/e, p) \right]$$

And finally:

$$\frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, g(\pi/p) d\pi$$
$$+ \frac{dD}{dc} \left[\frac{de}{dD} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} F_e(l/e) g(\pi/p) dl d\pi \right) \right.$$
$$\left. + \frac{dp}{dD} \left(- \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, G_p(\pi/p) d\pi \right) - \overline{F}(D/e, p) \right]$$

Notice that the term multiplied by de/dD (by dp/dD) is minus the derivative w.r.t. e (w.r.t. p) of $\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e))\, g(\pi/p) dl d\pi$. Indeed,

$$-\frac{\partial}{\partial e} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e))\, g(\pi/p) dl d\pi \right) = \int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} F_e(l/e) g(\pi/p) dl d\pi$$

and

$$-\frac{\partial}{\partial p} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e))\, g(\pi/p) dl d\pi \right) = - \int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e))\, g_p(\pi/p) dl d\pi$$
$$= - \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, G_p(\pi/p) d\pi,$$

so that:

$$\frac{dW}{dc} = \int_{\underline{\pi}}^{\overline{\pi}} (1 - F(\pi + c/e))\, g(\pi/p) d\pi$$
$$- \frac{dD}{dc} \left[\frac{de}{dD} \frac{\partial}{\partial e} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e))\, g(\pi/p) dl d\pi \right) \right.$$
$$\left. + \frac{dp}{dD} \frac{\partial}{\partial p} \left(\int_{\underline{\pi}}^{\overline{\pi}} \int_{\pi+c}^{L} (1 - F(l/e))\, g(\pi/p) dl d\pi \right) + \overline{F}(D/e, p) \right]$$

Thus Equation (24) is demonstrated.

Appendix M. Proofs related to the state contingent debt model.

M.1. *Private first-order conditions*

Recall the expected net revenue of the firm

$$R\left(e,p;B,E,D^0,D^l\right)$$
$$=q(e)\int_{\underline{\pi}}^{\overline{\pi}}(\pi-D^0)g(\pi/p)d\pi+(1-q(e))\int_{\pi^*}^{\overline{\pi}}(\pi-D^l-l)g(\pi/p)d\pi-v(E),$$

and the bank's zero-profit constraint

$$B(1+i)=q(e)D^0$$
$$+(1-q(e))\left[(1-G(\pi^*/p))D^l+\int_{l-c}^{\pi^*}(\pi-l)g(\pi/p)d\pi-G(\pi^*/p)A\right].$$

The private first-order condition related to e^P is such that:

$$R_e=0$$

$$\Leftrightarrow q'(e)\int_{\underline{\pi}}^{\overline{\pi}}(\pi-D^0)g(\pi/p)d\pi-q'(e)\int_{\pi^*}^{\overline{\pi}}(\pi-D^l-l)g(\pi/p)d\pi$$
$$=B_e.\left[D^0_B.q(e)+D^l_B.(1-q(e))(1-G(\pi^*/p))\right]$$

$$\Leftrightarrow q'(e)\left(\left[(\pi-D^0)G(\pi/p)\right]_{\underline{\pi}}^{\overline{\pi}}-\int_{\underline{\pi}}^{\overline{\pi}}G(\pi/p)d\pi-\left[(\pi-D^l-l)G(\pi/p)\right]_{\pi^*}^{\overline{\pi}}+\int_{\pi^*}^{\overline{\pi}}G(\pi/p)d\pi\right)$$
$$=B_e.\left[D^0_B.q(e)+D^l_B.(1-q(e))(1-G(\pi^*/p))\right]$$

$$\Leftrightarrow q'(e)\left(D^l-D^0+l-\int_{\underline{\pi}}^{\pi^*}G(\pi/p)d\pi\right)$$
$$=B_e.\left[D^0_B.q(e)+D^l_B.(1-q(e))(1-G(\pi^*/p))\right] \tag{40}$$

The term $D^l+l-D^0-\int_{\underline{\pi}}^{\pi^*}G(\pi/p)d\pi$ in (40) is positive: it is obtained thanks to an integration by part of $\int_{\underline{\pi}}^{\overline{\pi}}(\pi-D^0)g(\pi/p)d\pi-\int_{\pi^*}^{\overline{\pi}}((\pi-D^l-l)g(\pi/p)d\pi$, which is positive because $\pi-D^0>\pi-D^l-l$ for any π.

The first-order condition related to p^P is such that:

$$R_p=0$$

$$\Leftrightarrow q(e)\int_{\underline{\pi}}^{\overline{\pi}}(\pi - D^0)g_p(\pi/p)d\pi + (1-q(e))\int_{\pi^*}^{\overline{\pi}}(\pi - D^l - l)g_p(\pi/p)d\pi$$
$$= B_p.\left[D_B^0.q(e) + D_B^l.(1-q(e))(1-G(\pi^*/p))\right]$$

$$\Leftrightarrow q(e)\left(\left[(\pi - D^0)G_p(\pi/p)\right]_{\underline{\pi}}^{\overline{\pi}} - \int_{\underline{\pi}}^{\overline{\pi}} G_p(\pi/p)d\pi\right)$$
$$+(1-q(e))\left(\left[(\pi - D^l - l)G_p(\pi/p)\right]_{\pi^*}^{\overline{\pi}} - \int_{\pi^*}^{\overline{\pi}} G_p(\pi/p)d\pi\right)$$
$$= B_p.\left[D_B^0.q(e) + D_B^l.(1-q(e))(1-G(\pi^*/p))\right]$$

$$\Leftrightarrow -q(e)\int_{\underline{\pi}}^{\overline{\pi}} G_p(\pi/p)d\pi$$
$$-(1-q(e))\left(\int_{\pi^*}^{\overline{\pi}} G_p(\pi/p)d\pi\right)$$
$$= B_p.\left[D_B^0.q(e) + D_B^l.(1-q(e))(1-G(\pi^*/p))\right]$$

$$\Leftrightarrow -q(e)\int_{\underline{\pi}}^{\pi^*} G_p(\pi/p)d\pi - \int_{\pi^*}^{\overline{\pi}} G_p(\pi/p)d\pi$$
$$= B_p.\left[D_B^0.q(e) + D_B^l.(1-q(e))(1-G(\pi^*/p))\right] \tag{41}$$

In the same spirit as in Section 5, we obtain the following other results:

Proposition 5 *The firm will invest in prevention more than the optimal social level if and only if:*

$$-\frac{q'(e^S)\left[D^l + l - D^0 - \int_{\underline{\pi}}^{\pi^*} G(\pi/p)d\pi\right]}{q(e)\int_{\underline{\pi}}^{\pi^*} G_p(\pi/p^P)d\pi + \int_{\pi^*}^{\overline{\pi}} G_p(\pi/p^P)d\pi} > \frac{D_B^0.q(e^S) + D_B^l.(1-q(e^S))(1-G(\pi^*/p))}{D_B^0.q(e) + D_B^l.(1-q(e))(1-G(\pi^*/p^P))}$$

Proposition 6 *At optimum, the private expected marginal benefit of prevention equals the private expected marginal benefit of productive investment:*

$$-\frac{q'(e^P)\left[D^l + l - D^0 - \int_{\underline{\pi}}^{\pi^*} G(\pi/p^P)d\pi\right]}{q(e^P)\int_{\underline{\pi}}^{\pi^*} G_p(\pi/p^P)d\pi + \int_{\pi^*}^{\overline{\pi}} G_p(\pi/p^P)d\pi} = 1 \tag{42}$$

M.2. *Impact of D^0 and D^l on e and on p*

The ratios de/dD^0, dp/dD^0, de/dD^l and dp/dD^l are obtained thanks to differentiations of (42) in Proposition 6 just above. Thus we have

$$\frac{de}{dD^0} = \frac{q'(e)}{q''(e)\left[D^l - D^0 + l - \int_{\underline{\pi}}^{\pi^*} G(\pi/p)d\pi\right] + q'(e)\int_{\underline{\pi}}^{\pi^*} G_p(\pi/p)d\pi} < 0,$$

$$\frac{dp}{dD^0} = \frac{q'(e)}{-q'(e)\int_{\underline{\pi}}^{\pi^*} G_p(\pi/p)d\pi + q(e)\int_{\underline{\pi}}^{\pi^*} G_{pp}(\pi/p)d\pi + \int_{\pi^*}^{\overline{\pi}} G_{pp}(\pi/p)d\pi} > 0,$$

$$\frac{de}{dD^l} = \frac{-q'(e)\left(1 - G(\pi^*/p)\right) + G_p(\pi^*/p)(1 - q(e))}{q''(e)\left[D^l - D^0 + l - \int_{\underline{\pi}}^{\pi^*} G(\pi/p)d\pi\right] + q'(e)\int_{\underline{\pi}}^{\pi^*} G_p(\pi/p)d\pi} > 0$$

and

$$\frac{dp}{dD^l} = \frac{-q'(e)\left(1 - G(\pi^*/p)\right) + G_p(\pi^*/p)(1 - q(e))}{-q'(e)\int_{\underline{\pi}}^{\pi^*} G_p(\pi/p)d\pi + q(e)\int_{\underline{\pi}}^{\pi^*} G_{pp}(\pi/p)d\pi + \int_{\pi^*}^{\overline{\pi}} G_{pp}(\pi/p)d\pi} < 0.$$

M.3. *Impact of c on D^0 and D^l*

We have to differentiate the zero-profit constraint (27) recalled in M.1. By letting S denote the right-hand-side term of (27), we obtain that

$$\frac{dD^0}{dc} = \frac{cg(l - c/p)(1 - q(e))}{q(e)} > 0$$

and

$$\frac{dD^l}{dc} = \frac{cg(l - c/p)(1 - q(e))}{(1 - q(e))\left[(1 - G(\pi^*/p)) - g(\pi^*/p)A\right]} > 0$$

Here, we still refer to Froot et al. (1993) to show that the denominator of D^l/dc is positive (see footnote 25 in Appendix E). So, extending liability to the bank has a positive effect on both face values of debt.

M.4. *Impact of* c *on social welfare*
Recall that social welfare, when the firm privately chooses e and p, is:

$$W = q(e).\int_{\underline{\pi}}^{\overline{\pi}} (\pi - D^0)g(\pi/p)d\pi + (1-q(e))\int_{\pi^*}^{\overline{\pi}} (\pi - D^l - l)g(\pi/p)d\pi$$
$$-(1-q(e))\int_{\underline{\pi}}^{l-c} (l-(\pi+c))g(\pi/p)d\pi - v(E)$$

Hence:

$$\frac{dW}{dc} = W_c + \frac{dD^0}{dc}\left(W_{D^0} + W_e\frac{de}{dD^0} + W_p\frac{dp}{dD^0}\right)$$
$$+\frac{dD^l}{dc}\left(W_{D^l} + W_e\frac{de}{dD^l} + W_p\frac{dp}{dD^l}\right)$$

$$\Leftrightarrow \frac{dW}{dc} = G(l-c)/p)(1-q(e))$$
$$+\frac{dD^0}{dc}\left[-q(e) + \frac{de}{dD^0}\left(q'(e)\int_{\underline{\pi}}^{l-c}(l-(\pi+c))g(\pi/p)d\pi\right)\right.$$
$$\left.+\frac{dp}{dD^0}\left(-(1-q(e))\int_{\underline{\pi}}^{l-c}(l-(\pi+c))g_p(\pi/p)d\pi\right)\right]$$
$$+\frac{dD^l}{dc}\left[-(1-q(e))(1-g(\pi^*/p)) + \frac{de}{dD^l}\left(q'(e)\int_{\underline{\pi}}^{l-c}(l-(\pi+c))g(\pi/p)d\pi\right)\right.$$
$$\left.+\frac{dp}{dD^l}\left(-(1-q(e))\int_{\underline{\pi}}^{l-c}(l-(\pi+c))g_p(\pi/p)d\pi\right)\right]$$

$$\Leftrightarrow \frac{dW}{dc} = G(l-c)/p)(1-q(e))$$
$$+\frac{dD^0}{dc}\left[-q(e)+\frac{de}{dD^0}\cdot\left(q'(e)\int_{\underline{\pi}}^{l-c}(l-(\pi+c))g(\pi/p)d\pi\right)\right.$$
$$\left.+\frac{dp}{dD^0}\left(-(1-q(e))\int_{\underline{\pi}}^{l-c}G_p(\pi/p)d\pi\right)\right]$$
$$+\frac{dD^l}{dc}\left[-(1-q(e))(1-g(\pi^*/p))+\frac{de}{dD^l}\cdot\left(q'(e)\int_{\underline{\pi}}^{l-c}(l-(\pi+c))g(\pi/p)d\pi\right)\right.$$
$$\left.+\frac{dp}{dD^l}\left(-(1-q(e))\int_{\underline{\pi}}^{l-c}G_p(\pi/p)d\pi\right)\right]$$

The last equality is Equation (29) in the text.

Appendix N. Parametrized example for the debt-contingent model.

The computations have been made with[26] Maple V Release 2. The detailed program is presented in N.3.

N.1. *Social values of preventive and productive investments*

In this paragraph, we focus on the social problem. To compute the values with the debt-contingent model we assume that the environmental risk can take two possible values: zero or l, with probability $q(e)$ and $(1-q(e))$.

When information is perfect, the social expected welfare maximization program is

$$\max_{e,p} W = \int_{\underline{\pi}}^{\overline{\pi}} \pi g(\pi/p)d\pi - v(E) - l(1-q(e)) - B(1+i)$$

We assume the following parameters as given:
$\pi \in [1,6]$ (gross profits)
$l = 2$ (environmental damage)
$E = 0$ (no equity)
$B = e + p$ (borrowed funds)
$i = 0$ (the risk-free interest rate is normalized to zero without loss of generality).
$c = 0$ (no extended liability)
$A = 0$ (no audit costs)
$q(e) = 0.4e^{0.5}$ (probability of no accident)

In the course, we change the following notations: $\pi \equiv t$, $D^0 \equiv d$ and $D^l \equiv D$. Assume that the distribution of gross profits is $G(t/p) = \left(\frac{t}{6}\right)^p$. Thus we have

[26] With Maple V release 2, O4 means 0.4.

$g(t/p) = \left(\frac{p}{6}\right)\left(\frac{t}{6}\right)^{p-1}$. The maximization program becomes:

$$\max_{e,p} W = \int_1^6 t\left(\frac{p}{6}\right)\left(\frac{t}{6}\right)^{p-1} dt - 2(1-0.4e^{0.5}) - e - p$$

Computations lead to:

$$\begin{aligned} e^S &= 0.16 \\ p^S &= 1.526555674 \end{aligned} \tag{43}$$

With these values the expected social welfare equals $W social = 0.219469234$.

N.2. *Private values with contingent debt*
The optimization program is:

$$\max_{e,p} R = q(e)\int_{\underline{\pi}}^{\overline{\pi}} (\pi - D^0) g(\pi/p) d\pi$$
$$+(1-q(e))\int_{D^l+l}^{\overline{\pi}} (\pi - D^l - l) g(\pi/p) d\pi - v(E)$$
subject to
$$B(1+i) = q(e)D^0$$
$$+(1-q(e))\left[(1-G(D^l+l/p))D^l + \int_{l-c}^{D^l+l} (\pi - l) g(\pi/p) d\pi - G(D^l+l/p)A\right]$$
$$D^l < D^0 + l < \overline{\pi} \tag{44}$$
$$0 < D^l \tag{45}$$

With the previous parametrization, the program becomes:

$$\max_{e,p} R = 0.4e^{0.5}\int_1^6 (t-d)\left(\frac{p}{6}\right)\left(\frac{t}{6}\right)^{p-1} dt$$
$$+(1-0.4e^{0.5})\int_{D+2}^6 (t-D-2)\left(\frac{p}{6}\right)\left(\frac{t}{6}\right)^{p-1} dt$$
subject to
$$\begin{aligned} &(1-0.4e^{0.5})\left[\left(1-\left(\tfrac{(D+2)}{6}\right)^p\right)D + \int_2^{D+2} (t-2)\left(\tfrac{p}{6}\right)\left(\tfrac{t}{6}\right)^{p-1} dt\right] \\ &+0.4e^{0.5}d - e - p = 0 \end{aligned} \tag{46}$$

For the computations, the right-hand-side term of (46) will be noticed Ci with $i = 1...6$, depending on the step of the computations. Still notice that we do not need constraints (44) and (45): they are automatically satisfied with the selected parameters.

Now we have to show that there exists at least one couple (e^P, p^P) satisfying $e^P > e^S$ and $p^P < p^S$ such that the expected private net revenue of the firm is improved compared to that obtained with the social values e^S and p^S. To do so, we have disturbed the social values and we have computed the optimal value of D^0 (noticed d) for a given D^l (noticed D). Details are given in Paragraph N.3. Here we summarize the results.

For D fixed at 2 and with social values e^S and p^S given by (46) we obtain:

$$\begin{aligned} &e^S = 0.16 \\ &p^S = 1.526555674 \\ &D = 2 \\ &d^S = 3.740043099 \\ &C(e^S, p^S, D, d^S) = 0 \\ &R(e^S, p^S, D, d^S) = 0.4155099077 \end{aligned} \tag{47}$$

With the disturbed values $e^p = 0.2$ and $p^P = 1.486555674$ we obtain:

$$\begin{aligned} &e^P = 0.2 \\ &p^P = 1.486555674 \\ &D = 2 \\ &d^p = 3.567996813 \\ &C(e^P, p^P, D, d^P) \approx 0 \\ &R(e^P, p^P, D, d^P) = 0.4242655537 \end{aligned} \tag{48}$$

By comparing (47) and (48) we finally obtain that:

$$\begin{aligned} &e^P > e^S \\ &p^P < p^S \\ &C = 0 \\ &R(e^P, p^P, D, d^P) > R(e^S, p^S, D, d^S) \end{aligned}$$

N.3. *Computations*

We present here the detailed program computed with Maple V Release 2.

EXPECTED SOCIAL WELFARE

```
>
>
> W:=int(t*(p/6)*(t/6)^(p-1),t=1..6)-2*(1-0.4*e^0.5)-e-p;
>
```

$$W := \frac{6^{(p+1)}\left(\frac{1}{6}\right)^p p}{p+1} - \frac{\left(\frac{1}{6}\right)^p p}{p+1} - 2 + 2\ O4\ e^{.5} - e - p$$

```
>
```

Computations of the social values of e and p

```
>
>
> DIFF1:=diff(W,e);
```

$$DIFF1 := 1.0\,\frac{O4}{e^{.5}} - 1$$

```
>
> DIFF2:=diff(W,p);
```

$$DIFF2 := -\frac{6^{(p+1)}\left(\frac{1}{6}\right)^p p}{(p+1)^2} + \frac{6^{(p+1)}\left(\frac{1}{6}\right)^p}{p+1} + \frac{\left(\frac{1}{6}\right)^p p}{(p+1)^2} + \frac{\left(\frac{1}{6}\right)^p \ln(6)\, p}{p+1} - \frac{\left(\frac{1}{6}\right)^p}{p+1} - 1$$

```
>
> solve({DIFF1=0,DIFF2=0}, {e,p});
```

$$\left\{e = O4^2,\ p = 1.526555674\right\}$$

```
>
> Wsocial=subs(e=0.16,p=1.526555674,W);
```

$$Wsocial = -.100530766 + .8000000000\ O4$$

```
>
> evalf(-0.100530766+0.8*0.4);
```

$$.219469234$$

```
>
>
```

EXPECTED PRIVATE NET REVENUE

```
>

>
> R1:=0.4*e^0.5*int((t-d)*(p/6)*(t/6)^(p-1),t=1..6)
> +(1-0.4*e^0.5)*int((t-2-D)*(p/6)*(t/6)^(p-1),t=(D+2)..6);
```

>

$$R1 := .4\, e^{.5} \left(\frac{6^{(-p)} \left(p\, 6^{(p+1)} - d\, 6^{p}\, p - d\, 6^{p} \right)}{p+1} + \frac{6^{(-p)} (-p + p\, d + d)}{p+1} \right) + \left(1 - .4\, e^{.5}\right) \left(\frac{1}{6} \left(-6^{p}\, 6^{(-p+1)}\, p\, D - 6^{p}\, 6^{(-p+1)}\, D - 2\, 6^{p}\, 6^{(-p+1)}\, p - 2\, 6^{p}\, 6^{(-p+1)} + 6\, 6^{(-p)}\, p\, 6^{(p+1)} \right) / (p+1) + \frac{1}{6} \left((D+2)^{p}\, 6^{(-p+1)}\, p\, D + (D+2)^{p}\, 6^{(-p+1)}\, D + 2\, (D+2)^{p}\, 6^{(-p+1)}\, p + 2\, (D+2)^{p}\, 6^{(-p+1)} - 6\, 6^{(-p)}\, p\, (D+2)^{(p+1)} \right) / (p+1) \right)$$

>

```
> C1:=0.4*e^0.5*d+(1-0.4*e^0.5)*((1-((2+D)/6)^p)*D
> +int((t-2)*(p/6)*(t/6)^(p-1),t=2..(D+2)))-e-p;
```

>

$$C1 := .4\, e^{.5}\, d + \left(1 - .4\, e^{.5}\right) \left(\left(1 - \left(\frac{1}{6} D + \frac{1}{3} \right)^{p} \right) D + \frac{1}{3} \frac{3\, 6^{(-p)}\, p\, (D+2)^{(p+1)} - (D+2)^{p}\, 6^{(-p+1)}\, p - (D+2)^{p}\, 6^{(-p+1)}}{p+1} - \frac{1}{3} \frac{3\, 6^{(-p)}\, p\, 2^{(p+1)} - 2^{p}\, 6^{(-p+1)}\, p - 2^{p}\, 6^{(-p+1)}}{p+1} \right) - e - p$$

>

Computations of the expected private net revenue with social values of e and p

>

>

```
> R2:=subs(e=0.16,p=1.526555674,R1);
```

>

$$R2 := 1.938953400 - .1496192489\, d - .8400000003\, D + .05449894303\, (D+2)^{1.526555674}\, D + .1089978861\, (D+2)^{1.526555674} - .03292849295\, (D+2)^{2.526555674}$$

>

```
> C2:=subs(e=0.16,p=1.526555674,C1);
>
```

$$C2 := .1600000000\, d + .8400000000 \left(1 - \left(\frac{1}{6} D + \frac{1}{3} \right)^{1.526555674} \right) D + .03292849294\, (D+2)^{2.526555674} - .1089978861\, (D+2)^{1.526555674} - 1.562267946$$

\>

The first order conditions associated to d and D are dR2/dd=0 and dR2/dD=0. Notice that dR2/dd= - 0.1496192489, so that d is entirely defined by C2=0 for a given value of D. In what follows, we choose an arbitrar value of D and we look at the optimal value of d.

```
>
>
> C3:=solve({C2=0},{d});
>
```

$$C3 := \left\{ d = -5.250000000\, D + 5.250000000\, D\, (.1666666667\, D + .3333333333)^{\frac{763277837}{500000000}} - .2058030809\, (D + 2.)^{\frac{1263277837}{500000000}} + .6812367881\, (D + 2.)^{\frac{763277837}{500000000}} + 9.764174663 \right\}$$

\>

Assumption: D=2

```
> subs(D=2,C3);
>
```

$$\{ d = 3.740043099 \}$$

```
>
> R3:=subs(D=2,d=3.740043099,R2);
>
```

$$R3 := .4155099077$$

```
>
> C4:=subs(D=2,d=3.740043099,C2);
```

$$C4 := 0$$

\>

Computations of the expected private net revenue with private values of e and p

>

>

Here we show that there exists at least one couple (e,p) satisfying private e>social e and private p<social p that yields a private expected net revenue (R5) higher than that obtained with the social values of e and p (R3). Still there D is fixed at 2 and d is computed from C4=0.

>

>

```
> R4:=subs(e=0.2,p=1.486555674,R1);
>
```

$$R4 := 1.937340480 - .1664170638\, d - .8211145617\, D + .05723195713\,(D+2)^{1.486555674}\, D + .1144639143\,(D+2)^{1.486555674} - .03421539743\,(D+2)^{2.486555674}$$

```
>
> C4:=subs(e=0.2,p=1.486555674,C1);
>
```

$$C4 := .1788854382\, d + .8211145618\left(1 - \left(\frac{1}{6}D + \frac{1}{3}\right)^{1.486555674}\right)D + .03421539740\,(D+2)^{2.486555674} - .1144639142\,(D+2)^{1.486555674} - 1.557562047$$

```
>
> C5:=solve({C4=0},{d});
>
```

$$C5 := \left\{ d = -4.590169944\, D + 4.590169944\, D\,(.1666666667\, D + .3333333333)^{\frac{743277837}{500000000}} - .1912698862\,(D+2.)^{\frac{1243277837}{500000000}} + .6398727328\,(D+2.)^{\frac{743277837}{500000000}} + 8.707036541 \right\}$$

>

Assumption: D=2

```
> subs(D=2,C5);
>
```

$$\{ d = 3.567996813 \}$$

```
>
> R5:=subs(D=2,d=3.567996813,R4);
>
```

$$R5 := .4242655537$$

```
> C6:=subs(D=2,d=3.567996813,C4);
```

$$C6 := -.6\ 10^{-9}$$