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Public Regulation of Agricultural Biotechnology Field Tests

Economic Implications of Alternative Approaches

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Abstract

Federal regulation and oversight of agricultural biotechnology field testing are based on public concerns that unknown consequences or hazards could arise from such tests, and that private firms may not adequately consider the public consequences of their research and development activities. In this paper, four general types of regulatory approaches to limit public risks from field testing are explored: a fixed-cost regulatory standard, a marginal-cost standard, a property rule (environmental bond), and a liability rule. Our analysis shows that the four approaches are least effective at facilitating the research process while controlling public risks when the research firm is small (defined by wealth relative to potential returns) and the potential damages from the firm's activities exceed the value of the firm. Thus, public regulation of risk is most difficult for small and private biotechnology research firms, the very firms that are playing a central role in bringing new agricultural biotechnologies to market.

Keywords: Biotechnology, regulation, externality

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Introduction

The Food Security Act of 1985 authorized the Secretary of Agriculture to establish "appropriate" controls over the development and use of biotechnology in agriculture. Since that time, the U.S. Department of Agriculture (USDA), in conjunction with other Federal agencies, university officials, and private industry, has attempted to define "appropriate" controls and procedures for their implementation. The need for such controls was based on public concerns that unknown consequences or hazards could arise from agricultural biotechnology field tests, and that private firms may not adequately consider the public consequences of their research and development activities. For example, genetically altered microbes could escape from containment facilities of a field test and unexpectedly harm nearby fields. Modified crops with new specific traits, such as herbicide resistance, drought resistance, or pest resistance, could develop weedy cousins that take over local ecosystems and increase control costs.

Based on the National Institutes of Health's (NIH) "Guidelines for Research Involving Recombinant DNA Molecules" (NIH, 1986), the Office of Science and Technology Policy (OSTP) published the "Coordinated Framework for Regulation of Biotechnology" (Coordinated Framework) (OSTP, 1986). The Coordinated Framework, which outlines the Federal plan for regulating uses of biotechnology, was intended to guide researchers in the safe development of biotechnology.[1] However, the Coordinated Framework focused on laboratory testing while virtually ignoring field testing (USDA, March 1990).

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[1]The Coordinated Framework generally identifies the permits that may be needed from various agencies to conduct biotechnology experiments. The main agencies responsible for regulating agricultural technologies are USDA's Animal and Plant Health Inspection Service (APHIS), through various regulations for plants, seeds and weeds, and animal biologics; and the Environmental Protection Agency (EPA), through the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Toxic Substances Control Act (TSCA).

USDA's Office of Agricultural Biotechnology (OAB) also developed the "Guidelines for Research with Genetically Modified Organisms Outside Contained Facilities," which apply to institutions receiving any USDA support for research with genetically modified organisms (USDA, May 1990). While OAB recommendations under the guidelines are not binding on an institution or a private company, ignoring the OAB's recommendations might increase a company's liability should something go wrong with the experiment. Conversely, if the institution or company follows OAB recommendations, "those extra steps could be seen as 'reasonably prudent' should an unforeseen negative consequence result from the actual field trial" (USDA, March 1990, p. 6).

Despite Federal efforts, however, a unified approach for regulating biotechnology field testing has not been developed or implemented. How companies will gain approval to market some products developed, using modern methods of biotechnology, also remains unclear. As a result, some companies have decided to avoid using such methods in product development. A consistent and coordinated regulatory environment is necessary to reduce costs and uncertainty associated with the regulatory environment while assuring adequate protection for the environment and human health (General Accounting Office [GAO], 1988; National Research Council [NRC], 1989).

This paper explores how different policies alter a firm's incentive to conduct research and allocate funds to existing and new research and development activities. Within the context of a stylized model of the firm, we specifically analyze four general public policies for regulating the possible damage that might result from biotechnology field testing: a fixed-cost regulatory standard, a marginal-cost standard, a property rule, and a liability rule. While not addressed in this paper, the model can be easily extended to analyze the joint use of two or more policies. We focus on the case where only the firm can take precautionary action to reduce the externality. In field testing, this approach makes sense because the institute conducting the experiment has control over the test and any externality that the test produces. The case of unilateral accidents, where the firm's behavior alone affects risks, seems most relevant to environmental and technological policy when damage directly to the ecosystem is of concern or when potentially damaged parties do not know they are being exposed to risk.

Our analysis shows that the four approaches are least effective at controlling public risks and maintaining incentives to conduct the research activity when the research firm is small (defined by wealth relative to the potential benefits from the activity), the return to the new research activity is uncertain, and the potential damage from the firm's activities exceeds the value of the firm. Because the plant agricultural biotechnology industry includes smaller private firms, public regulation of risk is perhaps most difficult for the very firms that are playing a central role in bringing new agricultural biotechnologies to the market.

The remainder of the paper consists of three sections. First, we briefly review previous literature, introduce the basic model of the firm, and derive the efficient allocation of resources for the unregulated risk-neutral firm and for society. Second, we analyze how the alternative policies influence the allocation of wealth by the firm and the level of public risk. Conclusions, implications for the research and development community, and suggestions for future research are contained in the final section.

The Unregulated Firm and Society

Much of environmental economics and the integration of law and economics are devoted to studying the appropriate means of regulating potentially hazardous activities (such as pollution). Previous studies have analyzed two general types of ex ante policies for controlling stochastic externalities: a marginal pollution tax on firm choices equal to the expected marginal social damage, or a constraint on firm pollution equal to the expected social optimum (Fishelson, 1976; Watson and Ridker, 1984; Weitzman, 1974; White and Wittman, 1983; Yohe, 1976, 1978). In the end, either approach could be preferred depending on the shape of the expected benefit and cost functions.

Recognizing the stochastic and sequential nature of many externalities, another group of articles have analyzed the use of ex ante regulation and ex post liability to induce firms to internalize environmental risks (Johnson and Ulen, 1986; Rizzo, 1980; Segerson, 1986; Shavell, 1980, 1984a, 1984b, 1987; White and Wittman, 1983). For example, under a regulatory standard, a firm must comply with the standard--spend a certain amount on "safety"--before conducting an activity. Under strict liability for harm done (externalities created), the firm compensates injured parties only if an accident occurs and if the firm is successfully sued. Another form of liability is a negligence approach, where the firm may not be held responsible for any damage if it follows stipulated standards or guidelines. Characteristic of the literature on liability is that either safety decisions of the firm are assumed to be separable from its main economic activities, so that the firm's objective is to minimize the cost of care (Johnson and Ulen, 1986; Segerson, 1986; Shavell, 1984a; Tietenberg, 1989), or the firm is assumed to earn certain returns from a single activity (Shavell, 1980, 1987).

The Basic Model of the Firm

In contrast to existing studies, we explicitly consider the preventive-type incentives for a firm with the opportunity to engage in a new research activity with uncertain benefits and externalities; that is, field testing of crops produced using modern biotechnology methods. Thus, we analyze the case where (1) safety decisions are not separable from the main activities of the firm, (2) the firm engages in a riskless existing activity and a risky new activity, and (3) the firm has a fixed amount of initial wealth or research budget at its disposal. The case analyzed here, while a simplification of the real world, captures the decision problem facing research and development (R&D) firms in the biotechnology industry. In general, R&D firms engage in multiple research projects. Some R&D projects, such as further development of existing products, may offer relatively certain returns and pose little risk, while the returns to the firm and the potential for harm may be much more uncertain for more basic experiments.[2] On the other hand, the risks of harm

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[2]Randomness in benefits and externalities is common to many industries, not just biotechnology R&D, due to biological or geological uncertainties (for example, the spatial distribution of mineral reserves and animal populations) and weather. Another example in agriculture is the use of pesticides. While multiple cropping is common and pesticide application rates vary across crops, certain crops are more likely to be associated with off-site environmental problems such as water pollution. The returns to farmers from using pesticides as well as the off-site damage depend on application rates, biological characteristics of the farm, and weather (rainfall and wind).

associated with applied field testing of new crop varieties developed with modern biotechnology methods are considered to be more risky than varieties created through traditional breeding methods. It is primarily these two methods, traditional versus modern biotechnology, that represent the riskless and risky activities of plant breeding firms.

The allocation of firm wealth among existing and new research activities is a classic portfolio-allocation problem. For example, consider an R&D firm with initial assets (or research budget) of $x > 0$ that has the opportunity to conduct a riskless and a risky activity. The riskless activity earns a constant marginal rate of return of r on each dollar with no possibility of external damages. Examples of riskless activities include field testing of traditional varieties or a riskless financial asset. The risky activity, which involves field testing a new product developed with biotechnology methods, earns a reward equal to B with a probability of success $p(\bullet)$, where $p(\bullet)$ is an increasing and concave function of firm assets allocated to the risky activity.[3] The risky activity can also cause damage outside the firm equal to h with probability $d(\bullet)$, where $d(\bullet)$ is an increasing and convex function of firm assets allocated to activity 2.[4] Modeling uncertainty in the research process and the externality process as independent Bernoulli distributions with parameters $p(\bullet)$ and $d(\bullet)$ provides enough generality while retaining clear implications of the model. Such assumptions are common on the cost side of the problem, as in Shavell (1984a) or Tietenberg (1989), and could be easily generalized.

The structure of the model developed here is a straightforward generalization of existing models that focuses on minimizing the cost of safety precautions for the risk-neutral firm (Shavell, 1984a; Johnson and Ulen, 1986; and Tietenberg, 1989). However, the model is specifically designed to illustrate how a firm with the opportunity to conduct a particular research project responds to different regulatory approaches. Of course, since the cost of various R&D programs varies widely, different sized firms will generally select from a different set of projects.

While it is assumed that the probability functions $p(\bullet)$ and $d(\bullet)$ depend only on the amount of money allocated to the risky activity, the probability functions could be written more generally as $p(\mu_1 x)$ and $d(\mu_1 x, \mu_2 x)$, where μ_1 is the percentage of assets allocated to the risky activity, μ_2 is the percentage of assets allocated to safety activities, and $1-\mu_1-\mu_2$ is allocated to the riskless activity. The function $d(\bullet)$ would be increasing in μ_1 and decreasing in μ_2, with $d(\bullet)$ convex. For some problems, safety activities may impede the productivity of the resources allocated to the risky activity, or a reduction in potential damage can only be obtained by using a different and less productive technology. In such cases, the probability of success could also be written as $p(\mu_1, \mu_2)$, where $p(\bullet)$ is increasing μ_1, nonincreasing in μ_2, and concave.

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[3]While we use the term "risky" activity, the probability distributions may not be known with certainty and, therefore, the model could involve decisionmaking under uncertainty or risk.

[4]Because h is constant and $d(\bullet)$ depends only on firm actions, only the incentives for safety or precaution of the firm are considered. Thus, injured parties cannot take precautionary actions to reduce the level of harm.

To clarify the analysis without changing the basic qualitative nature of the analysis, although magnitudes will vary, we assume that resources allocated to safety activities substitute for resources allocated to the risky activity in the probability of damage function d(•). Thus, the firm implicitly chooses $\mu_2 = 0$ and controls the probability of damage through the allocation of resources to the risky activity. For example, situations of easy substitution in the probability of damage function occur in biotechnology field testing: the size of the experiment can be reduced but containment facilities and other safety activities can also be reduced, leaving the probability of damage relatively constant.

In summary, the following notation and assumptions are used throughout the paper:

- x = Firm wealth.
- B = Benefits from activity 2 if the firm is successful, or else zero benefits.
- $(1+r)$ = Riskless return on each dollar allocated to activity 1.
- μ = Percentage of firm's assets allocated to activity 2, where $0 \leq \mu \leq 1$.
- $p(\mu x)$ = Probability of success in activity 2, and $p'(\mu x)>0$ and $p''(\mu x)<0$.
- h = Harm if accident occurs.
- $d(\mu x)$ = Probability of accident from activity 2, and $d'(\mu x)>0$ and $d''(\mu x)>0$.

Allocation of Resources for the Unregulated Firm

In the absence of regulations, a firm has no incentive to internalize the possibility of damage from its actions into the decisionmaking process. In other words, the prevailing institutional environment protects the right of the firm to impose harm on other parties. Such a situation is often designated as one of zero liability for the firm (see Coase, 1960; and Randall, 1974). The firm is assumed to be risk-neutral and allocates wealth between the riskless and risky activities to maximize expected profits. The expected profit-maximization problem of the firm is:

$$\max_{0 \leq \mu \leq 1} \quad (1+r)(1-\mu)x + p(\mu x)B, \qquad (1)$$

where the first term in (1) is income from the riskless activity, and the second term is the expected return from the risky activity.

Assuming an interior solution, the first-order condition for expected profit maximization can be rearranged to yield:

$$(1+r) = p'(\mu^f x)B, \qquad (2)$$

where $\mu^f = \mu^f(1+r,x,B)$ is the firm's optimal percentage of assets allocated to the risky activity, which is decreasing in 1+r and x and increasing in B (see appendix 1, part A). Concavity of p(•) ensures second-order conditions for a maximum are satisfied at an interior solution. Equation (2) has the usual interpretation that the firm equates the marginal rate of return for the riskless activity to the marginal expected benefits for the risky activity. A corner solution $\mu^f = 0$ ($\mu^f = 1$) exists when the rate of return on the riskless activity is everywhere greater (less) than the expected marginal benefits from the risky activity.

Allocation of Resources for Society

We consider the case where a risk-neutral society maximizes the sum of expected net benefits from riskless and risky activities.[5] While the structure of social preferences is beyond the scope of this paper, the net-benefit objective remains a basis for comparing alternative regulatory approaches found in earlier works.

The expected net-benefit maximization problem for society is:

$$\underset{0 \leq \mu \leq 1}{\text{maximize}} \quad (1+r)(1-\mu)x + p(\mu x)B - d(\mu x)h, \tag{3}$$

where the terms in (3) are returns from riskless and risky activities and expected harm from the risky activity.

The first-order condition for society's problem can be rearranged to yield:

$$(1+r) = p'(\mu^s x)B - d'(\mu^s x)h, \tag{4}$$

where $\mu^s = \mu^s(1+r,x,B,h)$ is society's optimal investment choice, which is decreasing in 1+r, x, and h, but increasing in B (see appendix 1, part B). Concavity of $p(\bullet)$ and convexity of $d(\bullet)$ ensure that second-order conditions are satisfied at an interior solution. Equation (4) has the usual interpretation that society equates the return from the riskless activity to the expected marginal net-social benefits from the risky activity.

Equations (2) and (4) identify the dilemma facing society and policymakers. Society values the benefits from both riskless and risky activities, but wants to limit its exposure to harm. As potential harm grows relative to potential benefits, society may refrain from allocating resources to the risky activity. Thus, the regulatory question involves designing institutions that provide the incentives for the firm to include expected damages $d(\mu x)h$ from the risky R&D activity.

Approaches for Controlling Public Risk

In the absence of a regulatory authority that can force a firm to allocate funds according to some social optimum, indirect methods must be used to provide the incentives for the firm to internalize potential externalities from the risky activity. The model is now used to examine four approaches: a fixed-cost regulatory standard, a marginal-cost regulatory standard, a property rule, and a liability rule. We also assume that a regulatory body can enforce each rule. However, when enforcement of a standard or property rule is imperfect, the use of liability contingent on following a regulatory standard or property rule can be considered a negligence rule. Two conditions

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[5]Because benefits and costs do not fall on identical parties, in which case the utility effects are not comparable, we do not imply that expected net benefits should be society's welfare criteria.

must be met for a firm to be liable for damages under a negligence rule (Kahan, 1989). First, the firm must have acted "negligently;" that is, in this paper, the firm must not have followed the regulatory standard. And second, an accident must occur and the firm must have caused the accident. Thus, ignoring a standard is not sufficient for there to be negligence. A standard may not be enforced simply because a regulatory agency does not monitor the firm. Even though negligence could be proven afterward, a firm may decide to ignore a standard because the risky activity may still not cause any damage. While not explicitly considered in this paper, the model could also be generalized to analyze the joint use of ex ante and ex post institutional approaches, such as a standard combined with a liability rule.

A Fixed-Cost Regulatory Standard

Consider first the case of a fixed-cost regulatory standard. Let q represent the cost of following the standard to conduct the risky activity. Such a cost directly reduces a firm's assets available for risky and riskless activities. Thus, the expected-profit maximization problem of the firm becomes:

$$\underset{0\leq\mu\leq 1}{\text{maximize}} \quad (1+r)(1-\mu)(x-q) + p(\mu(x-q))B, \qquad (5)$$

where the first term is income from the riskless activity, the second term is expected returns from the risky activity, and μ should be interpreted as the percentage of assets (x-q) allocated to the risky activity. Although q is a fixed cost of conducting the risky activity, the level of q reduces firm wealth which in turn affects the firm's choice of μ. The firm will allocate funds to the risky investment according to the optimum in equation (5) as long as the resulting expected profit is greater than (1+r)x. Thus, it is possible that a standard could drive the firm out of the risky activity altogether, even though some level of the activity is socially desirable.

At an interior optimum, the first-order condition to (5) can be rearranged to yield:

$$(1+r) = p'(\mu^n(x-q))B, \qquad (6)$$

where $\mu^n = \mu^f(1+r,x-q,B)$ is the firm's optimal investment decision under the standard, which is decreasing in r and x and increasing in B and q (see appendix 1, part C).

When $0<\mu^n<1$, equations (2) and (6) imply that $1+r = p'(\mu^n(x-q))B = p'(\mu^f x)B$, which implies that $\mu^f x = \mu^n(x-q)$ and the total level of investment in the risky activity under a standard remains equal to the level of investment for the unregulated firm. To maintain this equality of the marginal rates of return across the two activities, the firm under a regulatory standard must increase the percentage of its remaining assets to the risky activity. It should be emphasized that a corner solution where $\mu^n = 0$ remains a distinct possibility. Thus, all else equal, firms smaller than a minimum size x', where $p(x-q)B < (1+r)x$ for all $x < x'$, will find it unprofitable to conduct the risky activity under a regulatory standard.

Since the level of investment in the risky activity remains the same with or without the standard at an interior solution, society also faces the same amount of risk (that is, $d(\mu^f x) = d(\mu^n(x-q))$). This result, while extreme in quantitative magnitude, is qualitatively similar to a result in Segerson

(1986) and focuses on a very important feature of a standard approach. The firm's ability to substitute around a standard to equalize rates of return across activities determines the effectiveness of a fixed-cost standard in reducing public risk. In Segerson (1986), where standards are placed only on observable actions of the firm, a regulatory standard provides the incentive to substitute into unobservable actions. Thus, the degree of substitution in the probability function d(•) between directly productive activities and safety activities determines how effective the standard is in reducing risk. Of course, at a corner solution where $\mu^n = 0$, society faces no risk from the firm's activities.

A Marginal-Cost Regulatory Standard

The second approach is a constant marginal-cost regulatory standard, where a firm pays a fixed amount τ per unit of investment in the risky activity. Thus, if μx is invested in the risky activity, the firms pays $\tau\mu x$ in tax, and invests $(1 - \mu - \tau\mu)x$ in the riskless activity. Thus, the cost of following the standard increases with the investment in the risky activity.

For example, USDA guidelines state that the four levels of confinement (the physical barriers to limit the release of an organism to the environment) correspond to five levels of safety concerns identified in the document (USDA, May 1990). The NIH guidelines refer to four levels of containment, with level four being the most restrictive and costly (NIH, 1986). While both guidelines refer to the "safety" of the experiment, one way to improve safety is to reduce the size of the field test, either by "decreasing the number of organisms used in the experiment or decreasing the land area" (USDA, March 1990, p. 32). In terms of the model outlined here, an improvement in safety is obtained through a reduction in investment in the risky R&D activity.

The firm's expected-profit maximization problem becomes:

$$\max_{\mu} \quad (1+r)(1-\mu-\tau\mu)x + p(\mu x)B \qquad (7)$$
$$\text{subject to } 1/(1+\tau) \geq \mu \geq 0,$$

where the constraint ensures the firm does not violate the budget constraint.

Assuming an interior solution, the first-order condition can be rearranged to yield:

$$(1+r) = p'(\mu^{\tau}x)B - \tau(1+r), \qquad (8)$$

where $\mu^{\tau} = \mu^{\tau}(1+r,x,B,\tau)$ is decreasing in 1+r, x, and τ is increasing in B (see appendix 1, part D). The firm allocates funds to the risky investment according to equation (8) as long as expected profit at the optimum in (7) is greater than (1+r)x.

Due to the wealth constraint of the firm, the marginal-cost standard implies an equal reduction in wealth (τ) as well as the opportunity cost of the lost investment from that wealth (τr). Thus, the total marginal cost of the standard is equal to $\tau(1+r)$. Equation (8) shows that investment under the marginal-cost standard is always less than that for the unregulated firm or for the fixed-cost standard.[6]

A Property Rule (Environmental Bond)

With a property rule, the firm must post a bond S to conduct the risky activity, which is returned with interest if no accident occurs.[7] Because the firm would like to retain ownership of the bond S, the property rule partially eliminates the incentive to increase the amount of available wealth allocated to the risky activity found in the fixed-cost standard approach.

Under the property rule, the expected-profit maximization problem of the firm becomes:[8]

$$\max_{0\leq\mu\leq 1} \quad (1+r)(1-\mu)(x-S) + p(\mu(x-S))B + [1-d(\mu(x-S))](1+r)S, \qquad (9)$$

where the first two terms in (9) are the returns from the riskless investment and the expected returns from the risky activity, and the last term is the amount the firm expects to have returned after conducting the risky activity. From the firm's point of view, the bond is equivalent to allocating a predetermined amount in a third asset with an uncertain rate of return $(1+r)(1-d(\mu(x-S))) < (1+r)$.

Assuming an interior solution, the first-order condition for the firm under a property rule can be rearranged to yield:

$$(1+r) = p'(\mu^p(x-S))B - S(1+r)d'(\mu^p(x-S)), \qquad (10)$$

where $\mu^p = \mu^p(1+r, x-S, B, (1+r)S)$ is decreasing in 1+r and x, increasing in B, and indeterminant in S (see appendix 1, part E). The firm will conduct the risky activity according to equation (10) as long as profits at the optimum in equation (9) are greater than $(1+r)x$.

The allocation of funds under a property rule can be readily compared with firm choices under a regulatory standard and society's net-benefits problem.

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[6]The marginal-cost standard can also be interpreted as a marginal-tax rule. Note, however, from equations (4) and (8), that the optimal tax, when the firm has a wealth constraint, is $\tau^* = d'(\mu^s x)h/(1+r)$. Thus, at society's optimum and in the presence of constained firm wealth, the optimal tax is less than expected marginal social damage.

[7]We use the term "property rule" following Bromley (1978) and Calabresi and Melamed (1972). In other words, under the property rule, a firm cannot interfere with society's entitlement to not be exposed to the risky activity unless the firm pays prior compensation (insurance in this case) in the form of the bond.

[8]Another type of property rule could specify a bond S that must be posted before conducting the risky activity, but the firm is reimbursed $S(1+r)-h$ if an accident occurs when $S(1+r)>h$, and the firm is liable for the additional amount $h-S(1+r)$ if an accident occurs when $h>S(1+r)$. For brevity, only one type of property rule is examined here. A variable bond rule of $S(\mu x)$ could also be considered, where $S'(\mu x)>0$.

First, assuming interior solutions, equations (6) and (10) imply that $p'(\mu^n(x-q))B = 1+r = p'(\mu^p(x-S))B - d'(\mu^p(x-S))S(1+r)$. Rearranging, $p'(\mu^p(x-S)) - p'(\mu^n(x-q)) = (S/B)(1+r)d'(\mu^p(x-S)) > 0$, due to $d'(\bullet)>0$. As a result, due to $p'(\bullet)>0$ and the concavity of $p(\bullet)$, $\mu^p(x-S) < \mu^n(x-q)$. Thus, with interior solutions, total investment in the risky activity under a property rule with bond S is less than total investment under a standard with costs q, and expected damage is less under the property rule than the regulatory standard.

Second, assuming interior solutions and a bond of $S = h/(1+r)$, equations (4) and (10) imply that $p'(\mu^s x)B-d'(\mu^s x)h = 1+r = p'(\mu^p(x-S))B-d'(\mu^p(x-S))h$, which can occur only when $\mu^s x = \mu^p(x-S)$. Thus, when the bond is set such that $S = h/(1+r)$, total investment in the risky activity under the property rule is equal to the social optimum. As a result, investment in the risky activity and expected damage are larger than socially desirable under a property rule for levels of S below the value $h/(1+r)$, and vice versa.

A Strict Liability Rule

Under a strict liability rule, the firm pays compensation for damage if an accident occurs and if the firm is successfully sued (with probability t). Previous literature on liability recognizes that bankruptcy laws or finite firm assets may reduce the incentives for precaution (Cooter, 1986; Johnson and Ulen, 1986; Rizzo, 1980; Shavell, 1980, 1984a, 1984b, 1987). In effect, firm decisions do not influence the maximum amount of compensation that the firm can pay. Thus, two cases are considered: one where the firm can compensate fully for damages, and one where the firm cannot.

In the model analyzed here, the firm's final wealth position is random before decisions are made. As a result, the firm's ability to pay compensation is also random. If h is the level of damage caused by the risky activity when an accident occurs, the potential compensation the firm can pay under strict liability is $\min[h,(1+r)(1-\mu)x]$ if the risky activity is not successful and $\min[h,(1+r)(1-\mu)x + B]$ if successful.

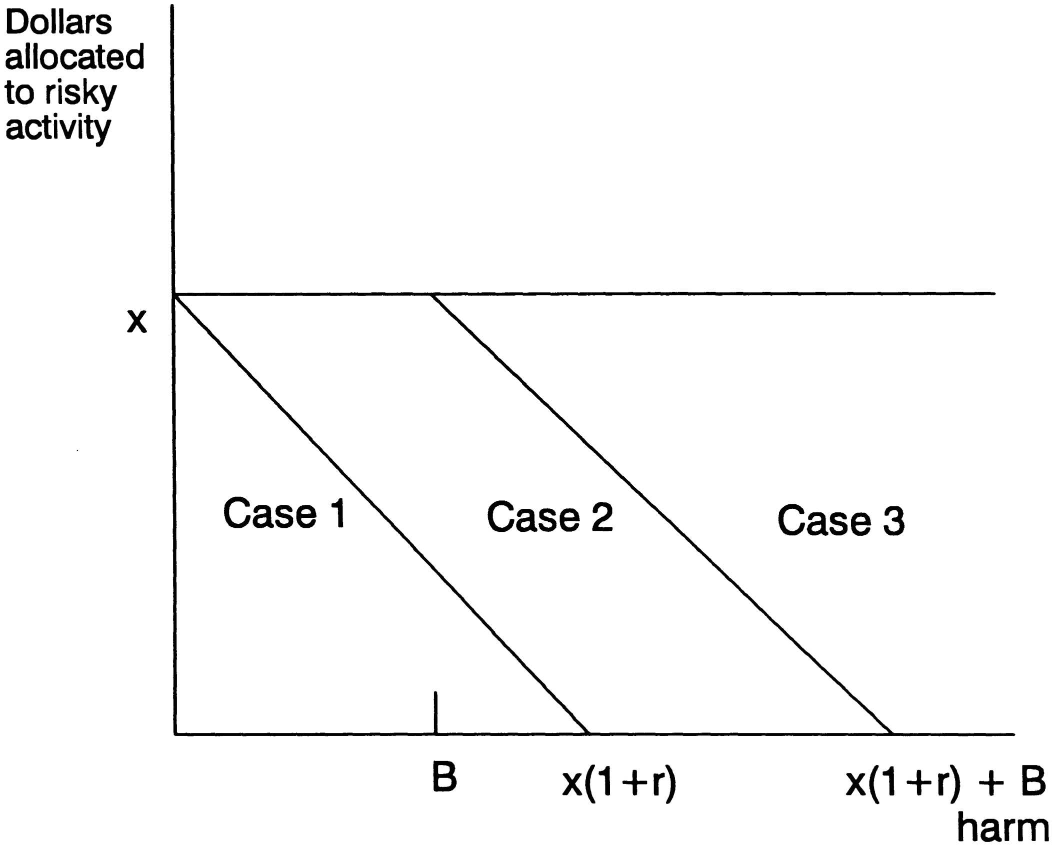
In effect, three situations may be relevant for the firm and society after the risky activity is conducted. As shown in figure 1, the relevance of these three cases depends on the size of the firm (x), the potential return from the risky activity (B), the riskless rate of return (1+r), and the potential harm (h). In case 1, the firm is always able to compensate fully for harm after conducting the risky activity and $0 \le h \le (1+r)(1-\mu)x$. In case 2, the firm is only able to compensate fully for harm if it is successful in the risky activity and $(1+r)(1-\mu)x \le h \le (1+r)(1-\mu)x + B$.[9] And, in case 3, the firm is not able to compensate fully for harm even if it is successful in the risky activity and $(1+r)(1-\mu)x + B \le h$.[10]

In general, to determine the optimal allocation of wealth under the liability rule, the firm must solve:

[9]The line separating case 1 from case 2 in figure 1 is defined by $f(h) = x - h/(1+r)$ for $0 \le h \le x(1+r)$.

[10]The line separating case 2 from case 3 is $g(h) = x - (h-B)/(1+r)$ for $B \le h \le x(1+r) + B$.

Figure 1
Three cases under liability



x = Size of the firm.
B = Potential return from the risky activity.
1+r = The riskless rate of return.

$$\max_{0\leq\mu\leq1} \quad (1+r)(1-\mu)x + p(\mu x)B - d(\mu x)t\{p(\mu x)\min[h,(1+r)(1-\mu)x + B] + (1-p(\mu x))\min[h,(1+r)(1-\mu)x]\} \tag{11}$$

where the first two terms are expected income from the riskless and risky activities, $d(\mu x)t$ is the joint probability of an accident and being successfully sued, and the last term is expected liability from conducting the risky activity. As shown in appendix 2, the firm's decision problem (11) can be analyzed as follows. Given the parameters of the problem, the firm first chooses for each case that is possible the optimal μ_i^1, where i = 1, 2, 3, for the three cases. From this set of μ_i^1's, the firm then chooses the μ_i^1 that maximizes overall expected profits.

The firm's optimal choice in case 1, where full compensation is possible, is essentially the standard result for a strict liability rule (Shavell, 1984a) when bankruptcy or limited liability is not an issue. The firm's first-order condition in case 1 is identical to society's decision rule (4) except that expected liability is now only th because the firm is not sued with certainty.

Thus, resources allocated to the risky activity under a liability rule for case 1 are greater than for society's expected net-benefit criteria.[11] However, investment in the risky activity in case 1 is less than that for the unregulated firm and for the firm under the regulatory standard. A strict liability rule in case 1 is also equivalent to a property rule where the bond is set such that $S = th/(1+r)$.

The firm's first-order condition for case 2, where full compensation for damage is possible only if the firm is successful, and the first-order condition for case 3, where full compensation is never possible, show how the presence of random firm wealth complicates the standard liability results. In case 2 expected liability is equal to $t\{p(\mu_2 x)h + (1 - p(\mu_2 x))(1+r)(1-\mu_2)x\}$, while in case 3 expected liability is equal to $t\{p(\mu_3 x)B + (1+r)(1-\mu_3)x\}$. Because expected liability falls from case 1 to case 2 to case 3, one would expect that the allocation of wealth to the risky activity should increase in cases 2 and 3 relative to case 1. In fact, from figure 1, this intuition is directly validated. For example, cases 1 and 2 are possible when $h \leq B$. For any level of $h \leq B$, the allocation of assets to the risky activity for case 1 must be less than that for case 2. All three cases are possible when the level of harm is in the range $B \leq h \leq x(1+r)$, which implies that the allocation of assets to the risky activity is lowest for case 1 and greatest for case 3. When the level of harm is in the range $x(1+r) \leq h \leq x(1+r)+B$, cases 2 and 3 are possible, and the allocation of assets to the risky activity for case 2 must be less than that for case 3. Only case 3 is possible when $x(1+r)+B \leq h$.

For the multiactivity firm under uncertainty, random firm wealth and the option of bankruptcy can dilute the incentives for safety beyond what is already recognized in the literature. The incentives for safety also fall as the size of the firm falls relative to the returns that it seeks. Thus, the results in this section are qualitatively similar to earlier studies (see, for example, Shavell, 1987), but the magnitude of this dilution grows as potential benefits and/or harm increase in relation to firm wealth. A firm that is wealthy relative to h and B will probably choose μ_1^1 or μ_2^1, generating a case 1 or case 2 outcome. However, all three cases may be relevant for medium-size firms relative to h and B. Cases 2 or 3 may be most relevant for the smallest firms relative to h and B. Research is needed to consider the relative importance of the three cases for different situations--types and location of firms in various industries, and how liability might provide the incentives to conduct certain risky activities in a small-firm setting.

Conclusions

This paper examines the effects of alternative policies for controlling public risk by the allocation of resources by firms. In contrast to previous literature, the model presented here shows that the firm conducts a riskless activity and has the opportunity to conduct a new and potentially risky activity, safety decisions of the firm are not separable from its main income-

[11]As Shavell (1984a) notes, a liability rule of the form h/t creates the incentive to allocate resources according to the social net-benefit criterion.

generating activities, the firm has a wealth constraint, and both the direct benefits to the firm and externalities from the risky activity are stochastic.

Standards and property rules are possible policies with which a firm must comply before a certain activity can be conducted. A fixed-cost standard specifies certain safety measures and technical practices that the firm must follow, regardless of the level of investment in the risky activity. A marginal-cost standard requires the firm to follow certain safety measures and technical practices, which increase with the level of investment in the risky research and development activity. The property rule requires the firm to post a lump-sum bond prior to conducting the risky activity, which is then returned with interest to the firm if no harm occurs. If an accident occurs, the bond is used to pay for damage.

Under both standards and property rules, prior bargaining over the appropriate safety procedures or the level of bond takes place between the firm, the regulatory body, and other concerned parties of whom the firm's activities may benefit and/or harm. Standards place the responsibility for safety on the regulatory body, since it defines the procedures that a firm must follow. The fixed-cost regulatory standard is similar to the safety regulation in Shavell (1984a), which requires the firm to spend a required amount of money on "care." However, since the firm loses wealth to safety measures, whether or not an accident occurs, the firm has the incentive to increase the allocation of its remaining assets to the risky activity to equalize the rates of return among its two activities.

A property rule places the responsibility for safety on the firm, since it decides on the appropriate safety strategy. Since the firm loses access to assets directly through the bond, but loses ownership only if an accident occurs, the firm internalizes how its decisions influence the probability of success and the probability of damage to other parties. However, unlike a standards approach, the firm can be expected to conduct cost-minimizing safety strategies under the property rule.

Legal liability is an ex post enforcement mechanism. The liability rule considered here is strict liability, which places the full responsibility for damage on the firm if it is successfully sued. The liability rule is identical to that in Shavell (1984a), and similar to that in Segerson (1986) and Johnson and Ulen (1986), with one fundamental exception. In previous models, the possibility of bankruptcy is not explicitly analyzed or the firm is liable only up to a given level of assets that are independent of a firm's decisions. In other words, decisions of the firm do not alter its ability to compensate for damages after an accident occurs. However, when benefits are random, a firm's decisions affect both the likelihood of an accident and its ability to compensate for any damages. Thus, while the incentives for safety under a liability approach are diluted due to finite firm assets and uncertainty in litigation (Shavell, 1987), legal liability further dilutes the incentives for safety when potential harm and benefits are large relative to initial firm wealth.

Implications for the Biotechnology Industry

Our model shows how the four policy approaches create different incentives to conduct risky research activities. Two important implications for the biotechnology industry follow from this analysis and need to be analyzed further. All of the approaches are least effective at controlling public risks and providing the incentives to conduct the research activity when the research firm is small in size (defined by wealth) relative to the benefits that may follow from the research. For example, under the fixed-cost regulatory standard, a marginal-cost standard, or a property rule, it is very possible that a firm would find a corner solution optimal and allocate no wealth to the risky activity. As a result, public regulation could drive relatively small firms out of the industry--the very firms that are playing a central role in bringing new agricultural biotechnologies to the market.

As described in the USDA guidelines for field testing (USDA, May 1990), USDA has essentially taken the following approach for field testing conducted with public funding: if an accident occurs and the researchers do not follow the research guidelines, then public funding for the research may be withdrawn. However, following the guidelines is not a prerequisite for actually obtaining a permit for field testing, which may be required for certain types of activities, and the exact ex post responsibility for any damage from field tests is unclear.

Directions for Future Research

This paper assumed that a regulatory agency can adequately enforce the different types of policies. However, the costs of implementing and enforcing environmental policies are central to regulation under uncertainty. In the presence of asymmetric and imperfect information, which often implies imperfect enforcement of policies, firms may choose which regulatory regime is preferred through compliance with regulatory standards or a property rule or through noncompliance and the liability regime. Thus, firm decisions can be expected to depend on the design, implementation, and enforcement of the various regulatory mechanisms.

While this paper begins to address the effects of institutional choice on resource allocation by the firm, many issues remain. For example, the property rule suffers from informational problems similar to the liability rule: who proves the firm is responsible for damages and pays the cost of such information, and what if damage is observed only with a delay or is not compensable? In the model developed here, the bond is returned to the firm in the following period if no accident occurs. But in an actual policy setting, especially where human health is an issue, long time lags before damage is observed and low-but-sustained exposures to dangerous substances greatly complicate the decision of when to return the bond to the firm.

In a liability context, suits for damage could be brought at any time when damage is observed, but the damaged party must initiate the suit and pay the initial cost of such litigation. However, there is flexibility for determining burden of proof of damage as well as responsibility. For example, damaged parties may have to prove to the court that a specific firm caused the damage or, on the other hand, a firm may have to prove that its activities did not cause the damage. The issues involved with allocating the burden of proof also arise with a property rule. With respect to toxic waste cleanup under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), joint and several liability is another litigation strategy. Under joint and several liability, one firm can be held responsible for all the damage created by a group of firms. This type of liability could have important implications for joint biotechnology research conducted by private firms and public groups such as universities or government agencies.

The signals for innovation are also transmitted differently under alternative policy approaches. For example, even though the regulatory standards specify certain acceptable production practices, there are in reality many different technologies and strategies that research and development firms can use to control risks, some of which cannot be regulated by public agencies. Thus, a standards approach may constrain the firm's ability to innovate its safety activities (Cooter, 1986), especially since standards can regulate only observable practices (Segerson, 1986), even though less observable activities of the firm may be a less costly means of reducing risk.

Under a property or liability rule, where the firm is responsible for determining its own safety strategy, the incentives for the firm to innovate and use cost-efficient methods may be more direct. In addition, as firms use different technologies and strategies, the process of learning by doing, combined with new experience and better information, will begin to improve the productivity of those technologies.

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Appendix 1: Comparative Statics

This appendix provides the comparative static results for the optimum allocation of resources to the risky activity for the various cases analyzed in the paper.

Part A

The comparative statics of $\mu^f=\mu^f(1+r,x,B)$ for 1+r, x, and B are derived as follows. The differential of equation (2) with respect to μ^f and (1+r) can be rearranged to yield $d\mu^f/d(1+r) = 1/p''(\mu^f x)xB < 0$ due to the concavity of $p(\mu x)$. The differential of equation (2) with respect to μ^f and x can be rearranged to yield $d\mu^f/dx = -\mu^f/x < 0$. The differential of equation (2) with respect to μ^f and B can be rearranged to yield $d\mu^f/dB = -p'(\mu^f x)/p''(\mu^f x)xB > 0$.

Part B

The comparative statics of $\mu^s=\mu^s(1+r,x,B,h)$ for 1+r, x, B, and h are derived as follows. The differential of equation (4) with respect to μ^s and (1+r) can be rearranged to yield $d\mu^s/d(1+r) = 1/(p''(\mu^s x)xB - d''(\mu^s x)xh) < 0$ due to the concavity of $p(\mu x)$ and convexity of $d(\mu x)$. The differential of equation (4) with respect to μ^s and x can be rearranged to yield $d\mu^s/dx = -\mu^s/x < 0$. The differential of equation (4) with respect to μ^s and B can be rearranged to yield $d\mu^s/dB = p'(\mu^s x)/(-p''(\mu^s x)B + d''(\mu^s x)h) > 0$. The differential of equation (4) with respect to μ^s and h can be rearranged to yield $d\mu^s/dh = d'(\mu^s x)/(p''(\mu^s x))B - d''(\mu^s x)h)x < 0$.

Part C

The comparative statics of $\mu^n=\mu^n(1+r,x-q,B)$ for 1+r, x, q, and B are derived as follows. The differential of equation (6) with respect to μ^n and (1+r) can be rearranged to yield $d\mu^s/d(1+r) = 1/[(p''(\mu^n(x-q))(x-q)B] < 0$ due to the concavity of $p(\bullet)$. The differential of equation (6) with respect to μ^n and x can be rearranged to yield $d\mu^n/dx = -\mu^n/(x-q) < 0$. The differential of equation (6) with respect to μ^n and B can be rearranged to yield $d\mu^n/dB = - p'(\mu^n(x-q))/[p''(\mu^n(x-q))B(x-q)] > 0$. The differential of equation (6) with respect to μ^n and q can be rearranged to yield $d\mu^n/dq = \mu^n/(x-q) > 0$.

Part D

The comparative statics of $\mu^\tau=\mu^f(1+r,x,B,\tau)$ for 1+r, x, B, and τ are derived as follows. The differential of equation (8) with respect to μ^τ and (1+r) can be rearranged to yield $d\mu^\tau/d(1+r) = (1+\tau)/p''(\mu^\tau x)xB < 0$ due to the concavity of $p(\mu x)$. The differential of equation (8) with respect to μ^τ and x can be rearranged to yield $d\mu^\tau/dx = -\mu^\tau/x < 0$. The differential of equation (8) with respect to μ^τ and B can be rearranged to yield $d\mu^\tau/dB = -p'(\mu^\tau x)/p''(\mu^\tau x)xB > 0$. The differential of equation (8) with respect to μ^τ and τ can be rearranged to yield $d\mu^\tau/d\tau = (1+r)/p''(\mu^\tau x)Bx < 0$.

Part E

The comparative statics of $\mu^p = \mu^p(1+r, x-S, B, (1+r)S)$ are derived as follows. The differential of equation (8) with respect to μ and (1+r) can be rearranged to yield $d\mu/d(1+r) = [1+Sd']/[Bp''(x-S) - S(1+r)d''(x-s)]$, where the derivatives are evaluated at $\mu^p(x-S)$. The differential of equation (8) with respect to μ and B can be rearranged to yield $d\mu/dB = - p'/[Bp''(x-S) - S(1+r)d''(x-s) > 0$, where the derivatives are evaluated at $\mu^p(x-S)$. The differential of equation (8) with respect to μ and x can be rearranged to yield $d\mu/dx = - \mu/(x-S) < 0$. The differential of equation (8) with respect to μ and S can be rearranged to yield $d\mu/dS = [\mu/(x-s)] + (1+r)d'/[(x-S)(Bp''-S(1+r)d'')]$, where the derivatives are evaluated at $\mu^p(x-S)$.

Appendix 2: Firm Choices Under a Liability Rule

This appendix briefly analyzes the firm's choice problem under a liability rule for the three cases identified in the text.

Case 1

The firm's problem in case 1 becomes:

$$\max_{\mu_1} \quad (1+r)(1-\mu_1)x + p(\mu_1 x)B - d(\mu_1 x)th \tag{12}$$

$$\text{subject to } 0 \le \mu_1 \le 1 - h/(x(1+r)).$$

At an interior solution, the first-order condition for problem (12) can be rearranged to yield:

$$(1+r) = p'(\mu_1^1 x)B - d'(\mu_1^1 x)th \tag{13}$$

where μ_1^1 denotes the optimal choice in state 1.

Case 2

For case 2, since the returns from the firm's activities are random, the firm does not know before the activity whether it will be able to compensate fully for damages if an accident occurs. Thus, the firm's problem in case 2 becomes:

$$\max_{\mu_2} \quad (1+r)(1-\mu_2)x + p(\mu_2 x)B - d(\mu_2 x)t\{ L \} \tag{14}$$

$$\text{subject to } 1 - h/(x(1+r)) \le \mu_2 \le 1 + (B-h)/(x(1+r))$$

where $L = p(\mu_2 x)h + (1 - p(\mu_2 x))(1+r)(1-\mu_2)x$ is expected liability for case 2 if an accident occurs.

Assuming an interior solution, the first-order condition to problem (14) can be rearranged to yield:

$$1+r = p'(\mu_2^1 x)B - d'(\mu_2^1 x)t[L + d(\mu_2^1 x)(1/x)(\delta L/\delta\mu)/d'(\mu_2^1 x)] \tag{15}$$

where μ_2^1 is the optimal choice in case 2, and the sign of $\delta L/\delta\mu = x\{p'(\mu_2^1 x)[h-(1+r)(1-\mu_2^1)x] - [1-p(\mu_2^1 x)](1+r)\}$, which is the partial derivative of L with respect to μ, is in general indeterminant. The objective function in (14) is not necessarily concave at an interior solution. Sufficient conditions to ensure concavity of (14) in μ are $\delta L/\delta\mu \geq 0$ and $\delta^2 L/\delta\mu^2 \geq 0$.[12]

Equation (15) generalizes the standard result on strict liability given constant firm assets to the case where firm wealth is determined by the firm's allocation of wealth. Note that equation (15) takes a very similar form to equation (13), except that the last term in brackets acts as an adjustment to expected liability of the firm L. Thus, while L is expected liability for case 2, the firm acts as if the total term in brackets, $[L - d(\mu_2^1 x)(1/x)(\delta L/\delta\mu)/d'(\mu_2^1 x)]$, is expected net liability.

Case 3

The firm's problem for case 3 becomes:

$$\max_{\mu_3} \quad (1+r)(1-\mu_3)x + p(\mu_3 x)B - d(\mu_3 x)t\{\ M\ \} \tag{16}$$

$$\text{subject to} \quad 1 + (B-h)/(x(1+r)) \leq \mu_3 \leq 1$$

where $M = p(\mu_3 x)B + (1+r)(1-\mu_3)x$ is expected liability for case 3 if damages occur.

Assuming an interior solution, the first-order condition to (16) can be rearranged to yield:

$$1+r = p'(\mu_3^1 x)B - d'(\mu_3^1 x)t[M + d(\mu_3^1 x)(1/x)(\delta M/\delta\mu)/d'(\mu_3^1 x)] \tag{17}$$

where μ_3^1 is the optimal choice for case 3, and the sign of $\delta M/\delta\mu = x\{p'(\mu_3^1 x)B - (1+r)\}$, which is the partial derivative of M with respect to μ, is in general indeterminant.[13]

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[12]The second-order condition for (12) is:

$$p''xxB - d''xxtL - 2d'xt(\delta L/\delta\mu) - dt(\delta^2 L/\delta\mu^2) < 0.$$

[13]The objective function in (15) is also not necessarily concave at an interior solution. Sufficient conditions to ensure concavity of the objective function are $\delta M/\delta\mu \geq 0$ and $\delta^2 M/\delta\mu^2 \geq 0$.

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