Innovation and Regulation in the Pesticide Industry

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This paper examines the impact of pesticide regulation on the number of new pesticide registrations and pesticide toxicity. Results suggest that regulation adversely affects new pesticide introductions but encourages the development of pesticides with fewer toxic side effects. The estimated regression model implies that a 10% increase in regulatory costs (about $1.5 million per pesticide) causes a 5% reduction in the number of pesticides with higher toxicity.

Researchers, such as Headley (1968) and Campbell (1976) have shown empirically that chemical pesticides have played a major role in increasing agricultural productivity. However, there is concern that chemical pesticides may contaminate ground and surface water, have harmful effects on wildlife, leave residues on agricultural products, and cause health risks to farm workers (Harper and Zilberman 1989). These potential side effects have prompted strict regulation.

Critics of chemical pesticide regulation, such as Green, Hartley, and West (1977), assert that the cost of complying with regulations reduces the incentive to develop the new active ingredients needed for use in herbicides, insecticides, fungicides, and other chemical pesticides. Consistent with this view, Gianessi and Puffer (1992) argue that regulatory costs have encouraged firms to register chemical pesticides only for major crop uses, such as corn, and have deterred firms from registering chemical pesticides for minor crop uses, such as fruits and vegetables. Others (Lichtenberg, Spear, and Zilberman 1993) claim that more stringent regulations may result in chemical pesticides with higher toxicity.

Questions of the impact of regulation on registrations, chemical pesticide crop uses, and pesticide toxicity may be closely linked. Greene, Hartley, and West (1977) believe that high regulatory costs reduce the incentive to develop chemical pesticides for minor crop uses and encourage firms to develop chemical pesticides that are effective in controlling many types of pests and in diverse weather conditions. However, these wide-spectrum chemical pesticides are the ones most likely to have more undesirable environmental side effects.

Historical evidence suggests a link between health and environmental testing costs and pesticide development time and the number, type, and toxicity of new pesticide introductions. Between 1970 and 1989, as pesticide research expenditures used for health and environmental testing rose from 14% to 47% of total pesticide research spending and chemical pesticide product development time rose from seven to eleven years, the number of chemical pesticides dropped from 46 over the 1972–76 period to 30 over the 1985–89 period. The number of new chemical pesticide registrations for vegetables and other minor crops declined from 62 over the 1972–76 period to 15 for 1985–89, even though registrations for corn and other major crops remained almost unchanged, and the number of pesticides with chronic toxicity effects declined from 22% of new pesticides over the 1972–76 period to 6% of new pesticides for 1985–89 (table 1).

This paper has two purposes: (1) to examine the impact of Environmental Protection Agency (EPA) regulation on chemical pesticide innovation and (2) to investigate the relationship between regulation and the toxicity of new pesticides.[1] The paper

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[1] By innovation, we mean the first-time registration of a new chemical active ingredient for use as a pesticide. We use first-time registrations rather than patents as a measure of innovation because many patents are issued but not used and thus have no economically useful value. First-time registrations are novel chemical compounds developed by pesticide firms investing millions of dollars in research in several scientific dis-

Table 1. Number of New Chemical Pesticides and Toxicity Effects

	Toxicity Effects					
Year	Acute	Chronic	Fish and Wildlife	Other	Total[a]	Total Registrations
1972	3	1	3	4	5	12
1973	1	2	5	2	7	4
1974	2	2	4	2	6	11
1975	1	1	3	1	6	12
1976	0	1	3	1	3	7
1977	1	1	1	0	1	1
1978	0	0	0	0	0	0
1979	2	1	5	2	7	9
1980	2	2	2	1	5	9
1981	1	0	2	1	3	5
1982	1	1	3	3	5	7
1983	1	2	4	0	6	8
1984	0	2	3	0	4	7
1985	1	1	3	2	4	4
1986	1	0	2	0	2	8
1987	3	0	3	3	6	4
1988	2	0	2	2	3	4
1989	1	0	2	1	3	10
1972–76	7	6	18	8	27	46
1977–81	6	4	10	4	16	24
1980–84	5	7	13	5	23	36
1985–89	7	1	12	8	18	30

[a]Since one chemical pesticide may have multiple health and environmental effects, this number is less than the sum of all pesticide registrations with at least one health or environmental effect.

differs from previous studies in that it uses firm-level rather than industry-level data to examine the impact of regulation on innovation (new chemical pesticide introductions), and it empirically examines the impact of pesticide regulation on pesticide toxicity.

Pesticide Regulation

Concern over the health consequences of agricultural chemicals led Congress to enact the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) in 1948. This legislation and several subsequent amendments required that pesticide producers develop data showing the health effects of pesticides, register pesticides against the claim of effectiveness by the manufacturer, and state pesticide toxicity on the label. Pesticides are also regulated by various provisions of the Federal Food, Drug, and Cosmetic Act of 1938 (FFDCA), which requires pesticides to meet tolerances to gain registration and establishes that enforcement is to be carried out by the Food and Drug Administration (FDA) and the USDA (Hatch 1982).[2]

After transferring FIFRA enforcement to the EPA in 1970, Congress greatly strengthened pesticide regulation with a 1972 FIFRA amendment. Under this legislation, Congress gave the EPA responsibility for reregistering existing chemical pesticides, examining the effects of pesticides on fish and wildlife, and evaluating chronic and acute toxicity effects. Overall, the amendment greatly increased the health and safety data needed to support pesticide registrations, required existing pesticides to be brought up to current standards, and gave the EPA authority to cancel or suspend pesticides that may pose unreasonable health or environmental risks (Hatch 1982).

A 1978 FIFRA amendment clarified several aspects of the 1972 legislation. These included the

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ciplines, including chemistry and botany, and requiring extensive field testing.

[2] Both statutes (FIFRA and the FFDCA) were amended by the Food Quality Protection Act (FQPA) of 1996. Under FIFRA, EPA regulates pesticide use through registration and labeling requirements. Under FFDCA, EPA establishes maximum allowable levels (tolerances) for pesticide residues in foods sold in interstate commerce. FQPA eliminated the distinction between raw and processed food tolerances, as stipulated in the Delaney clause, and required that pesticide tolerances be set such that they would ensure a reasonable certainty that no harm would result from aggregate exposure to the chemical pesticide residues (Schierow 1996).

registration of pesticides with low measurable environmental risks, the regulatory costs of minor use pesticides, the reregistration of existing pesticides, and the use of existing field data by a second pesticide developer.

Regulatory stringency usually increases gradually. Any regulatory body requires time to write formal regulatory rules to implement legislation. Prior to these new rules, status quo rules are used. EPA rule-making practices for the 1972 FIFRA amendment were no exception. The EPA published formal rules in 1978, 1982, and 1994. Each set of rules was in addition to those in existence in 1972 and increased regulatory stringency beyond that which existed previously.

Testing requirements for chemical pesticides now include up to seventy different types of tests. They consist of a two-generation reproduction and teratogenicity study, a mutagenicity study, and toxicology studies, i.e., acute, subchronic, chronic oncogenicity, and chronic feeding effects. These tests cost millions of dollars and can take several years to complete. Additional tests are used to evaluate the effects of pesticides on aquatic systems, wildlife, and other environmental areas, and farm worker health.

Firm and Industry Attributes Associated with Innovation

A large body of economic research exists on the impact of regulation on pharmaceutical innovations. Pharmaceutical industry research is particularly useful for analyses of the pesticide industry because of the many similarities between the two industries. Both industries are dominated by large multiproduct firms that rely on internal research to develop new products that have long development cycles. Both industries also face stringent government product regulation. For example, pesticide firms in 1992 had a research-to-sales ratio of 23% and environmental and toxicity testing costs that consumed about 50% of research expenditures (National Agricultural Chemical Association [NACA] 1992). Pharmaceutical firms had a similar research-to-sales ratio and also had high regulation-related costs.

Previous economic research has characterized technological innovation as a function of research and development spending, past success in developing innovative products, regulatory costs, firm size, market structure, and demand conditions. Economists studying new pharmaceutical product innovation assert that firms increase profits by generating economically useful knowledge from research effort. Empirically, researchers have found a strong positive impact of research expenditures on new pharmaceutical introductions (Grabowski, Vernon, and Thomas 1978; Thomas 1990) and sales per new pharmaceutical (Thomas 1990).

Research productivity may vary across firms: Demsetz (1973) argues that superior firms grow at the expense of less efficient firms, and Klepper and Graddy (1990) assert that firms with higher product quality and higher productivity prosper at the expense of rivals with lower product quality and productivity. In a research-intensive industry, this research suggests that recent success encourages future success through new product development. For example, Thomas (1990) attributes the inability of small firms to grow in the pharmaceutical industry to a decline in their research productivity.

A central theme of innovation studies is the impact of regulation on research productivity. Economists have shown that regulation adversely affects new pharmaceutical introductions (Peltzman 1973; Grabowski, Vernon, and Thomas 1978; Thomas 1990), and, by discouraging the development of drugs that serve small markets, increases sales per new pharmaceutical (Thomas 1990).

In the pesticide industry, the Council for Agricultural Science and Technology (CAST 1981) found that EPA regulation encouraged an increase in research expenditures, a delay in the time required to register and reregister pesticides, a decline in the number of new pesticides registered per year, and a shift in the allocation of research expenditure from synthesis, screening, and field testing to administration, environmental testing, and residue analysis. Additionally, using annual data, Hatch (1982) found that increased regulatory stringency led to a 7%–9% decline in pesticide registrations.

Greene, Hartley, and West (1977) and Teece (1982) assert that multinational firms enhance research efficiency by centralizing research in one country and marketing products on a worldwide basis. They also argue that multinational firms are better able to take advantage of product research than are single-market firms because multinational firms have more market outlets. These claims suggest that multinational firms with low U.S. research expenditures may have a large portfolio of chemical pesticides that could be sold in the United States, giving them higher "apparent" U.S. research productivity than competitors with well-established U.S. research operations.

Galbraith (1952) suggests that large firms have greater financial capacity and thus can better bear research risks than can smaller rivals. Acs and Audretsch (1987) empirically show that large firms have higher research productivity than do small firms in capital-intensive, differentiated-goods, oligopolistic industries. Hence, firm size may enhance research productivity.

Kamien and Schwartz (1982) remind us that innovations are a response to profit opportunities. The robustness of demand influences the number of products a market can absorb and thus may affect innovation. In addition, Kaplinsky (1983) suggests that the relationship between firm size and innovation varies for different phases of the industry growth cycle. Kamien and Schwartz (1982) agree, suggesting that growing industries generate more inventive activity than stagnating or declining industries.

The Innovation Process in the Chemical Pesticide Industry

The cost of pesticide development includes research and regulatory costs. Increases in either research or regulatory costs cause the gap between potential revenues and costs to narrow and result in some pesticides becoming unprofitable.

The objective of research and development is to develop new chemical pesticides with high efficacy that can generate substantial revenues and, hence, profits. Ollinger and Fernandez-Cornejo (1995) found that research expenditures positively affect new chemical pesticide product sales. Beach and Carlson (1993) determined that a tradeoff exists between pesticide efficacy and user safety and environmental qualities. However, with an efficacy elasticity exceeding 2.4 and user safety and water quality elasticities ranging from –0.10 to –0.14, farmers appear to value efficacy much more than safety and environmental qualities. Accordingly, a pesticide firm must first and foremost develop a chemical pesticide with high efficacy. However, insecticides (Plapp 1993) and other pesticides (Lichtenberg, Spear, and Zilberman 1993) with high efficacy are also very toxic. Hence, in order to develop a pesticide that can generate high revenues, a firm must select a chemical pesticide candidate from a group of very toxic compounds.

To obtain registration, a chemical pesticide candidate must pass EPA standards. If a firm selects only chemical compounds with high efficacy and these compounds are very toxic, then many chemical compounds will not meet EPA standards and would have to be dropped. Moreover, as efficacy rises, more chemical pesticide candidates are likely to be discarded, but the remaining successful chemical pesticides are likely to generate more sales and be more toxic than chemical pesticides with lower efficacy. Hence, higher search costs (research expenditures) are expected to lead to the development of chemical pesticides with greater efficacy and higher toxicity relative to all chemical pesticides.[3]

A rise in regulatory stringency suggests either a reduction in existing tolerances or stricter enforcement of current standards. In either case, an increase in stringency reduces the number of chemical pesticide–candidates that can pass regulatory tests because chemical pesticides that formerly complied with regulatory standards may no longer meet new guidelines. Hence, an increase in regulatory stringency should reduce chemical pesticide toxicity.

Pesticide Innovation Model

Equation (1) is an empirical model of the relationship between economically useful innovations—new chemical pesticide registrations (N_{it})—and several factors believed to affect innovation.

$$(1) \qquad \begin{aligned} \ln(N_{it}) = {} & \beta_0 + \beta_1 \ln(RESEARCH_{it}) \\ & + \beta_2 \ln(LG3SHR_{it}) + \beta_3 INT_{it} \\ & + \beta_4 RDINT_{it} + \beta_5 \ln(LSHARE_{it}) \\ & + \beta_6 \ln(ARUL72_t) \\ & + \beta_7 \ln(GROW5_t) + \epsilon_{it}, \end{aligned}$$

where $RESEARCH_{it}$ is firm pesticide research expenditures; $LG3SHR_{it}$ is firm market share growth; INT_{it} is a dummy variable for firms with large overseas sales but no U.S. research and development and low or no U.S. sales in 1972; $RDINT_{it}$ is an interaction term between INT_{it} and $RESEARCH_{it}$; $LSHARE_{it}$ is firm market share; $ARUL72_t$ is pesticide regulation; and $GROW5_t$ is industry growth. All variables except the dummy

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[3] This positive relationship between research expenditures and pesticide toxicity (and pesticide efficacy) does not imply that pesticide toxicity is greater than that which would be acceptable to farmers. Cropper, et al. (1992) found that EPA regulators respond to diverse interest groups, such as consumers, environmentalists, and farmers, when they decide to cancel or continue the registrations of carcinogenic pesticides. They also estimated that the implicit value EPA regulators place on human safety risks is $35 million per applicator cancer case avoided. Since this implicit $35 million value of a human life exceeds the more common $3 million to $7 million statistical value (1990 dollars) used by Viscusi (1993) for a life and the $5 million used by Food and Drug Administration regulators, EPA regulators appear to establish toxicity standards that are far more stringent than those standards farmers demand. As a consequence, when pesticide firms comply with EPA regulations, they also satisfy farmer demand for user safety and environmental qualities. This does not imply that all pesticides approved by the EPA barely meet regulatory standards. Pesticides do vary in user safety and environmental qualities. Farmers recognize this variation and, for pesticides with equal efficacy, would likely choose the pesticide with superior user safety and environmental qualities.

variable are in log form. Precise variable definitions are given in Appendix A.

Lagged market share growth is used as a measure of firm success. Firms can increase market share by developing new and better products or buying another firm. In either case, an increase in market share reflects superior ability (Demsetz 1973).

The dummy variable INT_{it} is used to control for potentially higher international entrant research productivity. Historical data indicates that over the 1972–89 period, the number of research-intensive pesticide companies dropped from 33 to 19, but the number of foreign-based companies rose by three and the market share held by foreign-based companies rose from 18% to 43% (Ollinger and Fernandez-Cornejo 1995). All of the foreign-based entrant firms were major international chemical pesticide producers with large portfolios of chemical pesticides but no U.S. research expenditures in 1972.

As international entrants begin research in the United States, their apparently high research productivity should diminish. International entrants used pesticides developed in overseas laboratories for overseas markets as vehicles for entry into the U.S. market. Since most pesticide development was completed prior to U.S. introduction, international entrant U.S. pesticide research costs were low and their apparent research productivity should have been high. However, as the international entrants established pesticide laboratories in the United States in order to develop pesticides for the U.S. market, their research costs per new pesticide innovation rose and their apparent high research productivity should have diminished. Accordingly, we interact the international entrant dummy variable and research expenditures ($RDINT_{it}$). This variable should negatively affect innovation.

Market share is a proxy for firm size. Pesticide firms included in the study sample are part of larger chemical companies, and each has significant resources for research on chemical pesticides. Yet reputation effects (Nelson 1959) and the ability to distribute and market products (Kamien and Schwartz 1982) encourage innovation. Since firms with high market share are likely to be larger and better known and to have more products than firms with low market shares, market share should encourage innovation.

$ARUL72_t$ is a proxy for regulation. Economists examining pharmaceutical innovation (Peltzman 1973; Grabowski, Vernon, and Thomas 1978; and Thomas 1990) and pesticide innovation (Hatch 1982; CAST 1981) have suggested that regulation adversely affects innovation. Thus, regulation should discourage innovation. Empirically, since firms must use research expenditures to conduct various toxicity and environmental tests in order to comply with EPA regulations, results showing that EPA regulation adversely affects innovation accounts for the share of firm research devoted to human safety and environmental purposes.

$GROW5_t$ serves as a measure of industry growth. Klepper and Graddy (1990) assert that high sales growth exists in the early stages of industry evolution and low or negative growth occurs in the later stages. Some evidence suggests that the pesticide industry made a transition from growth to maturity over the 1966–92 period. Between 1966 and 1976, the sales of herbicides, the most commonly used type of pesticide, rose from 101 million pounds to 373.9 million pounds of active ingredients (a.i.). By 1982, herbicide sales increased to 455.6 million pounds of a.i. and then stabilized, reaching 478.1 million pounds of a.i. in 1992 (Osteen and Szmedra 1989; Delvo 1993). This transition from growth to maturity suggests that industry growth may or may not affect pesticide innovation.[4]

Regulatory Variables

In previous studies of EPA regulation, Hatch (1982) used the time required from pesticide discovery to EPA registration (development time) as a measure of regulatory stringency. The CAST study (1981) used three measures of stringency: time required to register a pesticide with the EPA, the coincidence of legislation and productivity changes, and the change in the uses of research and development expenditures, i.e., pesticide development for pesticide-testing.

Severe measurement problems exist for use of the change in the development time and change in the time required to register a pesticide with EPA as proxies for regulation. Baily (1972) argues that the least costly and most easily developed innovations are discovered and developed at the beginning of an industry life cycle and that future innovations require greater research expenditures and longer development time, suggesting that a change in development time can be attributed to either

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[4] As pointed out by an anonymous reviewer, the Osteen and Szmedra (1989) and Delvo (1993) and Delvo (1993) data may not be precise because budget priorities prior to 1987 prevented the collection of high-quality pesticide usage information. However, these data do capture the overall pesticide usage trends, are consistent with pesticide producer data collected by the EPA, and thus do reflect the major changes in the growth of pesticide use over the 1972–91 period.

innovation depletion or regulatory intensity. Similarly, since EPA registration time depends on the number of tests that regulators must examine and not necessarily on the rigor of those tests, the time required to register a pesticide with the EPA may change even though stringency does not. Thomas (1990) make a similar point for pharmaceuticals.

We consider three definitions of the regulatory variable—*ARUL72*, *AVREG*, and *PESLAB*—in order to show that results do not depend on a particular definition of regulation. Each regulatory proxy also relates strongly to the other proxies and corresponds directly to the regulation of chemical pesticides.

$ARUL72_t$ is based on the EPA cost estimates of mandated testing requirements for registering chemical pesticides under FIFRA, and is similar to the legislation changes measure of stringency used by CAST (1981). We use mandated testing requirements rather than legislation because firms must be in compliance with testing requirements in order to register a pesticide.

The EPA formally issued rules in 1978 and 1982. The EPA also wrote, but did not formally adopt, another set of rules in 1994. These rules included requirements that were in addition to those in existence in 1972. Each set of rules required an economic impact assessment, which gives cost estimates and can be used to calculate an index of estimated costs (EPA-estimated costs). Using 1972 as a base year, this index suggests that the 1978 regulations increased environmental and toxicity testing costs by 30% over those in 1972; the 1982 rules raised environmental and toxicity testing costs by 95% over those in 1972; and the 1994 rules increased environmental and toxicity testing costs by about 100% over those in 1972.

According to Arnold Aspelin (interview with author, January 1995) and Gary Ballard (interview with author, January 1995) of the EPA, who wrote the economic impact analysis for the rule changes, new chemical pesticide registrants complied with new rules prior to their formal publication. For example, chemical pesticide registrants currently adhere to all testing requirements proposed in 1994 and followed all of the 1978 rules in 1977 and some of the 1978 rules in 1972. Hence, 1978 rules formalized the new procedures established by the EPA over the 1972–77 period, 1982 rules reflect revised testing procedures introduced during the 1978–81 period, and 1994 rules reflect changes introduced after 1982.

Since pesticide development is a lengthy process, which increased from seven to eleven years over the 1972–89 period, firms must anticipate future regulatory requirements in order to avoid a future rejection by the EPA. As a result, for $ARUL72_t$, we assume that actual compliance occurred in 1972 for the 1978 rules, in 1979 for the 1982 rules, and in 1983 for the 1994 rules.

To verify the robustness of our results, we also use two other measures of regulation. As one proxy we employ industry pesticide research expenditures used for toxicological and environmental testing as a fraction of all pesticide research and development expenditures ($AVREG_t$). This measure is similar to the research and development expenditures variable used by CAST (1981).

The pesticide approval period at the EPA becomes longer when regulation becomes more stringent and drops when the number of personnel evaluating new pesticide candidates increases. Since approval times at the EPA have been relatively constant over the past twenty years, a change in employment should provide a measure of the change in regulatory stringency. Hence, employment at the Office of Pesticide Programs ($PESLAB_t$) acts as the third proxy of regulation.

We define each regulatory term as a lag structure over the industry average chemical pesticide development cycle because firms exclude sunk costs when making development plans. For example, if a firm were at the beginning of the chemical pesticide development process, it would balance development and testing costs (DT) against potential revenues. If regulation becomes more stringent, then DT rises and a marginally profitable product under the old regulatory regime would become unprofitable under the new regime. Thus, the firm would not develop it. However, if initial development is complete, a firm ignores past (sunk) development costs, balances expected testing costs (T) against potential revenues, and may continue development.

Of the three regulatory variables, *ARUL72* is our preferred proxy for EPA regulation because it is a strictly exogenous variable that is based on the actual EPA-estimated costs of human safety and environmental testing requirements. As indicated above, the other two proxies are used to verify the robustness of our results. Although industry human safety and environmental testing costs as a percentage of research expenditures ($AVREG_t$) change with changes in regulatory stringency, *AVREG* may overstate regulatory impact. Firms would likely do some toxicological and environmental testing in the absence of regulation because, as shown by Beach and Carlson (1993), farmers value the user safety and environmental attributes of pesticides. Additionally, the proxy using the number of employees at the Office of Pesticide Programs (*PESLAB*) may suffer from measurement errors because it includes employees dedicated to registration activities and employees performing other pesticide-related activities.

Chemical Pesticide Toxicity Model

Chemical pesticides are biologically active, and many may be toxic either to fish and wildlife or to human health. Concern over toxicity led the EPA to require producers to place acute toxicity ratings (I, II, III, or IV) for the chemical pesticide on the label of the container. A rating of I is the most toxic. Acute toxicity ratings are based on the LD50 value, which is the dose of a toxicant necessary to kill 50% of the test animals studied within the first thirty days after exposure. The EPA also requires labels to include information about chronic human effects and harm from inhalation, about skin absorption, and about eye damage. Additionally, registrations must state whether the chemical pesticide harms fish or wildlife.

The various reporting requirements stem from differences in the health and environmental effects of chemical pesticides. Those chemical pesticides that have a high acute toxicity rating, cause chronic health effects, or are harmful to fish and wildlife may be considered "more toxic." Those that have a low acute toxicity rating, have no chronic health effects, and do not harm fish or wildlife may be classified as "less toxic."[5] This ability to identify degrees of toxicity allows one to create a binary toxicity variable for each chemical pesticide.

We define "less toxic" in two ways. Under one definition, a chemical pesticide is defined as "less" toxic if it has a Class II, III, or IV acute toxicity rating, has no chronic health toxicity, and is not toxic to fish or wildlife. Under the other definition, a chemical pesticide is considered "less toxic" if it has no chronic health effects and is not toxic to fish or wildlife. The first definition includes all types of chemical pesticide toxicity considered by the EPA. The second definition includes only those aspects of regulation that changed with the 1972 FIFRA amendment.

In equation (2) we regress the ratio of less toxic chemical pesticides to all chemical pesticides (*LESSTOX*) on pesticide industry research expenditures (*RDIND*), the Herfindahl Index (*HERF*), the proportion of international entrants (*INT2*), regulation (*ARUL72*), and control variables for farm sector market conditions (*PRICES*) and chemical pesticide sales growth (*GROW2*). Again, we use three proxies of regulation to examine model robustness (see Appendix A for complete definitions):

$$(2)\ LESSTOX_t = \beta_8 + \beta_9 RDIND_t + \beta_{10} HERF_t + \beta_{11} INT2_t + \beta_{12} ARUL72_t + \beta_{13} PRICES_t + \beta_{14} GROW2_t + \epsilon_t.$$

We argue above that research expenditures should negatively affect the number of "less toxic" chemical pesticides and that regulation should positively affect the number of less toxic pesticides. This is not to say that firms do not respond to the demand for human health and environmental qualities. Since we have controlled for research expenditures devoted to the demand for human and environmental qualities (*ARUL72*), the sign of the coefficient on research should reflect the impact of research expenditures for effectiveness qualities. Since pests are governed by biological processes, greater effectiveness results from greater toxicity.

The Herfindahl Index should positively affect the number of less toxic chemical pesticides because prior research suggests that surviving pesticide companies tended to be larger and better able to avoid regulatory penalties than other companies (Ollinger and Fernandez-Cornejo 1995). The proportion of international entrants, agricultural prices, and industry growth are control variables for the influence of international entrants, farm sector demand conditions, and the industry life cycle.

Data and Estimation

Data

Data include all new chemical pesticide registrations introduced by the major (top twenty) chemical pesticide firms over the 1972–91 period identified in Kline and Company reports (1974–91). Biological pesticides, which comprise about 2% of the pesticide market, are not considered because they are naturally occurring organisms with less rigorous regulatory requirements and much lower regulatory costs than chemical pesticides.

New chemical pesticide registrations came from Aspelin and Bishop (1991). Pesticide toxicity data came from the *Farm Chemicals Handbook '93* (Meister 1993), CPCR (1992), and EXTOXNET

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[5] During the late 1960s and early 1970s, scientists determined that many pesticides previously thought to be harmless, such as chlorinated hydrocarbons, were actually carcinogenic or had an adverse impact on the environment. As a result, some previously approved pesticides were banned by the EPA after promulgation of FIFRA. Since we base toxicity ratings on current scientific knowledge, our toxicity definition is consistent with all current understanding of pesticide toxicity.

(1994). Firm research expenditures came from the Bureau of the Census (1972–89a), Kline and Company (1989, 1991) reports, annual reports, and SEC (1972–89) filings.[6] The Bureau of the Census (1972–89b) and Kline and Company firm sales data (1974–91) were used to determine firm market share. Industry pesticide research, industry average product development period, and industry sales data came from NACA (1971–92). Industry value added came from census files. The Herfindahl Index is based on the computed market shares. Agricultural prices and planted acreage came from the USDA (1974–91). Price-sensitive data were deflated by the GNP price deflator.

Rule descriptions and the costs of performing new environmental and toxicity tests for the 1978, 1982, and 1994 EPA rules came from the EPA (1978, 1982, 1994).

Industry regulatory costs came from NACA (1971–92). These costs were assumed to include all environmental testing, toxicology studies, and EPA registration costs. Search, synthesis, field testing, and process development costs were assumed to be nonregulatory costs. Labor employment at Office of Pesticide Programs (OPP) of the EPA came from EPA budgets. Further information about these data is available from the authors upon request.

Estimation

Sutton (1991) shows that exogenous sunk costs, such as pesticide product regulation, positively affect endogenous sunk costs (research expenditures), making a two-stage regression necessary. In the first stage, we purge research (*RESEARCH*) of its dependence on regulation and other factors by creating the instrumental variable *FIRMRD*—the predicted value of firm pesticide research expenditures. We use all exogenous variables and total firm research expenditures as instruments.

New chemical pesticide registrations approximately follow a Poisson distribution, with most firms in most years introducing no new chemical pesticides. One approach may be to use a Poisson regression, but this specification requires that the mean be equal to the variance. Interfirm differences in research productivity cause the variance to grow faster than the mean and result in over (under) dispersion (Gourieroux, Monfort, and Trongon 1984).

McCullagh and Nelder (1983) demonstrated that the use of quasi-likelihood techniques (QL) overcomes problems of over (under) dispersion by providing added flexibility to a Poisson regression. Rather than strictly defining a statistical relationship, this method allows the mean (*u*) to be only proportional to the variance. Moreover, the unknown distribution is specified to be of the linear exponential family, a general class of distributions (Thomas 1990).

Quasi-likelihood estimates can be obtained with the use of nonlinear weighted least squares. The variance of the mean *V*(*u*) is used as a weight. The dispersion parameter ($\sigma_{est}{}^2$) is estimated from the weighted sum of the square divided by the difference between the number of observations (*k*) and model degrees of freedom *p* (equation [3]). A value of one indicates an absence of over (under) dispersion. The dispersion parameter (table 2) indicates that some underdispersion exists.

$$\sigma^2_{est} = \frac{\sum_k \frac{(y-u)^2}{V(u)}}{(k-p)}. \tag{3}$$

Inference about individual parameters is based on the asymptotic standard errors and t-statistics reported by the statistical package. Inference for multiple parameters is based on the QL function for a Poisson distribution, l(*u*; *y*) (Carrol and Rupert 1988), in equation (4).

$$\text{l}(u; y) = y \log(u) - u \tag{4}$$

Equation (5) shows that the difference between the restricted and unrestricted model estimates is approximately equal to the dispersion parameter times the chi-square statistic, χ^2. The restricted parameter estimate is b_{rest} and the unrestricted estimate is b_{max}. The χ^2 statistic is reported in table 2.

$$2\Delta QLF = 2\left(\sum_k l(U(b_{max}; y)) - \sum_k l(U(b_{rest}; y))\right) \sim \sigma^2_{est}\chi^2_{p-q} \tag{5}$$

Equation (2) is estimated with a two-stage SUR method and industry-level data covering the 1972–89 period. Since an increase in exogenous sunk

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[6] The Bureau of the Census's *Survey of Industrial Research* (1972–89a) contains research expenditures only for chemical pesticides, while Kline and Company (1989, 1991) data contains pesticide research data. Neither data set includes other types of research expenditures. Various issues (1972–89) of annual reports from the following companies were examined: BASF, Bayer, Chevron, Dow, Eli Lilly, FMC, Monsanto, Rhone Poulenc, Rohm and Haas, Shell, Stauffer, Union Carbide, and Velsicol. Various issues (1972–89) of SEC filings for the following companies were examined: BASF, Chevron, Rhone Poulenc, Rohm and Haas, Shell, and Stauffer.

Table 2. Estimates of the Determinants of Chemical Pesticide Innovations

Variable	Case 1 *ARUL72*	Case 2 *AVREG*	Case 3 *PESLAB*
	(standard errors in parentheses)		
INTCPT	0.61	−13***	−15***
	(4.22)	(2.59)	(2.29)
FIRMRD	0.88***	0.94***	0.96***
	(0.19)	(0.18)	(0.19)
LG3SHR	0.77	0.91*	0.97*
	(0.54)	(0.54)	(0.55)
INT	5.27**	5.47***	5.89***
	(2.24)	(2.16)	(2.28)
RDINT	−0.53*	−0.56**	−0.59**
	(0.29)	(0.28)	(0.30)
LSHARE	−0.14	−0.17	−0.13
	(0.13)	(0.13)	(0.13)
ARUL72	−2.0***		
	(0.88)		
AVREG		−1.5***	
		(0.42)	
PESLAB			−1.6***
			(0.46)
GROW5	0.82	0.36	2.76
	(3.07)	(2.51)	(2.07)
Observations	388	388	388
Sigma	0.96	0.94	0.94
χ^2	55.5	68.0	58.5

NOTE: Dependent variable: number of chemical pesticide registrations. Cases 1, 2, and 3 refer to models using *ARUL72*, *AVREG*, and *PESLAB* as regulatory terms, respectively.
Sigma = dispersion parameter.
***1% significance; **5% significance; *10% significance.

(regulatory) costs may affect the level of endogenous sunk (research) costs (Sutton 1991), we create an instrumental variable (*INDRD*) for industry pesticide research (*RDIND*). Instruments include value added and all the exogenous variables of equation (2). Value added was obtained from census bureau files.

Either autocorrelation or the theoretical limits imposed by the upper and lower bounds could confound the estimates of equation (2). However, an OLS regression indicates that autocorrelation is not present. Additionally, since the regression was estimated within its theoretical bounds, estimates of equation (2) with a "two limit" tobit (Maddala 1983) are similar. Hence, since neither autocorrelation nor the theoretical bounds bias the results, the model was estimated with a SUR econometric approach. The instrumental variable for industry research and the other variables of equation (2) are used as the explanatory variables. There were no adjustments for autocorrelation. The Durbin-Watson statistics are reported in table 3.

Results

Chemical Pesticide Innovation

Results of the three alternative regulatory cases over the 1972–91 period are reported in table 2. They suggest that pesticide research expenditures, firm market share growth, and international entrants relate positively to new chemical pesticide registrations. Regulation and the interaction term between international entrants and pesticide research negatively affect new chemical pesticide registrations. Market share is negative but insignificant, and industry growth is positive but insignificant. Since we use an instrumental variable for research, the regulatory term is an expression that is net of its impact on research expenditures and reflects increases in research expenditures for human health and environmental testing costs on innovation.

Of considerable interest are the negative and significant signs on all of the alternative regulation term coefficients. Since the variables are in log form, the coefficient on EPA-anticipated costs (*ARUL72*) suggests that a 10% increase in the EPA-anticipated cost leads to a 20.2% decline in innovation. The coefficient of the ratio of regulatory costs to industry pesticide research (*AVREG*) shows that a 10% increase in expenditures used for toxicological and environmental testing as a fraction of all pesticide research and development expenditures results in a 15% reduction in innovation. The coefficient for pesticide division labor (*PESLAB*) suggests that an increase in regulatory effort of 10% leads to about a 16% decline in innovation. These results are consistent with CAST (1981). They are also consistent with Hatch (1982) who estimated that the increase in the time required to bring a new pesticide to market over the 1968–82 period resulted in a 7%–9% decrease in pesticide registrations.

We also considered changes in regulatory stringency. We split the 1972–91 period into two subperiods—1972–81 and 1982–91. First period results are similar to those reported for the overall period. Second period results for regulation are not significant. Since the first period regulatory effects are similar to those for the whole period and the second period has no consistently significant change, there appears to be little change in stringency over the 1972–91 period. We do not report results, but they are available from the authors.

The positive and significant influence of pesticide research expenditures is consistent with research on pharmaceutical innovation (Thomas

Table 3. Estimates of the Determinants of Less Toxic Chemical Pesticides

	Toxicity Types					
Variable	Case 1 Fish/Wildlife Acute/Chronic	Case 2 Fish/Wildlife Chronic	Case 3 Fish/Wildlife Acute/Chronic	Case 4 Fish/Wildlife Chronic	Case 5 Fish/Wildlife Acute/Chronic	Case 6 Fish/Wildlife Chronic
			(standard errors in parentheses)			
INTCPT	−1.08	−1.41**	−0.47	−0.81	−0.39	0.80
	(0.63)	(0.66)	(0.49)	(0.50)	(0.51)	(0.50)
INDRD	−5.90**	−5.05**	−2.08**	−1.33	−1.33**	−0.60
	(2.00)	(2.06)	(0.89)	(0.87)	(0.63)	(0.61)
HERF	0.55	0.85***	0.27	0.52*	0.27	0.55*
	(0.32)	(0.34)	(0.29)	(0.28)	(0.30)	(0.28)
ARUL72	0.94**	1.00**				
	(0.39)	(0.39)				
AVREG			2.36*	2.38**		
			(1.23)	(1.15)		
PESLAB					0.52*	0.57**
					(0.29)	(0.28)
PRICES	−0.012***	−0.009***	−8.24***	−5.38**	−7.94**	−5.08**
	(0.002)	(0.002)	(2.11)	(2.23)	(2.18)	(2.21)
GROW2	1.63***	1.45***	1.28**	1.21**	1.14**	1.09**
	(0.41)	(0.44)	(0.44)	(0.47)	(0.47)	(0.48)
Observations	18	18	18	18	18	18
DW	1.99	1.81	1.67	1.95	1.61	1.72
R^2	0.59	0.53	0.45	0.31	0.43	0.47

NOTE: Dependent variable: proportion of less toxic chemical pesticides to all chemical pesticides. Cases 1, 2, 3, 4, 5, and 6 refer to alternative specifications of the toxicity regressions.

***1% significance; **5% significance; *10% significance.

1990). The positive influence of market share growth is consistent with Demsetz (1973) and Klepper and Graddy (1990) in that past success fosters future success. The insignificance of the market share term suggests that market power had no effect on innovation. This result is consistent with Kline and Company sales data (1974–91), which shows that many firms with high market share produced mainly nonproprietary agricultural chemicals.

The positive sign of the international entrant variable indicates that foreign-based entrants had a lower cost of innovation than did firms with a larger U.S. pesticide research presence. This does not, however, imply that international entrants had higher pesticide research productivity. As suggested by Teece (1982), international entrants could use pesticides developed for overseas markets in the United States without undertaking U.S. research. The negative sign on the international entrant and research interaction term supports this view, suggesting that international entrants with more than $20 million in U.S. pesticide research expenditures did not have higher research productivity than other companies.

Results of the impact of pesticide regulation on chemical pesticide innovation are similar to yet different from previous studies. Like Grabowski, Vernon, and Thomas (1978) and Thomas (1990) and consistent with Hatch (1982) and CAST (1981), we find that EPA regulation has a negative influence on innovation. Unlike Thomas, we do not find an increase in regulatory stringency over time.

Chemical Pesticide Toxicity

Table 3 contains the results of six regression models of the proportion of less toxic chemical pesticides on several independent variables. Cases 1, 3, and 5 are for the three alternative regulatory variables and the definition of a "less toxic" pesticide as being a pesticide with a low acute toxicity rating, no chronic health toxicity, and no toxicity to either fish or wildlife. Cases 2, 4, and 6 are for the three alternative regulatory variables and the definition of a "less toxic" pesticide as being a pesticide with no chronic health toxicity and no toxicity to either fish or wildlife.

Results suggest that regulation encouraged the development of less toxic chemical pesticides. A 10% increase in EPA-anticipated costs would result in a 10% increase in new chemical pesticides being classified as "less" rather than "more" toxic. A 10% increase in health and environmental testing costs (about $1.5 million per pesticide) would result in a 5% increase in the number of pesticides classified as "less" rather than "more" toxic. Since results for Cases 1, 3, and 5 are almost identical to those for 2, 4, and 6, it appears that EPA regulation mainly affected chronic health toxicity and fish and wildlife toxicity.

The negative sign on the coefficient for pesticide research spending in equation (2) suggests that an increase in pesticide research expenditures leads to the development of a smaller proportion of less toxic chemical pesticides.[7] This result is consistent with the hypothesis that farmers value pesticide efficacy more than health and environmental effects, and that chemical pesticides with high efficacy are also very toxic and costly to develop.

The chemical pesticide toxicity regression also shows that the Herfindahl Index and industry growth had positive influences on the proportion of less toxic chemical pesticides. Farm prices negatively influenced the proportion of less toxic chemical pesticides. The positive effect of the Herfindahl Index is consistent with previous research indicating that larger firms incur lower regulatory-related costs than do smaller ones (Ollinger and Fernandez-Cornejo 1995).

The proportion of international entrants had no effect on chemical pesticide toxicity and was dropped. Since the above results include only chemical pesticides developed by the major pesticide companies, we also evaluated changes in the proportion of less toxic chemical pesticides for the entire pesticide industry. The results for this larger sample are similar.

Concluding Comments

A major finding of this paper is that the regulatory costs (i.e., research expenditures required for human health and environmental testing costs) negatively affect the number of new chemical pesticide registrations and drive up the cost of bringing a new pesticide to market. These results support Greene, Hartley, and West (1977) in that regulation negatively affects innovation and encourages firms to focus more of their research effort on the development of chemical pesticides for major field crops.[8]

Another major result is that regulation encourages firms to develop less toxic chemical pesticides. Although this finding is in conflict with some experts, such as Greene, Hartley, and West (1977), who suggest that regulation likely causes firms to develop more toxic chemical pesticides, it agrees with historical evidence. After the EPA banned DDT and several other chemical pesticides that persist in the environment, pesticide firms focused their research on pesticides that degrade rapidly and stopped the development of harmful chemical pesticides that persist in the environment.

Results of this paper are consistent with research on the effect of pesticide regulation on innovation (Hatch 1982; CAST 1981) and the effect of pharmaceutical regulation on innovation (Peltzman 1973; Grabowski, Vernon, and Thomas 1978; Thomas 1990). Results extend previous research by suggesting that regulation forces a tradeoff in which fewer novel pesticides are introduced, but those pesticides tend to have fewer toxic side effects than those introduced previously.

Results of this paper are reassuring from a public policy perspective. Most economic studies acknowledge that pesticide regulation adversely affects innovation. Much more controversial is the impact of regulation on pesticide toxicity. The empirical research presented here supports those economists and policymakers who argue that regulation encourages the development of less toxic pesticides and who suggest that a tradeoff exists between less toxic pesticides and less innovation.

The decline in chemical pesticide innovation suggests that market opportunities exist for more environmentally appealing nonchemical pesticide alternatives. Microbial and biochemical pesticides are environmentally appealing because they occur naturally. Genetically modified plants with pest-resistant characteristics are also environmentally appealing because they reduce the need for chemical pesticides. However, even though sales of nonchemical pesticide alternatives are increasing

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[7] The regulation variable captures farmer and societal demand for user health and environmental qualities, while the research expenditures variable reflects the demand for greater pesticide effectiveness. As argued above, since pests are governed by biological processes, greater effectiveness should result from greater toxicity.

[8] Since an increase in regulatory stringency increases development costs and thus reduces the gap between potential revenues and costs, the development of some minor crop pesticides becomes unprofitable as regulatory stringency increases. Hence, an increase in regulatory costs should cause new chemical pesticide registrations for vegetables and other low-revenue (minor) crops to decline and should encourage firms to focus their research effort on chemical pesticides for major crop uses.

We examined this hypothesis by regressing crop uses (i.e., proportion of pesticides used on major crops) on regulation, research expenditures, the Herfindahl Index, and industry growth. Preliminary results indicate that regulation encourages firms to develop proportionately more pesticides for major crops.

rapidly because of recent technological advancements permitting protection against numerous pests—a formerly limiting factor (Krimskey and Wrubel 1993)—they are unlikely to replace chemical pesticides in the medium term because most nonchemical pesticide alternatives protect crops against harmful insects and fungi and offer little protection against harmful weeds.

Appendix A

Table A.1. Definitions of Variables in Equations 1, 2, and 3

Variable	Definition
N	New chemical pesticide registrations at the EPA.
FIRMRD	(A.1) $FIRMRD_{i,t} = (\sum_{j=0}^{n} RD_{t-j})/n$ where *RD* is firm pesticide research expenditures and *n* is the time from discovery to pesticide registration. Thomas (1990) used a similar definition for pharmaceutical innovations because that industry also had a variable lag structure for product development. Also, Sharp and NACA (1971–92) data suggest that pesticide research costs are evenly distributed over the product development cycle.
INT	A dummy variable equal to one for international entrants, i.e., firms that have large overseas sales but no U.S. research expenditures and low U.S. sales in 1972, and zero otherwise.
RDINT	Interaction term between *INT* and *FIRMRD.*
LSHARE	Lag of market share, which is based on company and industry sales.
LG3SHR	Lag of the three-year average of $LSHARE/LSHARE_{t-1}$. Used as a measure of firm growth because our specification is in log form, which does not allow the use of negative numbers.
ARUL72	Defined in the same composite form as *FIRMRD* in equation (A.1) above, except that the ratio $(PROPSE_t + RULE_t)/RULE71$ replaces *RD*. $PROPOSE_t$ is the EPA-anticipated cost of proposed rules in year *t*. $RULE_t$ is the cost of all rules in existence in year *t*. *RULE71* is the cost of rules in existence in 1971. A composite form is used because research requires many years and regulatory effects occur throughout the chemical pesticide product development cycle. *ARUL72* assumes that firms began adhering to the 1978 rule changes in 1972, to 1982 rule changes in 1978, and to 1994 rule changes in 1983. For further justification see "Regulatory Variables" section of the text.
AVREG	Defined in the same way as *FIRMRD* in equation (A.1) above, except that the ratio of pesticide research for environmental tests to total research expenditures replaces RD_t. For further explanation see "Regulatory Variables" section and the definition of *ARUL72.* See also description of regulatory costs in "Data" section.
PESLAB	Defined in the same way as *FIRMRD* in equation (A.1) above, except that BUDGETED STAFF-YEARS at the OPP replace *RD.* Warren and Chilton (1989) maintain that staffing levels reflect regulatory intensity. See "Regulatory Variables" section and the definition of *ARUL72* for further discussion.
PRICES	Deflated agricultural prices.
GROW5	The five-year average of S_t/S_{t-1}, in which S_t is current year sales and S_{t-1} is previous year sales. This definition of growth is employed because our specification is in log form, which does not allow the use of negative numbers.
LESSTOX	Ratio of the four-year moving average of the number of less toxic new chemical pesticides to the four-year average of all new registered chemical pesticides. We used a moving average because some years have very few registrations and other years have numerous registrations, making smoothing the data necessary.
INDRD	Industry research expenditures, in hundreds of millions of dollars, defined in a way similar to firm research (*FIRMRD*), with industry research expenditures replacing *RD.*
HERF	The Herfindahl Index, defined as the sum of the squares of company market shares.
INT2	The proportion of international entrants.
GROW2	The two-year moving average of the ratio of current year planted acreage to previous year planted acreage.

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