# Innovation and Regulation in the Pesticide Industry

**by**

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## ABSTRACT

This paper examines the hypothesis that regulation negatively affects pesticide innovation, causes pesticide companies to introduce more harmful pesticides, and discourages firms from developing pesticides for minor crop markets. The results confirm that pesticide regulation adversely affects innovation and discourages firms from developing pesticides for minor crop markets. Contrary to the hypothesis, however, regulation encourages firms to develop less toxic pesticides. Estimates suggest that it requires about $29 million in industry expenditures on health and environmental testing to affect the toxicity of one new pesticide.

Keywords: pesticide innovation, regulation, pesticide industry

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## I. Introduction

In 1992 U.S. farmers spent almost $6 billion on chemical pesticides to control pests (National Agricultural Chemical Association - NACA, 1993). Researchers (Headley, 1968; Campbell, 1976), among others, have shown that chemical pesticides have played a major role in increasing farm productivity. For example, corn yields rose threefold over the past forty years and, even as corn land usage declined by 10%, corn output increased dramatically. Despite the positive effect of chemical pesticides on agricultural productivity, there is growing concern over their use. A number of economists, including Harper and Zilberman (1989) contend that pesticides cause risks to farm workers, contaminate ground and surface water, have harmful effects on wildlife, and, because of residues, cause health risks to consumers. Hence, pesticides are necessary for high agricultural productivity but have potentially harmful side-effects. These potential side-effects have prompted the government to strictly regulate the introduction of new chemical pesticides.

Some critics of Environmental Protection Agency (EPA) pesticide regulation assert that the cost of complying with regulations reduces the incentive to develop new pesticides.

Additionally, some researchers, such as Lichtenberg, Spear, and Zilberman (1993), question whether more stringent regulations result in safer pesticides. Other researchers (Gianessi and Puffer, 1992) argue that regulatory costs have encouraged firms to register pesticides only for major crop market uses, such as corn, and has deterred firms from registering pesticides for minor crop market uses, such as fruits and vegetables. Questions of the impact of regulation on registrations, pesticide toxicity, and pesticide crop market uses may be closely linked. Greene, Hartley, and West (1977) argue that high regulatory costs reduce the incentive to develop pesticides for minor crop uses and encourages firms to develop pesticides that are effective on many types of pests and under diverse weather conditions. However, these wide spectrum pesticides are the ones most likely to have more undesirable environmental side-effects.

Some evidence suggests that regulation became more stringent after the establishment of the EPA in 1972. Between 1970 and 1989, pesticide research expenditures used for health and environmental testing rose from 14 to 47 percent of total pesticide research spending; product development time rose from seven to eleven years; and, the EPA cost estimates of mandated testing requirements for registering pesticides under FIFRA (EPA-anticipated costs) almost doubled. Meanwhile, the number of new pesticide registrations dropped from 46 over the 1972-76 period to 24 over the 1987-91 period (Table 1). In terms of markets served, the number of new pesticide registrations for minor crops (vegetables, fruits, and nuts) declined from 62 over the 1972-76 period to 15 for the period 1985-89, while registrations for major crops (corn, soybeans, wheat, cotton, sorghum) remained almost unchanged (Table 1).

Previous studies (Council of Agricultural Science and Technology - CAST, 1992; Office of Technology Assessment - 1981; Hatch, 1982) of the effect of pesticide industry regulation have shown that, during the 1970s, the average cost of developing a new pesticide rose, pesticide research resources shifted towards toxicological and environmental testing and away from synthesis and screening, and the lag between discovery and commercialization of new pesticides rose. These studies did not address the effect of regulation on innovation, however. Additionally, they examined industry rather than firm level data.

Studies of the pharmaceutical industry may shed additional light on how regulation affects new pesticide registrations. Several economists (Peltzman, 1973; Grabowski, Vernon, and Thomas, 1978; Thomas, 1990) have shown that Food and Drug Administration (FDA) regulation adversely affects new pharmaceutical registrations. Thomas (1990) attributes most of the decline to the drop in pharmaceuticals that serve as close substitutes to existing drugs. However, Thomas (1990) neither investigates the impact of regulation on novel pharmaceuticals for small drug markets, nor addresses how pharmaceutical regulation affects drug quality. For example, did the harmful side effects of drugs that passed FDA approval drop after regulation became more stringent?

The purpose of this paper is to (1) examine the impact of EPA regulation on pesticide innovation, (2) investigate the relationship between regulation and the toxicity of new pesticides, and (3) evaluate whether regulation discourages firms from developing pesticides for minor crop markets. This paper differs from studies of the effects of pesticide regulation on innovation in that it uses firm-level rather than industry data. It differs from other studies of regulation in that it examines how regulation affects the toxic side effects of a newly registered product and identifies the industry submarkets affected by regulation. The paper is organized as follows. After first describing the regulatory and economic environment, we present a theoretical framework to examine the effect of EPA regulation on pesticide innovation, pesticide toxicity, and pesticide crop market uses. Next, we present our empirical models. Then, we briefly describe the estimation procedures. Finally, we present our results and concluding comments. The appendix contains a description of the variables and the data.

## II. Pesticide Regulation, Research Lags, and Industry Transition.

Concern over the health consequences of agricultural chemicals led Congress to enact the Federal Food, Drug, and Cosmetic Act (FFDCA) in 1938 and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) in 1948. Congress gave the Food and Drug Administration (FDA) the authority to establish procedures for setting tolerances under the FFDCA. FIFRA mandated that all agricultural chemicals for sale in interstate commerce be registered against manufacturers' claims of effectiveness and that the label state the toxicity of the pesticide. Congress assigned authority to enforce FIFRA to the USDA.

Congress amended FFDCA in 1954 and 1958 and FIFRA in 1959, 1964, and 1967. The FFDCA amendments required pesticide producers to thoroughly evaluate the safety of substances in food and to supply data showing the acute (immediate), intermediate, subchronic (up to 90 days), chronic (long-term), and other miscellaneous effects of the pesticides. The amendments also stated that no food additive that increases cancer potential in humans or animals can be considered safe. The FIFRA amendments granted the USDA the authority to regulate all pesticides, closed a loophole that enabled companies to register pesticides when regulators felt that more data were required, and made it necessary for pesticides to meet a finite tolerance to gain registration ( Hatch, 1982).

Hatch (1982) asserts that concern over the carcinogenic and environmental effects of pesticides led to the transfer of jurisdiction of pesticide regulation from the USDA to the EPA in 1970 and to a 1972 amendment to FIFRA that toughened existing pesticide laws. Under this new legislation, Congress gave the EPA responsibility for reregistering existing 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).

Some aspects of the 1972 amendment were ambiguous and were not resolved until the 1978 amendment. Part of the concern was over the costs of registering pesticides with low measurable environmental risks; the development of pesticides for minor crop markets (minor use pesticides); and, the reregistration of existing pesticides. A major concern addressed in the amendment was the use of existing field data by a second pesticide developer. The 1972 amendment stated that one legislative objective was to lower regulatory costs but it did not indicate how to resolve issues related to data transfers. A conflict arises when a second manufacturer wants to sell a product similar to one already on the market. Overall regulatory costs would be lower if the new manufacturer could use existing data. However, data used by a second pesticide developer puts this new developer in conflict with the interests of the owner of the data.

The 1978 amendment eased data requirements for pesticides that posed low environmental risks and gave the EPA the right to reduce data requirements for minor crop pesticides. The 1978 legislation also strengthened the enforcement function of the states and the authority to register pesticides for specific local needs. Additionally, the amendment allowed certain crop uses that were not inconsistent with the label. Finally, the 1978 amendment gave new manufacturers the right to use original producer data but required them to compensate the original developers. The amount of compensation was to be decided through arbitration.

The translation of the 1972 legislation into new pesticide field testing requirements took place gradually. The physical change in jurisdiction and staffing at the EPA involved the transfer of people to the EPA from the USDA and the FDA; thus, many of the early testing procedures were based on what these regulators had done previously.

The rule-making practices necessary to implement the 1972 FIFRA amendment also suggests a gradual increase in regulatory stringency. The EPA formally wrote rules in 1978 and 1982. These rules were in addition to those in existence in 1972. Another set of rules is currently in the review process. Gary Ballard and Arnold Aspelin of the EPA indicate that the EPA required pesticide firms to informally adhere to all rules before they were formally published. For example, 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.

The 1978 rules dealt mainly with chronic testing and, in terms of the EPA-anticipated costs, represented a 30% increase in regulatory stringency over the 1972 rules. The 1982 rules included many new environmental and chronic tests and increased anticipated stringency by 95% over that which existed in 1972. The current rule changes have increased stringency by about 100% over that which existed in 1972.

Testing requirements now include up to 70 different types of tests that consist of a two generation reproduction and teratogenecity 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 and wildlife, farm worker health, and other environmental effects. Staffing levels of workers devoted to enforcement of FIFRA reflect the growing EPA regulatory activity. During the 1972-75 period, EPA budgets indicate an average of 54.2 EPA Office of Pesticide Programs (OPP) employees for each new pesticide registration. By the 1986-89 period, the number of employees per new pesticide had risen to 91.4.

Aside from the regulatory lag, a significant lag also exists between the discovery of a new pesticide and the time when the pesticide is ready for commercial use. In 1972 it took an average of seven years to go from discovery to marketable product. Thus, pesticides registered in 1972 were discovered in 1965. It was not until 1982 that pesticides discovered after 1972 came onto the market, as the average development time had risen to ten years (NACA. 1983). Since all pesticides introduced before 1982 were in various stages of development when the EPA was established in 1972 and EPA regulatory stringency increased over time, the types of pesticides that firms introduced in the early 1970s may have differed substantially from the pesticides introduced during the mid 1980s. For example, during the 1970s, pesticide firms abandoned the development of organochlorines and other related pesticides because the EPA believed that these chemicals posed health risks and adversely affected the environment.

## III. Industry Transition

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 ingredient (a.i.). By 1982 herbicide sales increased to 455.6 million pounds of a.i. and stabilized, reaching 478.1 million pounds of a.i. in 1992 (Osteen and Szmedra, 1989; Delvo, 1993). In terms of acres treated, farmers applied pesticides to almost 95% of their corn, cotton, and soybean acreage by 1982 and application quantities per acre were stable during the 1980s. In addition to this apparent saturation of the market as expressed in the percentage of acreage treated, acreage planted declined after 1982. From 1970 to 1982, total U.S. grain production rose from 187 to 332 million metric tons, but then dropped to 283.7 million metric tons by 1989 as foreign and domestic demand declined. Reflecting these changed circumstances, farm real estate values dropped from $304 in 1982 to $215 billion in 1989 USDA, 1992). Hence, in the post-1982 period most new pesticides had to displace existing products to generate revenue.

Changes in the composition of the pesticide industry correspond with the maturation of the pesticide industry and the decline in farm output. In 1972 there were 33 companies actively engaged in pesticide innovation and pesticide sales by foreign-based companies were approximately 18% of the market. By 1989, the number of innovative pesticide companies dropped to 19 but the number of innovative foreign-based companies rose by three and the market share held by all foreign-based companies rose to 43% (Ollinger and Fernandez-Cornejo, 1993).

## IV. Firm and Industry Attributes Associated with Innovation

Previous economic research has characterized technological innovation as a function of research and development spending, regulatory costs, firm size, market structure, and demand conditions. Jaffe (1985), among other economists, considers research expenditures an investment in the development of economically useful knowledge. Mansfield (1968) and many subsequent researchers have found positive relationships between research and development spending and the rates of technological innovation. In an industry similar to the pesticide industry, Grabowski, Vernon, and Thomas and Thomas (1978) found a strong positive relationship between firm pharmaceutical research expenditures and the number of new drug introductions.

Sutton (1991) demonstrates that regulatory costs may affect research expenditures and thus also influence innovation. He shows that a rise in exogenous sunk costs, such as regulatory costs, makes it necessary for a firm to either exit the industry or increase revenues. Firms increase revenues by increasing endogenous sunk costs, such as research and development. The increase in research expenditures can be directed at making an existing product useful in more markets, improving products in larger markets, or both.

Firms may vary in their innovative success. Klepper and Graddy (1990) argue that, as a market evolves, firms with higher product qualities and lower costs prosper at the expense of firms with lower product qualities and higher costs. In an innovative industry, this suggests that recent success encourages innovators to generate more new products and thus continue to grow. For example, Thomas (1990) attributes the inability of small firms to grow in the pharmaceutical industry to a decline in their research productivity.

Several economists assert that high cost research, as that required for chemical pesticides, may favor large firms. Schumpeter (1961) and Galbraith (1952) suggest that large firms have greater financial capacity and thus can better spread risks. More recently, Greene, Hartley, and West (1977) and Teece (1982) claim that large firms are better able to take advantage of their research because they have more market outlets. In addition, Acs and Audretsch (1987) empirically show that large firms have an innovative advantage in industries that are capital-intensive and produce a differentiated good. Hence, size gives a firm more market opportunities and greater financial capacity to fund research.

Kamien and Schwartz (1982) remind us that invention is a response to profit opportunities. Two aspects of demand are relevant. The robustness of demand influences the number of products a market can absorb and thus may affect innovation. In addition, Kaplinsky (1983) argues 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.

## V. The Innovation Process in the Pesticide Industry

The process of developing new pesticides is lengthy and costly. After discovery, the development process passes through a number of steps. First, researchers conduct secondary screenings in which biological thresholds are determined. Next, a multi-disciplinary group determines which compounds deserve further investigation. Afterwards, process development personnel synthesize the most promising chemicals in larger quantities. Other experts use the larger batches of chemicals to conduct efficacy tests in the laboratory and the field, examine chemical toxicity, and estimate production costs. This technical and cost data is then passed on to managers who determine whether the company should pursue small plot field testing.

Selected chemicals must pass through a series of ever more demanding field tests. First, agricultural researchers use small scale field testing in order to determine the efficacy of the chemical compound relative to existing pesticides. They also evaluate the impact of soil, sunlight, microbes, and the climate on its effectiveness. If the pesticide candidate fares well against existing pesticides, the firm obtains an experimental use permit (EUP) from the EPA. This EUP allows the company to conduct larger field tests. The EPA grants the EUP only if it believes that evidence, provided by the company, shows that no adverse environmental effects will occur. If the EPA does not grant a permit, then the company must either specify a new field test that meets EPA objections or abandon pesticide development.

In the larger field tests, biologists and other experts conduct metabolism, environmental, residue, and toxicology studies in order to determine the impact of the compound on humans, mammals, fish, and wildlife. Simultaneously, chemical engineers and other production personnel develop formulation techniques and production methods.

The ability to select chemical compounds with high efficacy that can also meet EPA toxicity tests is extremely important. Selecting a chemical compound that does not meet EPA requirements leads to lost research costs and time. The selection of a chemical with low efficacy may enable the pesticide to meet EPA toxicity standards, but cause it to fail in the marketplace. Developing an optimal testing strategy is important because, if a firm conducts too many tests, it incurs high development costs. Alternatively, if a company does not conduct enough tests or has poor data, then the additional tests or the revisions to the data delays the commercialization of the product and results in lost revenue.

As suggested earlier, increasing test requirements and perhaps declining research opportunities correspond with increases in the pesticide development cycle and regulatory costs. NACA (1972 and 1988) surveys indicate that the industry average time required to bring a pesticide from initial screening to market rose from seven years in 1971 to ten years in 1987. In addition, new pesticide research expenditures for health and environmental testing as a fraction of new pesticide research and total research expenditures for health and environmental testing as a fraction of total industry research spending each rose by over 200 percent.

Both the increase in research regulatory costs and the pesticide development cycle are costly and can deter firms from developing certain types of chemical pesticides. Higher development and regulatory costs discourage some types of innovation because a product must realize greater revenue in order to be profitable. The increase in pesticide development time is costly because it leads to a longer payout period. In addition, companies gain patent protection during the development process. Thus, a longer development time also gives a pesticide company less time to sell a pesticide as a proprietary product.

A pesticide can be developed for application on major crops, minor crops, or both. Potential revenue can vary from thousands to millions of dollars for each use and is limited because farmers already use pesticides on most of their farm acreage. Accordingly, increases in either research costs or pesticide regulatory expenses cause the gap between potential revenues and costs to narrow and results in some minor crop pesticides becoming unprofitable. Hence, an increase in either research or regulatory costs should cause new pesticide registrations to decline and should encourage firms to shift their research focus to the development of pesticides for major crop markets.

Higher research expenditures may lead to the development of more toxic pesticides. The objective of research and development expenditures is to develop new pesticides with high efficacy that can generate significant revenues and, hence, profits. Ollinger, Aspelin, and Shields (1993) found that research expenditures positively affect new pesticide product size (i.e. sales). Beach and Carlson (1992) show that farmers value the efficacy of pesticide much more than safety or environmental qualities. Accordingly, a pesticide firm must first and foremost develop a pesticide with high efficacy. Plapp (1993) observes that insecticides with high efficacy are also very toxic. Lichtenberg, Spear, and Zilberman (1993) support this view for pesticides in general. Hence, in order to develop a pesticide with the qualities demanded by farmers and thus generate high revenue, a firm must select a pesticide candidate from a group of highly toxic compounds.

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

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

## VI. Empirical Models

Below we consider reduced form empirical models of the determinants of new pesticide registrations, pesticide toxicity, and pesticide crop market size. We examine the hypotheses that EPA regulation adversely affects new pesticide innovation, encourages the development of more toxic agricultural chemicals, and discourages the development of pesticides for minor crop markets.

### A. Pesticide Innovation

Equation (1) is a reduced form empirical model of the relationship between new pesticide registrations ($N_{it}$), which is used as a measure of economically useful innovations, and pesticide research expenditures ($RESEARCH_{it}$), pesticide growth in market share ($LG3SHR_{it}$), a dummy variable for foreign-based firms that enter the U.S. pesticide market after 1972 ($INT_{it}$), an interaction term between $INT_{it}$ and $RESEARCH_{it}$ ($RDINT_{it}$), firm pesticide market share ($LSHARE_{it}$), pesticide regulation ($PESLAB_t$), farm output prices ($PRICES_t$), which is a proxy for farm demand, and industry growth ($GROW5_t$), which is a proxy for the industry life cycle.  All variables except the dummy variable are in log form.  (See the appendix for detailed variable definitions.)

$$\ln(N_{it}) = \$_0 + \$_1 \ln(RESEARCH_{it}) + \$_2 \ln(LG3SHR_t) + \$_3 INT_{it} + \$_4 RDINT_{it} + \$_5 \ln(LSHARE_{it}) + \$_6 \ln(PESLAB_t) + \$_7 \ln(PRICES_t) + \$_8 \ln(GROW5_t) + ,_{it}.) \quad (1)$$

Since, we are testing the hypothesis that regulation adversely affects innovation, we control for other factors that are either known to or are known likely to affect innovation. Previous research, as discussed above, suggests that research expenditures, growth in firm market share, the presence of foreign-based firms, firm size, and industry growth should positively affect innovations.

The dummy variable for foreign-based firms should positively affect pesticide registrations because foreign-based firms can introduce pesticides from overseas into the U.S. market while incurring very low research costs.  This apparent advantage should diminish as foreign-based firm U.S. pesticide research expenditures rise. The interaction term between the foreign-based firm dummy variable and research expenditures ($RDINT_{it}$) should, therefore, negatively influence pesticide innovations.

We use three proxies for regulatory stringency in order to verify the robustness of our results. Each of these regulatory proxies relates strongly to the others. As the first measure, we use labor at the Office of Pesticide Programs ($PESLAB_t$). The approval process becomes longer when regulation becomes more stringent and shortens when employment is increased. Since approval times at the EPA have increased slightly over the past twenty years, a change in employment should provide a measure of the change in regulatory stringency.

We also employ industry pesticide research expenditures used for toxicological and environmental testing as a fraction of all pesticide research and development expenditures ($AVREG_t$) as a measure of regulatory stringency. These costs change with changes in regulatory stringency, but may overstate the regulatory impact. Firms would likely do some toxicological and environmental testing in the absence of regulation because Beach and Carlson (1992) showed that farmers value health and environmental attributes of pesticides.

Our third measure of regulation is the anticipated costs of data requirements for registering pesticides under FIFRA (EPA-anticipated costs), $ARUL75_t$. The EPA established new regulatory rules in 1978, 1982 and 1994. In each instance, the EPA estimated the costs of the new and existing tests. Given these costs, we constructed an index of regulatory stringency.

According to Arnold Aspelin and Gary Ballard of the EPA who wrote the Economic Impact Analysis for the rule changes, new pesticide registrants complied with new rules prior to their formal publication. Hence, 1978 rules formalized the revised 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 1981. To define $ARUL75_t$, we assume that actual compliance occurred in 1975 for the 1978 rules, in 1979 for the 1982 rules, and in 1988 for the 1994 rules. Since it is possible that firms anticipate regulatory changes, we also estimate a model in which we assume that the 1978 rules were anticipated in 1972, 1982 rules were anticipated in 1979, and the current rules were anticipated in 1983. The results obtained with this alternative definition are similar to $ARUL75_t$ and thus we do not report them.

We define each regulatory term as a lag structure over the industry average pesticide development cycle because a firm excludes sunk costs when making development plans. For example, if a firm was at the beginning of the 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 and the firm does not develop it. However, if initial development is complete, a firm ignores past (sunk) development costs and balances testing costs (T) against potential revenues. As a result, a firm may seek registration of the product. Hence, the full effects of regulation are not immediately felt and one must consider the regulatory regime over the entire product development cycle.

**B. Pesticide Toxicity**

Pesticides are biologically active and many may be harmful either to the environment or to human health. Concern over pesticide toxicity led the EPA to require that producers place acute toxicity ratings (I, II, III, or IV) of the pesticide on the label. 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 percent of the test animals studied within the first 30 days after exposure. The EPA also requires producers to note on the label all chronic human effects and any possible harm from inhalation, skin absorption, or eye damage. Additionally, producers must indicate on the registration whether the pesticide harms fish or wildlife.

The various reporting requirements stem from differences in the health and environmental effects of chemical pesticides. For example, some pesticides have a high acute toxicity rating, cause chronic health effects, and are harmful to fish and wildlife.

Others may have a low acute toxicity rating, have no chronic health effects, and may not be harmful to fish and wildlife. These differences in toxicity allow one to classify pesticides as being "more" or "less" toxic.

Equation 2 regresses the proportion of less toxic pesticides to all pesticides ($LESSTOX_t$) on pesticide industry research expenditures ($RDIND_t$), the Herfindahl Index ($HERF_t$), the proportion of foreign-based firm entrants ($INT2_t$), regulation ($PESLAB_t$), and, control variables for farm sector market conditions ($PRICES_t$) and pesticide sales growth ($GROW5_t$). Again, we use three proxies of regulation to check model robustness.

$$LESSTOX_t = \$_9 + \$_{10}RDIND_t + \$_{11}HERF_t + \$_{12}INT2_t + \$_{13}PESLAB_t + \$_{14}PRICES_t + \$_{15}GROW5_t \qquad (2)$$

We test whether regulation causes firms to introduce a greater number of less toxic pesticides. We argued above that research expenditures should negatively affect the number of less toxic pesticides. In addition, previous research suggests that surviving pesticide companies tended to be larger and better able to avoid regulatory penalties than acquired companies (Ollinger and Fernandez-Cornejo, 1993). Hence, we expect the Herfindahl Index to positively affect the number of less toxic pesticides. We use the proportion of foreign-based firm entrants, agricultural prices, and industry growth as control variables for the influence of foreign-based firm entrants, farm sector demand conditions, and the industry life cycle.

**C. Pesticide Crop Markets**

Pesticides can only be sold if they are registered for use on a particular crop (crop use). Equation 3 regresses the ratio of the number of pesticides for major crop markets to the number of pesticides developed for all crop markets ($LARGCROP_t$) on pesticide industry research ($RDIND_t$), the Herfindahl Index ($HERF_t$), foreign-based firm entrants ($INT2_t$), regulatory intensity ($PESLAB_t$), agricultural prices ($PRICES_t$), and the growth of planted agricultural acreage ($GROW2_t$). Again, we use three proxies of regulation to check model robustness.

$$LARGCROP_t = \$_{15} + \$_{16}RDIND_t + \$_{17}HERF_t + \$_{18}INT2_t + \$_{19}PESLAB_t + \$_{20}PRICES_t + \$_{21}GROW2_t \qquad (3)$$

We are testing the hypothesis that higher regulatory costs reduce the margin between potential product revenues and product costs and thus encourages producers to develop broad spectrum pesticides that can service at least one major crop market (i.e. corn, soybean, sorghum, wheat, and cotton) and to abandon specialized minor crop markets, i.e. fruits and vegetables. Empirically, one would expect regulatory costs to positively affect the ratio of pesticides developed for major crop markets to pesticides developed for all crop markets.

We control for other factors that may influence pesticide crop market use. Research effort affects both the amount of research output and the type of research and, thus, may influence pesticide crop market use. Successful firms with larger market shares must develop pesticides for major crops in order to maintain their market position; thus, a rise in the proportion of these successful firms may affect pesticide crop market use. Hence, the Herfindahl index should positively affect the proportion of pesticides for major crop markets. In addition, we control for foreign-based firm entrants, agricultural prices, and industry growth. The expected profits from a given crop market varies with the potential size of the market. A decrease in planted acreage may make some minor pesticide uses unprofitable and an increase in planted acreage may make pesticide market uses profitable. Hence, planted acreage may negatively affect the proportion of pesticides for major crop markets.

Precise variable definitions are presented in Appendix A. The description of the data is located in Appendix B. Most of the data came from the U.S. Bureau of the Census, EPA publications, and NACA pesticide industry surveys.

## VII. Estimation Methods

We use a two stage Quasi-Likelihood (QL) method to estimate equation 1 over the 1972-91 period with firm-level data. New pesticide registrations approximate a Poisson distribution, with most firms in most years introducing no new 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 innovative efficiency causes the variance to grow faster than the mean and results in over (under) dispersion (see Gourioux, 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 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. (See Thomas, 1990, for a more complete discussion).

Quasi-likelihood estimates can be obtained with the use of nonlinear weighted least squares with the variance term V(u) as a weight. The dispersion parameter ($F_{est}^2$) is estimated with equation (4). A value of one indicates an absence of over (under) dispersion.

$$\sigma^2_{est} = \sum_k \frac{(y\text{-}u)^2}{V(u)} / (k\text{-}p) \,. \qquad (4)$$

Inference about individual parameters b is based on the asymptotic standard errors and t-statistics reported in the weighted least squares outputs of statistical packages.

Inference for multiple parameters is based on the QL function, $l(u;y)$. For a Poisson distribution this QL function is specified as

$$l(u;y) = y \log(u) - u \qquad (5)$$

(See Carrol and Rupert , 1988, for discussion).

The QL function and the dispersion parameter in equation (6) are then used to compute the chi-square statistic, $\chi^2$

$$2\Delta QLF = 2\left(\sum_k l(U(\boldsymbol{b}_{max};y) - \sum_k l(U(\boldsymbol{b}_{rest};y))\right) \sim \sigma^2_{est}\chi^2_{p-q} \qquad (6)$$

Note, $b_{rest}$ are restricted parameter estimates and $b_{max}$ are unrestricted estimates.

The dispersion parameter (Table 2) indicates that some underdispersion exists. Our econometric method has controlled for this; thus, our results are not biased. The $\chi^2$ statistics are computed from equation (6) and are reported in Table 2.

Sutton (1991) shows that exogenous sunk cost, such as pesticide product regulation, positively affect endogenous sunk costs, such as research spending. Hence, it is necessary to purge the research term ($RESEARCH_{i,t}$) of its dependence on regulation and other factors. Accordingly, we create the instrumental variable ($\boldsymbol{RESEARCH}_{i,t}$), which is the predicted value of firm pesticide research expenditures. We employ all exogenous variables and overall firm research as instruments. We define overall firm research in a way similar to $RESEARCH_{it}$ in equation A.1.

We use a two stage SUR method to estimate equations 2 and 3 over the 1972-89 period with industry-level data. First, we create an instrumental variable (***INDRD***$_t$) for industry pesticide research ($RDIND_t$) because an increase in exogenous sunk (regulatory) costs may affect the level of endogenous sunk (research) costs (See Sutton, 1991). We use value added and all the exogenous variables of equations 2 and 3 as instruments. Value added came from U.S. Bureau of the Census files.

In estimating equations (2) and (3) we first model some preliminary estimators with OLS to determine whether autocorrelation is present. We determine that it is not. Next, we estimate equations (2) and (3) with a "two limit" tobit because both equations (2) and (3) are bounded between zero and one (See Maddala, 1983). Results are similar to those of the OLS because the limits are not binding. Hence, neither autocorrelation nor the theoretical bounds bias the results. As a consequence, we use a SUR econometric model with the instrumental variable for industry research and the other variables of equations 2 and 3 as explanatory variables. We made no adjustments for autocorrelation. We report the Durbin-Watson statistics in Tables 3 and 4.

## VIII. Results

### A. Pesticide Innovation

Results for three time periods with three regulatory cases for each time period are reported in Table 2. We examine the 1972-81 and 1982-91 periods in addition to the overall period because anecdotal evidence suggests a phase-in period for new regulatory rules and a period of little change afterward. The EPA published its first rules for chronic toxicity in 1978 and it was not until 1982 that the EPA implemented a complete set of rules for both chronic and environmental testing. Later additions supplemented existing rules but did not go beyond the chronic and environmental testing mandates stated in the 1972 FIFRA amendments. Table 2 contains results for these three periods.

The three cases presented in Table 2 differ in the use of regulatory variables. Each regulatory variable measures a similar phenomenon - regulatory intensity - and correlates strongly with the other proxies for regulation. Since each regulatory term also affects research expenditures, we use an instrumental variable for research expenditures to make the regulatory term an expression that is net of its impact on research expenditures. Hence, each regulatory variable represents a net regulatory impact.

Results of the product innovation regression for the overall period indicate that pesticide research expenditures, firm market share growth, and foreign-based entrants relate positively to new pesticide registrations. Regulation and the interaction term between foreign-based company entrants and pesticide research relate negatively to new pesticide registrations. Market share is negative but insignificant. Industry growth is positive but insignificant in some periods of the first two regulatory cases and is dropped in the third case because of serious collinearity with $ARUL75_t$.

Of considerable interest is the negative and significant signs on the coefficients of the regulation terms. The coefficient for Pesticide Division labor ($PESLAB_t$) suggests that an increase of employment at the pesticide division of 10 percent leads to about a 16 percent decline in innovation. The coefficient of the ratio of regulatory costs to industry pesticide research ($AVREG_t$) suggests that a 10 percent increase in new pesticide regulatory costs results in a 2.4 percent reduction in innovation. The coefficient on the EPA-anticipated cost of data requirements for regulatory compliance ($ARUL75_t$) suggests that a 10 percent increase in the EPA-anticipated cost leads to a 15.2% decline in innovation. As indicated earlier, we also assumed that the complete effects of the 1978, 1982, and current rules occurred in 1972, 1979, and 1983. The results are similar and available from the authors.

The positive and significant influence of pesticide research expenditures is consistent with Thomas (1990) and other studies of pharmaceutical innovation. The positive influence of market share growth is consistent with Klepper and Graddy (1990) in that past success fosters future success. The insignificance of the market share term (Table 2) suggests that some large firms were producers of nonproprietary agricultural chemicals. Firms can generate sales from either new proprietary pesticides or non-proprietary pesticides. If it generates revenues from new pesticides then market share should be strongly related to innovation. However, if a firm derives revenue from well-established pesticides then market share may not affect innovation.

The positive sign of the foreign-based firm entrant dummy, also reported in Table 2, indicates that foreign-based entrants had a significant innovative advantage over firms with a larger U.S. pesticide research presence. This does not imply that foreign-based firms had higher pesticide research productivity. Teece (1982) argues that companies with greater geographic dispersion have greater opportunities to market their products and thus recover sunk costs. Along this line, a foreign-based company may use products developed overseas to enter the U.S. market. These companies would have lower U.S. research costs and an apparent innovative advantage over established U.S. companies. As foreign-based companies increase their U.S. pesticide research spending, however, their apparent advantage may diminish.

The interaction term represents the effect of size of U.S. pesticide research operations of international firm entrants on innovation. The negative sign of the coefficient supports the view that foreign-based firms lose their innovative advantage as they expand their U.S. presence. An examination of the dummy variable for foreign-based entrants and the interaction term indicates that foreign-based entrants with more than $20 million in U.S. pesticide research expenditures had no innovative advantage over other companies. The prices variable was dropped from all equations and industry growth was dropped from the model containing $ARUL_{75}$ because of insignificance due to collinearity.

Now contrast the 1972-81 and 1982-91 periods. Results indicate that regulation did not change in stringency in the second period. During the 1972-81 period, all regulatory coefficients are significantly negative. During the second ten year period, $PESLAB_t$ is positive but insignificant, $AVREG_t$ is negative and insignificant, and $ARUL75_t$ is significantly negative but with a lower coefficient than in the first period. Hence, after the EPA finalized implementing rules for the 1972 FIFRA amendment in 1982, there was little or no additional regulatory impact on pesticide registrations.

These results of the impact of pesticide regulation on pesticide innovation are similar yet different from previous studies in the pharmaceutical industry. Similar to Grabowski, Vernon, and Thomas (1978); and Thomas (1990), we find that EPA regulation has a negative influence on innovative productivity. Unlike Thomas (1990), our results do not indicate an increase in regulatory stringency over time.

**B. Pesticide Toxicity**

Table 3 contains the results of the pesticide toxicity regression. We examine six cases, including two specifications of the dependent variable and three regulatory expressions for each dependent variable specification. Of most significance is that regulation encouraged the development of less toxic pesticides. This result is consistent with the hypothesis that greater regulatory scrutiny raises the search and development costs of bringing a pesticide to market. The impact of more stringent regulation is costly, however. If the industry introduced 50 new pesticides over the next ten years, a 10 percent increase in toxicological and environmental testing costs would result in between 2 and 3 additional pesticides being "less" rather than "more" toxic. The cost of causing this change would be about $29 million per pesticide. In terms of $ARUL75_t$, a 10 percent increase in EPA-anticipated costs results in about 5 additional pesticides being "less" rather than "more" toxic over ten years. Results for $ARUL72_t$ are similar to those for $ARUL75_t$ and are available from the authors.

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 fewer less toxic pesticides. This result is consistent with the hypothesis that farmers value pesticide efficacy more than health and environmental effects and that pesticides with high efficacy are also very toxic. These toxic pesticides are less likely to pass regulatory scrutiny, making the search for pesticides with high efficacy that can pass regulatory guidelines a costly process. Hence, an increase in research and development expenditures causes an increase in efficacy but decreases the percentage of less toxic pesticides.

The pesticide toxicity regression also shows that the Herfindahl Index and industry growth had positive influences on the proportion of less toxic pesticides. Farm prices negatively influenced the proportion of less toxic pesticides. The positive sign on the coefficient for the Herfindahl Index is consistent with previous research (Ollinger and Fernandez, 1993) indicating that larger firms incur lower regulatory-related costs than smaller firms. The proportion of foreign-based entrants had no effect on pesticide toxicity and was dropped.[2]

**C. Pesticide Crop Markets**

Table 4 reports the results of the pesticide crop market regression. The six cases correspond to those in Table 3 for equation 2. We estimated equations (2) and (3) together using the SUR method. Regulation and the Herfindahl Index have a significantly positive effect on pesticides for major crop market use. Research expenditures and growth have no significant effect on pesticide crop market use. Estimates of the degree to which regulation influences pesticide crop market choices suggest that a 10 percent increase in regulatory costs causes a 3.4 percent increase in the proportion of pesticides for major crop markets to pesticides for all crop markets. Alternatively, a 10 percent increase in EPA-anticipated costs causes an 8 percent increase in the proportion of pesticides for major crops. Results for $ARUL72_t$ are similar to those for $ARUL75_t$ and are available from the authors.

The positive relationship between the regulatory cost ratio and crop market size is consistent with the hypothesis that firms respond to greater regulatory costs by focusing their research on pesticides for major crop markets. Two possibilities exist. Firms could develop many pesticides for minor crop markets but develop proportionately more pesticides for major crop markets. Alternatively, firms could increase or not change the number of new pesticides they develop for major crop markets and reduce the number of new pesticides for minor crop markets.

Table 1 shows that the number of pesticides for major crop markets dropped less than that for minor crop markets. For example, the number of pesticide introductions for herbicides for major crop markets remain almost constant throughout the 1972-89 period. Hence, the proportion of pesticides for major crop markets rose because firms developed fewer pesticides for minor crop markets.

The positive effect of the Herfindahl Index is consistent with the hypothesis that successful firms with larger market shares develop pesticides for major crops. Other variables, such as farm prices, the proportion of firms with mainly overseas pesticide research facilities and farm prices have no effect on crop market size and were dropped. Growth in planted farm acreage is reported but has an insignificantly negative effect on crop market size.

## IX. Concluding Comments

A major finding of this paper is that regulation negatively affects innovation, as measured by the total number of new pesticide registrations. The regulatory impact has its greatest effect on pesticides for minor crop markets, i.e. minor vegetable, fruit, and nut markets. These findings affirm the hypothesis of Green, Hartley, and West (1977) in that regulation did negatively affect innovation and firms did focus more on the development of pesticides for major field crops.

Another major result is that regulation encourages firms to develop less toxic pesticides. Although this last finding is in conflict with the view that regulation is likely to cause firms to develop more toxic chemical pesticides, it agrees with anecdotal evidence related to persistence.[3] This anecdotal evidence suggests that, after the EPA banned DDT and several other chemical pesticides that persist in the environment, pesticide firms focused their pesticide research on pesticides that degrade rapidly and stopped the development of pesticides that persist in the environment. Hence, regulation has encouraged firms to develop chemical pesticides that are both less toxic and are less persistent in the environment.

The reduction in the availability of new pesticides for minor crop markets could prove costly because pests eventually develop resistance. Eichers (1980), for example, indicates that insect resistance had caused a drop in sales of DDT, chlordane, and heptachlor before the EPA banned these organochlorine insecticides. Additionally, Eichers (1980) indicates that weed resistance to the herbicide 2,4-D led to the decline in market share from 32% in 1966 to 4% in 1976. Despite this tendency to develop resistance, new registrations of chemical pesticides for minor crops have not been forthcoming. Additionally, about 600 existing crop registrations will be dropped from use by 1997 because of reregistration costs (See Gianessi and Puffer, 1992).

The costs of pesticide regulation may also have favored the development of pest-control alternatives. Over the past four years, about 25% of all new registered pesticides have been biologicals, which have substantially lower regulatory costs than chemical pesticides. Major pesticide companies also have been active in plant biotechnology. By modifying plant gene structures, pesticide companies are developing some plants that are tolerant to pesticides and other plants that have inbred pest resistance. These two types of plant characteristics enable farmers to either use existing pesticides on more crop varieties or to avoid the use of some types of pesticides.

Three results of this paper are consistent with previous pharmaceutical industry studies in two ways. Grabowski, Vernon, and Thomas (1978) and Thomas (1990) found that stricter FDA regulation of the pharmaceutical industry caused innovative productivity to decline. Thomas (1990) also found that FDA regulation caused firms to focus their research resources on more fundamentally innovative products, which have the potential of generating very high levels of revenue, and to reduce the development of imitative products, which have lower potential revenues.

This paper differs from previous pharmaceutical industry studies in two principal ways. First, it shows that pesticide regulation caused the development of less toxic pesticides. Although Peltzman (1973) found that the incidence of ineffective drugs was less than 10% in the pre- and post-1962 periods, economic studies of the pharmaceutical industry do not examine side-effects. Second, rather than examining highly innovative and imitative products, we consider only novel pesticides. Like pharmaceutical industry studies, however, we find that firms changed their research focus to the development of pesticides with a potential of generating very high levels of revenue.

**Table 1**
**Pesticide Toxicity and Crop Market Use of Pesticide**
(Number of pesticides registered belonging to a given group)

| | Toxicity | | | | | Crop Market [1] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Year [2] | Class1 Acute | Chr | F/Wild | Oth | Tot [3] | Maj Fld [4] h,i,o [5] | Min Fld h,i,o | Veg h,i,o | Frt/N h.i.o | Nur/ Oth h,i,o |
| 1972 (12) | 3 | 1 | 3 | 4 | 5 | 2,3,0 | 4,3,1 | 3,5,0 | 4,4,2 | 3,2,1 |
| 1973 (4) | 1 | 2 | 5 | 2 | 7 | 1,1,1 | 2,1,2 | 4,0,2 | 3,1,2 | 0,2,0 |
| 1974 (11) | 2 | 2 | 4 | 2 | 6 | 3,2,1 | 4,2,1 | 3,4,2 | 3,2,2 | 2,2,2 |
| 1975 (12) | 1 | 1 | 3 | 1 | 6 | 4,1,0 | 5,1,1 | 2,1,0 | 4,3,0 | 7,1,1 |
| 1976 (7) | 0 | 1 | 3 | 1 | 3 | 2,0,0 | 2,0,0 | 3,0,0 | 3,0,0 | 2,0,2 |
| 1977 (1) | 1 | 1 | 1 | 0 | 1 | 0,0,0 | 0,0,0 | 0,0,0 | 0,0,0 | 2,0,1 |
| 1978 (0) | 0 | 0 | 0 | 0 | 0 | 0,0,0 | 0,0,0 | 0,0,0 | 0,0,0 | 0,0,0 |
| 1979 (9) | 2 | 1 | 5 | 2 | 7 | 1,4,2 | 1,3,3 | 2,6,6 | 2,5,6 | 3,5,2 |
| 1980 (9) | 2 | 2 | 2 | 1 | 5 | 3,1,0 | 2,0,0 | 0,1,0 | 0,0,0 | 1,3,0 |
| 1981 (5) | 1 | 0 | 2 | 1 | 3 | 0,0,2 | 0,0,1 | 0,0,2 | 0,0,4 | 0,0,3 |
| 1982 (7) | 1 | 1 | 3 | 3 | 5 | 2,2,1 | 1,0,0 | 0,1,0 | 0,1,0 | 1,0,2 |
| 1983 (8) | 1 | 2 | 4 | 0 | 6 | 3,0,0 | 4,0,0 | 5,0,2 | 4,0,2 | 3,2,1 |
| 1984 (7) | 0 | 2 | 3 | 0 | 4 | 0,2,0 | 0,0,0 | 0,2,0 | 0,3,2 | 2,2,3 |
| 1985 (4) | 1 | 1 | 3 | 2 | 4 | 0,0,0 | 0,0,0 | 0,2,0 | 0,0,0 | 2,2,0 |
| 1986 (8) | 1 | 0 | 2 | 0 | 2 | 6,0,0 | 3,0,0 | 1,0,0 | 0,0,0 | 3,1,0 |
| 1987 (4) | 3 | 0 | 3 | 3 | 6 | 3,0,0 | 2,0,0 | 0,0,0 | 0,0,0 | 2,1,0 |
| 1988 (4) | 2 | 0 | 2 | 2 | 3 | 3,1,0 | 2,1,0 | 0,2,0 | 0,0,0 | 1,0,0 |
| 1989 (10) | 1 | 0 | 2 | 1 | 3 | 2,1,1 | 2,0,2 | 0,0,2 | 2,2,4 | 2,0,1 |
| 1972-76(46) | 7 | 6 | 18 | 8 | 27 | 12,7,2 | 17,7,5 | 15,10,4 | 17,10,6 | 14,7,6 |
| 1977-81 (24) | 6 | 4 | 10 | 4 | 16 | 4,5,4 | 3,3,4 | 6, 7, 8 | 2,5,10 | 6,8,6 |
| 1980-84 (36) | 5 | 7 | 13 | 5 | 23 | 8,5,3 | 7,0,1 | 5, 4, 4 | 4,4,8 | 8,7,9 |
| 1985-89 (30) | 7 | 1 | 12 | 8 | 18 | 14,2,1 | 9,1,2 | 1, 4, 2 | 2,2,4 | 10,4,0 |

**1.** Since one type of pesticide can be used on several crops, the number of pesticide types in all categories exceeds the total number of new pesticides.
**2.** Number in parentheses is total new pesticides; table does not include 3 registrations in 1990 and 3 registrations in 1991; over 1982-86 period there were 34 and over 1987-91 there were 24 new registrations.
**3.** Since one pesticide may have multiple health and environmental effects, this number is less than sum of all health and environmental effects. Chr: chronically toxic; F/Wild: toxic to fish and wildlife; Oth: other effects.
**4.** Maj Fld: corn, cotton, sorghum, soybean, and wheat; Min Fld: alfalfa, barley, clover, flax, hops, lentils, mint, oat, peanut, peas, potatoes, rice, rye, safflower, sunflower, sugarbeet, sugarcane, sweet potato, tobacco; Veg: asparagus, beans, broccoli, cabbage, carrot, cauliflower, onions, sweet corn, cucumbers, lettuce, tomatoes, and 35 other vegetables, having less than 100,000 acres planted; Frt/N: apple, grape, nectarine, peach, pear, plum/prune, citrus, strawberry, almonds, filberts, pecans, walnuts, and 51

other fruits and nuts, products with generally less than 100,000 in acreage. Nurs/Oth: greenhouse, grass & turf, conifers, five other nursery uses, forage & pasture, storage, forestry, and five other non-crop and non-Nursery uses.
**5**. h is herbicides; i is insecticides; o is fungicides and other pesticides.

## Table 2

**Estimates of the Determinants of Pesticide Innovations**
(standard errors in parentheses)

| Variable | Case 1 | | | Case 2 | | | Case 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1972-91 | 72-81 | 82-91 | 1972-91 | 72-81 | 82-91 | 1972-91 | 72-81 | 82-91 |
| INTCPT | -14.6*** | -14.5*** | -21.0*** | -13.0*** | -11.4*** | -26.3*** | -0.74*** | 25.0*** | -0.66 |
| | (2.29) | (4.19) | (6.00) | (2.59) | (3.31) | (8.88) | (2.16) | (11.2) | (7.83) |
| ***INSTRD*** | 0.96*** | 0.66** | 1.55*** | 0.94*** | 0.65** | 1.49*** | 0.74*** | 0.46* | 1.55*** |
| | (0.19) | (0.27) | (0.42) | (0.18) | (0.27) | (0.41) | (0.19) | (0.28) | (0.43) |
| LG3SHR | 0.97* | 2.05** | 1.67** | 0.91* | 2.17** | 1.69* | 0.59 | 1.99* | 1.85** |
| | (0.55) | (1.05) | (0.85) | (0.54) | (1.07) | (0.88) | (0.54) | (1.08) | (0.88) |
| INT | 5.89*** | 4.62 | 2.17 | 5.47*** | 4.46 | 1.44 | 4.87** | 2.41 | 3.08 |
| | (2.28) | (3.03) | (6.30) | (2.16) | (3.14) | (6.04) | (2.34) | (3.27) | (5.84) |
| RDINT | -0.59** | -0.47 | -0.17 | -0.56** | -0.45 | -0.09 | -0.51* | -0.20 | -0.29 |
| | (0.30) | (0.41) | (0.79) | (0.28) | (0.43) | (0.75) | (0.31) | (0.45) | (0.72) |
| LSHARE | -0.13 | -0.08 | -0.58* | -0.17 | -0.09 | -0.61* | -0.12 | -0.06 | -0.59* |
| | (0.13) | (0.19) | (0.33) | (0.13) | (0.19) | (0.34) | (0.13) | (0.21) | (0.34) |
| PESLAB | -1.61*** | -1.57** | 7.28 | - | - | - | - | - | - |
| | (0.46) | (0.64) | (5.25) | | | | | | |
| AVREG | - | - | - | -1.52*** | -1.65*** | -5.72 | - | - | - |
| | | | | (0.42) | (0.67) | (3.58) | | | |
| ARUL75 | - | - | - | - | - | - | -1.52*** | -6.5*** | -3.30** |
| | | | | | | | (0.48) | (2.49) | (1.74) |
| GROW5 | 2.76 | 7.83*** | 0.85 | 0.36 | 7.10** | 0.50 | - | - | - |
| | (2.07) | (3.35) | (7.04) | (2.51) | (3.45) | (6.98) | | | |
| OBS. | 388 | 178 | 178 | 388 | 178 | 186 | 388 | 178 | 178 |
| SIGMA | 0.94 | 0.91 | 0.94 | 0.94 | 0.90 | 0.94 | 0.97 | 0.94 | 0.94 |
| $P^2$ | 58.5 | 31.9 | 33.7 | 68.0 | 33.3 | 40.0 | 52.6 | 30.9 | 40.4 |

Cases 1, 2, and 3: models using PESLAB, AVREG, and ARUL75 as regulatory terms. Dependent Variable: number of pesticide registrations; INTCPT=intercept term; ***INSTRD***= log of the instrumental pesticide research variable; LG3SHR=log of lag of firm pesticide growth in market share;
INT=a dummy variable for foreign-based firms that enter the U.S. pesticide market after 1972; RDINT=interaction of $INT_{it}$ and log of ***INSTRD***; LSHARE=log of lag of firm market share; PESLAB=log of employment at Office of Pesticide Program of EPA as regulation term; AVREG=log of industry environmental and health testing costs divided by idustry research expenditures; ARUL75=log of of regulation index; GROW5=log of pesticide industry sales growth. Table A.1 has detailed variable definitions.
SIGMA=dispersion parameter. ***=1% significance; level;**=5% significance;* 10% significance.

**Table 3**
**Estimates of the Determinants of Pesticide Toxicity**
(Standard Errors in parentheses)

| | Toxicity Types | | | | | |
|---|---|---|---|---|---|---|
| | Fish/Wild Acute/Chron Case 1 | Fish/Wild Chron Case 2 | Fish/Wild Acute/Chron Case 3 | Fish/Wild Chron Case 4 | Fish/Wild Acute/Chron Case 5 | Fish/Wild Chron Case 6 |
| INTCPT | -0.39 (0.51) | 0.80 (0.50) | -0.47 (0.49) | -0.81 (0.50) | -1.08 (0.64) | -1.41** (0.66) |
| ***INDRD*** | -1.33** (0.63) | -0.60 (0.61) | -2.08** (0.89) | -1.33 (0.87) | -0.59** (0.20) | -0.55** (0.20) |
| HERF | 0.27 (0.30) | 0.55* (0.28) | 0.27 (0.29) | 0.52* (0.28) | 0.55** (0.33) | 0.85*** (0.34) |
| PESLAB | 0.52* (0.29) | 0.57** (0.28) | - | - | - | - |
| AVREG | - | - | 2.36* (1.23) | 2.38** (1.15) | - | - |
| ARUL75 | - | - | - | - | 0.94** (0.39) | 1.00** (0.40) |
| PRICES | -7.94** (2.18) | -5.08** (2.21) | -8.24*** (2.11) | -5.38** (2.23) | -12.3** (2.12) | -0.90*** (0.23) |
| GROW5 | 1.14** (0.47) | 1.09** (0.48) | 1.28** (0.44) | 1.21** (0.47) | 1.63** (0.21) | 1.45*** (0.44) |
| OBS. | 18 | 18 | 18 | 18 | 18 | 18 |
| DW | 1.61 | 1.72 | 1.67 | 1.95 | 1.99 | 1.81 |
| $R^2$ | 0.43 | 0.47 | 0.45 | 0.31 | 0.59 | 0.53 |

Cases 1,2,3,4,5, and 6 refer to alternative specifications of the toxicity regressions that are paired with Cases 1,2,3,4,5, and 6 of the crop market size regression in the SUR econometric model. The results for crop market size regression are reported in Table 4.
Dependent Variable: proportion of less toxic pesticides to all pesticides.
INTCPT=intercept term; ***INDRD***=instrumental variable for industry research; HERF=Herfindahl Index, in hundreds, for pesticide industry; PESLAB=employment at Office of Pesticide Program of EPA; AVREG=industry environmental and health testing costs divided by industry research expenditures. ARUL75=regulation index. PRICES=agricultural prices; GROW5=pesticide industry sales growth. Table A.1 has detailed variable definitions.
*** 1% significance; ** 5% significance; * 10% significance.

**Table 4**

**Estimates of the Determinants of Pesticide Crop Market Size**
(standard errors in parenthesis)

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
|---|---|---|---|---|---|---|
| INTCPT | 10.65<br>(7.57) | 12.18<br>(8.32) | 11.81<br>(7.85) | 12.71<br>(8.72) | 10.43<br>(7.61) | 11.16<br>(7.91) |
| ***INDRD*** | 0.91***<br>(0.29) | 0.87**<br>(0.30) | 0.21<br>(0.57) | 0.17<br>(0.59) | -0.21<br>(0.15) | -0.22<br>(0.59) |
| HERF | 0.66***<br>(0.19) | 0.68***<br>(0.20) | 0.66***<br>(0.20) | 0.67***<br>(0.20) | 0.88***<br>(0.26) | 0.89***<br>(0.26) |
| PESLAB | 0.50**<br>(0.20) | 0.52**<br>(0.21) | - | - | - | - |
| AVREG | - | - | 2.13**<br>(0.92) | 2.17**<br>(0.94) | - | - |
| ARUL75 | - | - | - | - | 0.79**<br>(0.30) | 0.81**<br>(0.30) |
| GROW2 | -11.4<br>(7.67) | -13.0<br>(8.43) | -12.5<br>(7.9) | -13.42<br>(8.83) | -11.63<br>(7.78) | -12.37<br>(8.08) |
| OBS. | 18 | 18 | 18 | 18 | 18 | 18 |
| DW | 2.07 | 2.05 | 1.91 | 1.91 | 1.91 | 1.95 |
| $R^2$ | 0.87 | 0.83 | 0.83 | 0.83 | 0.83 | 0.86 |

Cases 1,2,3,4,5, and 6 refer to the crop market regression that was paired with Cases 1,2,3,4,5, and 6 pesticide toxicity regression in the SUR econometric model. Cases 1,2,3,4,5, and 6 for the pesticide toxicity regression are reported in Table 3. Dependent Variable: proportion of large volume crop markets registrations to small volume crop market registrations. INTCPT=intercept term;
***INDRD*** = instrument for average deflated industry pesticide research spending; HERF=herfindahl index, in hundreds, for pesticide industry; PESLAB=employment at offices or pesticide programs of EPA; AVREG=industry environmental and health testing costs divided by industry research expenditures. ARUL75= regulation index; GROW2 = two year moving of growth in planted acreage. Table A.1 has detailed variable definitions.
*** 1% significance; ** 5% significance; * 10% significance.

## APPENDIX A

### Table A.1

### Definition of Variables in Equations 1, 2, and 3

| Variable | Definition |
|---|---|
| $N_{i,t}$ | The number of new pesticide registrations at the EPA. |
| $RESEARCH_{i,t}$ | $$RESEARCH_{i,t} = \frac{\sum_{j=0}^{n_t} RD_{i,t-j}}{n_t} \qquad (a.1)$$ where $RD_{i,t}$ is firm pesticide research expenditures and $n_t$ is the time from discovery to commercialization of a pesticide. Thomas (1990) used a similar definition for pharmaceutical innovations because that industry also had a variable lag structure for product development. Also, Sharp (1986) and NACA data (1971-87) suggests that pesticide research costs are evenly distributed over the product development cycle. |
| $INT_{i,t}$ | A dummy variable equal to one for foreign-based companies that enter the U.S. market after 1972 and zero otherwise. |
| $RDINT_{i,t}$ | Interaction term between $INT_{i,t}$ and $RESEARCH_{i,t}$. |
| $LSHARE_{i,t}$ | The lag of market share, which is based on company and industry sales. |
| $LG3SHR_{i,t}$ | The lag of the three year average of $LSHARE_t/LSHARE_{t-1}$. This definition of growth is employed because our specification is in log form, which does not allow us to use negative numbers. |
| $PESLAB_t$ | Regulatory effects occurs throughout the pesticide product development cycle. At any point, a firm may wish to curtail further development because of a change in the regulatory environment. For example, the pesticide research opportunity set is limited to only those chemicals that can pass EPA approval. After selecting a promising chemical compound, costs include additional or more rigorous field testing and the possible withdrawal of products that are not able to meet environmental constraints. The next step is for firms to submit their test data to the EPA and commercialize the product. A lag structure in the model is, therefore, necessary. Hence, we create a moving average term. This regulation variable is defined in the same form as $RESEARCH_{i,t}$ in equation (a.1) above, except that staffing level at the OPP ($LABOR_t$) replaces $RD_{i,t}$. Warren and Chilton (1989) maintain that staffing levels reflect regulatory intensity. |

| Variable | Definition |
|---|---|
| $AVREG_t$ | This regulation variable is defined in the same way as $RESEARCH_{i,t}$ in equation (a.1) above, that the ratio of pesticide research for environmental and health tests ($R_t$) to total research expenditures ($R_t$+$NR_t$) replaces $RD_t$.[4] We use this measure of regulation because workers are added in response to greater reporting requirements and thus may understate regulatory impact. We take the average over the product development time because regulatory effects occur throughout the product development cycle. See $PESLAB_t$ for more complete description. |
| ARUL75 | This regulation variable is defined in the same composite form as $RESEARCH_{i,t}$ in equation (a.1) above, except that the ratio ($PROPOSE_t$+$RULE_t$)/$RULE71_t$ replaces $RD_t$ $PROPOSE_t$ is the EPA-anticipated cost of proposed rules in year *t*. $RULE_t$ is the cost of all rules in existence in year *t*. $RULE71_t$ is the cost of rules in existence in 1971. The EPA established new rules in 1978 and 1982. New rules are currently under review and in manuscript form. According to Arnold Aspelin and Gary Ballard of the EPA, who wrote the economic analyses for the rule changes, new pesticide registrants adhered to the new rules prior to their formal publication. Hence, 1978 rules reflect rule changes over the 1972-77 period, 1982 rules reflect rule changes during the 1978-81 period, and 1994 rules reflect rule changes after 1981. $ARUL75_t$ assumes that the actual rule change occurred in 1975 for the 1978 rule changes, 1979 for the 1982 rule changes, and 1988 for the 1994 rule changes. We average all lagged periods over the product development cycle because the impact of regulation on the pesticide research process occurs throughout the product development cycle. See $PESLAB_t$ for more complete description. |
| $PRICES_t$ | Deflated agricultural prices. |
| $GROW5_t$ | The five year average of $S_t/S_{t-1}$, in which $S_t$ is current year and $S_{t-1}$ is sales in the previous year. This definition of growth is employed because our specification is in log form, which does not allow us to use negative numbers. |
| $LESSTOX_t$ | The ratio of the four year moving average of the number of less toxic new pesticides to the four year average of all new registered pesticides. We used two definitions for "more toxic". Under the first definition, a pesticide is "more toxic" if it either has a Class 1 acute toxicity rating, is chronically toxic, or is toxic to fish or wildlife. This definition includes all types of pesticide toxicity considered by the EPA. The second definition includes only those pesticides with chronic effects and those that are toxic to fish/wildlife. We define "more toxic" in this way because the 1972 amendment dealt with only chronic effects and toxicity to fish/wildlife (See Hatch, 1982). |

| | |
|---|---|
| $INDRD_t$ | Industry research expenditures, defined in a way similar to firm research $RESEARCH_{i,t}$ with industry research expenditures replacing $RD_t$. |
| $HERF_t$ | The Herfindahl Index, defined as the sum of the squares of company market shares. |

| **Variable** | **Definition** |
|---|---|
| $INT2_t$ | The proportion of foreign-based firm entrants. |
| $LARGCROP_t$ | The ratio of the four year moving averages of the number of crop registrations for major field crops to the number of pesticides registered for major and minor field crops, major and minor vegetables, fruits and nuts, and for nursery and other crops. Major field crops include corn, cotton, sorghum, soybean, and wheat. Minor field crops include alfalfa, barley, clover, flax, hops, lentils, mint, oat, peanut, peas, potatoes, rice, rye, safflower, sunflower, sugarbeet, sugarcane, sweet potato, and tobacco. Vegetables include asparagus, beans, broccoli, cabbage, carrot, cauliflower, onions, sweet corn, cucumbers, lettuce, tomatoes, and 35 other vegetables, having less than 100,000 acres planted. Fruit and nuts include apples, grapes, nectarines, peaches, pears, plums/prunes, citrus, strawberries, almonds, filberts, pecans, walnuts, and 51 other fruits and nuts, products with generally less than 100,000 in acreage. Nursery and other crops include greenhouse crops, grass and turf crops, conifers, five other nursery uses, forage & pasture, storage, forestry, and five other non-crop and non-Nursery uses. |
| $GROW2_t$ | The two year moving average of the ratio of current year planted acreage to previous year planted acreage. |

## APPENDIX B

### Data

This study contains all firms that introduced at least one new pesticide, that were ranked in the top twenty pesticide companies at least once, and for whom research and development data were available over the 1972-91 period.

New pesticide registrations came from Aspelin and Bishop (1991). We used Kline Associates publications to determine the companies in the sample.[5] If a firm was not on the first report, its year of entry was assumed to be the year in which they registered their first pesticide, conducted pesticide research in the U.S. as indicated in the *Survey of Industrial Research and Development*, (1972-89) or entered the pesticide market by merging with an American company, whichever came first. Eichers (1980) data indicates that all firms in the top twenty in 1974 existed in 1967.

Overall and industry firm research expenditures came from the *The Survey of Industrial Research and Development* (1972-89) at the U.S. Bureau of the Census, Kline and Company Data (1989, 1991), and *Moody's Industrial Manual* (1972-91). The U.S. Bureau of the Census conducts the survey for National Science Foundation and asks questions on firm-level research for each year from 1972 to 1989 and research expenditures for specific categories, such as industry, state, and environmental, for all years except 1978, 1980, 1982, 1984, 1986, and 1988. We define all research in the category on agricultural chemical research as expenditures on pesticide research because the firms in the sample did not produce fertilizers.

All firms did not report at the same level of detail because research expenditures by category is voluntary. One firm did not report agricultural chemical research expenditures and was dropped. Several other companies failed to report agricultural chemical research expenditures during some reporting years. Supplemental data for 1989 and all of the data for 1991 came from Kline and Company reports. For years in which firms provided no voluntary data, companies often provided detailed research data in their annual reports, SEC filings, or in EPA estimates. Accordingly, if annual report, SEC filings data, or EPA data were more detailed than Census Bureau data, we used that information. Employing this methodology, we obtained a time series of firm industry level research data for the 1972-91 period, excluding some firms in 1978, 1980, 1982, 1984, 1986, 1988, and 1990. We estimated agricultural research expenditures during these years from agricultural research expenditures in the surrounding years and overall firm research.

We also used estimates of agricultural research spending for the period from 1965 to 1972 because of the lag between research spending and pesticide registration. Our estimates are based on firm agricultural chemical research spending in 1972, overall firm research spending over the 1965-72 period, and pesticide industry research. Combining these data with our other data yield a data set that covered the 1965-91 period. All values were deflated by the GNP price deflator.

We used the *Product File* at the U.S. Bureau of the Census and Kline and Company data to determine firm sales and market share. The *Product File* contains total value of production, values for single products defined at the five digit SIC level, and miscellaneous production data at the establishment level. We used the value of shipments to determine domestic production of pesticides. These are listed under SIC 28694 and 2879. Since domestic production includes pesticides for exports for domestic producers and nothing for foreign producers, we also considered Kline Company data, which contains estimates of domestic and foreign sales. If the reported value of Census shipments was greater than 120% of the Kline estimates or less than 80% of the Kline estimates, we assumed the company was either an exporter or importer and used Kline estimates. If values of Census production fell within these limits, then the firm was assumed to be producing only for domestic consumption and Census data were used. After making these adjustments, we computed estimated industry sales and compared them to values reported by NACA.

Labor employment at the EPA Office of Pesticide Programs (OPP) for computing $PESLAB_t$. came from EPA budgets. Industry regulatory costs, which were required for $AVREG_t$, came from NACA (1971-89). These costs were assumed to include all environmental testing, toxicology studies, and EPA registration costs. Non-regulatory costs were assumed to be search, synthesis, field testing, and process development costs.

Rule descriptions and the costs of performing new tests came from the *Federal Register (September 6, 1978 - Part II)* for the 1978 rules, an August of 1982 EPA manuscript entitled *Regulatory Impact Analysis Data Requirements for registering Pesticides under the Federal Insecticide, Fungicide, and Rodenticide Act* (1982), and a June 22, 1994 manuscript entitled *Changes to Part 158*. Each manuscript describes the proposed rule changes and gives a cost of the rule. The 1978 and 1982 documents give the costs of existing and proposed rules. Rules are weighted by their expected costs because rules may be of different rigor. The authors of the reports (Arnold Aspelin and Gary Ballard of the EPA) indicate that new pesticide registrants complied with all regulatory changes prior to the formal establishment of the new rules. Ballard says that the EPA had implemented the 1978 rule changes by 1975. Hence, an assumption that rule changes became effective in 1978, 1982, and 1994 would be misleading. More satisfying are assumptions that rule changes occurred during the period between the written rules, i.e. 1975, 1979, and 1988. Alternatively, it is plausible to assume that pesticide registrants anticipated rule changes. In this vein, assumptions that the rule changes took place in 1972 for the 1978 rules, 1979 for the 1982 rules, and 1983 for the 1994 rules are appealing.

We used the Farm Chemicals Handbook, CPCR, and EXTOXNET to determine pesticide toxicity. Data on pesticide crop market uses came from the *Pest Bank - November 1991*, which is provided through the National Pesticide Retrieval System. Toxicity and crop market classifications are provided in Table 1.

Industry pesticide research, industry average product development period, and industry sales for $GROW5_t$ came from NACA. Industry value added came from Census files. The Herfindahl Index is based on the computed market shares. Agricultural prices and planted acreage, which was required to compute the growth in planted acreage, came from *Agricultural Statistics* (1974-91). Agricultural prices were deflated by the GNP price deflator.

## ENDNOTES

1. One critic of pesticide regulation is the National Agricultural Chemical Association (NACA). Pesticide innovation can refer to the development of either novel pesticides (active ingredients) or mixtures of existing active ingredients with inert materials used to improve safety, storage, handling, or application characteristics. In this paper, new pesticide registrations and pesticide innovations refer to active ingredients. The term pesticide includes insecticides, herbicides, fungicides, and other agricultural chemicals such as growth regulators.

2. The above results include only pesticides developed by the major pesticide companies. We also evaluated changes in the proportion of less toxic pesticides for the entire pesticide industry. The results for the larger sample are similar to those reported in Table 3 for the major pesticide firms.

3. Lichtenberg, Spear, and Zilberman (1993) believe that regulation encourages firms to develop more toxic pesticides.

4. The National Agricultural Chemicals Association (NACA) publishes a detailed description of pesticide industry research costs that includes several types of environmental expenditures. See National Agricultural Chemicals Association, Pesticide Industry Profile Study, National Agricultural Chemicals Association, various issues, 1971-89.

5. Kline and Company, The U.S. Pesticide Market (various issues) contains company sales data over the 1974-91 period and pesticide research spending for 1989 and 1991.

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