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Sprayed to Death: Pest Control Strategies and Technological Lock-In

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SPRAYED TO DEATH:
PEST CONTROL STRATEGIES AND TECHNOLOGICAL LOCK-IN

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Theoretical literature on the economics of technology has emphasized the effects on technological trajectories of positive fedbacks. In a competition among technologies that all perform a similar function, the presence of increasing returns to adoption can force all but one technology from the market. Furthermore, the victor need not be the superior technology. This paper provides an empirical study of one technological competition which illuminates this theoretical work. It uses theoretical results to explain why chemical control of agricultural pests remains the dominant technology in spite of many claims that it is inferior to its main competitor, Integrated Pest Management.

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Recent theoretical research on the economics of technology has emphasised the tendency for technological developments to become self-reinforcing. Of major concern in this literature has been the issue of ex post efficiency—the possibility of self-reinforcing mechanisms locking the economy in to an inferior technology. While the theoretical literature has made a compelling case regarding the powers of positive feedbacks in this regard, it has been difficult to subject to empirical scrutiny.[1] There are two reasons for this. The concern with efficiency is largely a counter-factual one, regarding the possibility that had a different technology been heavily adopted and developed in the past, we would now be better off. This is obviously a difficult claim to examine empirically. The second reason is related, and has to do with the fact that in order to understand the evolution of a self-reinforcing system, it is necessary to examine relatively 'minor' details of the history, since these minor details can play an instrumental role in pushing the system towards one outcome or another. There is, therefore, a problem of availability of data, both in terms of historical detail, and in terms of comparing actual evolution to possible evolutions.

This paper provides a case study of a technological competition which illustrates several of the properties highlighted in the theoretical literature.[2] Technologies for controlling agricultural pests have many of the positive feedback mechanisms discussed in the theory. We will argue that the history of agricultural pest control displays several of the features predicted by the analytical work. In section 1 we introduce the competition between pest control strategies, and briefly summarize theoretical results that are apropos. In sections 2 and 3 we discuss in detail pest control strategies and the possibility that the dominant technology is inferior to another. The fourth section details the sources of positive feedbacks in the technologies and the final section presents two examples in some detail. One addresses the historical entrenchment of a technology for controlling pests, the other discusses the feasibility and difficulty of overcoming such an entrenchment.

Technology Competition in Pest Control

In 1962 Rachel Carson's *Silent Spring* was published. Twenty years later *Silent Spring Revisited* concluded that Carson's indictment of the extensive use of chemical pesticides continued to be warranted. Green politics and Green products are now enjoying a popularity of enormous proportions. For thirty years we have been aware of

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[1] Cowan (1990), David (1985), David and Bunn (1988), and Foray and Grubler (1990), are examples of empirical studies that use the competint technologies theoretical framework.

[2] This paper extends and develops work in Cowan (1991).

the very serious negative effects of chemical pesticides, yet in that time there has been little shift away from their use. Indeed, between 1964 and 1982 in the United States the application of active chemical ingredients increased 170 percent by weight. Since 1970, herbicide use has more than doubled.[3] An immediate response to these figures is that there must be no alternative to the use of chemical controls. This may not be true. Many claim that profitable alternatives do exist and have been implemented in several cases. It remains the case, though, that the major alternative pest control strategy, Integrated Pest Management (IPM), was used on only 18% of total sown acreage of 12 major crops in the U.S. in 1986.[4] What, then, accounts for the failure to shift away from chemical pesticides?[5]

Competing Technologies in Theory

Recent theoretical work on competing technologies has focused on situations in which superior technologies can disappear from the market.[6] Central to this literature has been the notion that the value of adopting a particular technology rises with the degree of adoption of that technology. There have been several ways of thinking about the "degree of adoption" and its relation to the value of adoption.

Farrell and Saloner (1985 and 1986) address coordination problems. When technologies have externalities in use, such that the net benefit of using a technology increases with the number of agents currently using it, "excess inertia" can obtain. By this Farrell and Saloner refer to the idea that no agent is willing to adopt a technology without the knowledge that (many) others will also adopt it, since such a move would mean leaving a large network to join a small or non-existent one. Thus a system can become stranded on a, possibly inferior, technology unless some coordinating device appears.

Arthur (1989) addresses the issue of improving technologies. When technologies are improving, either through learning by using or learning by doing, experience with a

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[3] NRC 1989 p. 175. Over these years, sown acreage was approximately constant. A decline in use (measured in terms of weight per acre) occurred after 1982, largely due to idled land and newer, more potent products. (NRC p. 44.)

[4] Crops include alfalfa; apples; citrus; corn; cotton; peanuts; potatoes; rice; sorghum; soybeans; tomatoes; and wheat. In calculating these figures, IPM is loosely defined as the use of basic scouting and economic threshold techniques. (NRC 1989, p. 178 USDA Agricultural Statistics 1987.)

[5] There seem to be three types of answers. First, social and private costs may diverge, so that individual farmers do not pay the costs of the negative effects of chemical use. Second, farm policy may favours the use of chemicals over the use of other control strategies, by (perhaps inadvertently) lowering the relative costs, or increasing the relative benefits of the use of chemical pesticides. The third type of explanation appeals to the dynamics of technological competitions. This paper, while acknowledging the importance of the first two considerations, focusses on the third. For an examination of the divergence between private and social costs, see Archibald (1988). For a discussion of the effects of policy see NRC (1989 Ch. 2).

[6] See Arthur (1988) for a review of this literature.

technology will increase the benefits of adopting it. Thus in a competition between two young technologies, a lead in market share will push a technology quickly along its learning curve, thereby making it more attractive to future adopters than is its competitor. A snow-balling effect can lock a market of sequential adopters into one of the competitors.

Cowan (1991) examines a different type of learning, namely learning about payoffs. This is a form of reduction of uncertainty regarding which of the possible technologies is preferable from the user's point of view. As experience with the competing technologies accumulates, estimates about their properties and relative merits become sharper (though not necessarily more accurate in the short run). As the estimates become sharper, the incentive to use a technology thought to be less than the best, 'just to learn something about it' declines, and the market locks in to one technology.

All three forces, technological externalities, learning, and unceratinty reduction, operate as positive feedbacks, making technologies more valuable as the number of users increases. Systems that operate under positive feedbacks of this type tend to share three features:[7] path dependence, in the sense that the long run equilibrium can be changed by historical events along the path to it; inflexibility, in that as the process proceeds the ability to affect the final outcome with small interventions disappears; and potential regret, which refers to the possibility of locking in to a technology that does not provide maximal payoffs. Positive feedbacks, and the resultant characteristics can be observed in the competition between two types of technologies for controlling agricultural pests.

Pest Control Technologies

The history of agricultural pest control this century can be treated as a case of competing technologies. For the purposes of this analysis, we can refer to two pest control strategies: the chemical pesticide strategy; and integrated pest management (IPM). This is clearly a simplification, as there are other strategies, and farmers can, and sometimes do, use combinations of the two. This simplification will not alter the argument or general conclusions.

Chemical control of agricultural pests consists in covering a crop (or a field if the application is prior to planting) with insecticide or herbicide in order to kill offending weeds, insects and diseases. Application is typically done by timetable, and dosages are fixed. There is only limited response to current conditions in the use of this strategy.

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[7] See Arthur (1989).

IPM, by contrast, is largely a set of responses to current conditions. The focus is on economic rather than physical damage, and a variety of measures are used to minimize economic losses. An IPM program might contain biological controls such as predator or sterile insects and pheromone traps, and cultural controls like crop rotation, as well as focussed pesticide application. To implement an IPM strategy a farmer typically monitors his crop and the insect populations, making estimates of potential economic damage. If the damage threshold seems likely to be reached the farmer decides which counter-measure will be most effective and applies it. "Effective" here includes both biological and economic considerations. IPM is knowledge intensive, and requires considerable farm management skills.

Prior to the second world war pest control included chemical, cultural and biological techniques. Crop rotations and the introduction of predators were used alongside sulphur, paris green and lead arsenate. Immediately following the war, though, synthetic organic insecticides such as DDT were introduced. The effectiveness and the low cost of the new compounds meant that they were embraced by the farm community, and quickly became the favoured means of reducing insect damage. They almost completely replaced other types of controls and made significant contributions to yield increases between 1945 and 1960. At the same time, the new chemical controls were taken up with great vigour by research scientists.[8] The chemical industry saw large profits to be made in the development of new pesticides, and invested accordingly.

The rapid increase in use of chemical pesticides, and the consequent decline in use of other pest control strategies is in keeping with the theory described above. Earlier this century, both technologies were being used. At the end of the second world war, though, there appeared information indicating that pesticides represented a much better technology than its competitors, and there was a rapid increase in adoption. On the heels of this came more research and development and further improvement to the technology. Further, farm policy was gradually built around the assumption that farming techniques included extensive use of chemicals. If all farmers use the same technology, then using yield, say, as the key to particular policy measures will introduce no biases. If other strategies are available which do not maximize yield, however, they may be put at a distinct disadvantage. These factors have combined to give chemical controls a large advantage in the competition for market share.

In recent years, in some areas and some crops (cotton crops in the southern U.S. provide a good example) severe decreasing returns have set in, largely in the form of

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[8] In 1937, 33% of the articles in the *Journal of Economic Entomology* dealt with the general biology of insects, 58% were devoted to testing pesticides. By 1947 these proportions were 17% and 76% respectively.

pesticide resistance. As a result, there has been a shift away from chemical controls toward IPM, in spite of IPM's previous lack of use and development. Where these decreasing returns have not set in, however, chemical controls remain dominant, and appear to be well-entrenched.

None of this history, of course, is logically inconsistent with chemicals being a superior or even the optimal technology. There are indications that it may not be though. What is claimed here is not necessarily that IPM, as it exists now, is a superior technology (though some assert this to be the case), but rather that had IPM had the use and development that chemical pesticides have had, it would be superior. This is a difficult counter-factual, and the evidence in its support is not absolutely overwhelming. The evidence is strong enough, though, that the claim must be taken seriously.

The Merits of IPM

Integrated pest management has several inherent advantages over conventional controls. First, it is based on the notion of economic rather than physical damage. In the presence of a pest infestation controls are applied only if the cost of application is less than the value of the damage that would be caused by the pests. This is consistent with allowing some physical damage to the crop to occur. Clearly, a strategy that seeks to minimize (net) economic damage is in principle at least as good economically as one that seeks to minimize physical damage.

A second feature of IPM, which argues for its technical superiority, is that it attempts to take advantage of natural controls. In developing strategies, researchers look for and try to use those controls of nature that already prevent population explosions of damage causing species. IPM strategies generally attempt to enhance natural interactions rather than to override them by eliminating some species. This is not the argument that "nature does it best," but rather that it is probably going to be more effective to work with natural forces than against them.

There have been many studies of the economics of IPM.[9] They tend to find that after a switch to IPM yields increase, net returns increase, and economic risk declines after a switch from conventional controls to IPM. Reichelderfer and Bender (1981), for example, using a micro simulation approach, find that in the Delaware, Maryland and Virginia region, biological control of the Mexican bean beetle by a parasitic wasp is economically "more than competitive" (p. 266) with conventional controls using the insecticides disultoton and carbyl . Greene et al. (1985), using a criterion of stochastic

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[9] See McCarl (1981) for a survey .

dominance, find that all of several IPM strategies are superior to the two conventional chemical strategies for control of the Mexican bean beetle in Virginia. Hall (1977), examining cotton and citrus in the San Joaquin Valley in California, concludes that "there is no statistically significant difference in profit between supervised control [IPM] and conventional control for both crops." (p. 272) In a survey of 3500 farmers, Allen et al. (1987) find that on average net returns are $15,000 higher for users of IPM. (p. 102.)

Two cautionary remarks must be made about these studies. First, several of the crops studied were in crisis before the introduction of IPM. Pest resistance was so strong that conventional control was essentially failing. Naturally IPM, if it works at all, will look good by comparison. Second, it is very difficult to include the fixed costs of the switch from conventional controls to IPM. Yields and returns tend to fall for several years, and rise slowly to higher levels. Thus while the payoff of the fifth year of IPM use may be higher than the current payoff to conventional controls, if the first four years provide lower payoffs, a farmer who discounts the future may have no incentive to switch.

It does seem to be the case, though, that the stable payoff level of IPM is at least as good as the current payoff level of conventional controls for many crops. What is striking about this result is that it obtains even given the enormous advantage, in terms of development and use, that conventional controls hold. It is estimated that R&D expenditures on chemical control techniques have been 5 times the expenditures on bio-control (NRC 1987).[10]

As stated above, these arguments that IPM would have been superior are not definitive. But in spite of a relatively small amount of development IPM seems able to produce satisfactory long run yields and returns. Further, the transition effects, though significant, are small enough that some farmers have been willing to bear them. Partly because research in this area demands a farm level systems approach, it has been difficult to do. Had IPM had the use and development of conventional controls over the past 45 years, it seems not unlikely that many of the transitions effects would be alleviated, and IPM would be a much stronger alternative today.

Pest Control and Competing Technologies Theory

The theory discussed above suggests that the presence of increasing returns or technological uncertainty make it difficult for a market or group of users to switch from

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[10] To be fair, IPM, as it uses chemical pesticides, has benefited from this research to some extent.

an entrenched technology to a new one.[11] The type of increasing returns present in Integrated Pest Management makes it relatively costly to be the first to adopt it, and makes the risk of being the only adopter costly. Further, IPM exhibits technological uncertainty. Many farmers believe that they cannot make an accurate prediction of the payoffs to its adoption.

Increasing Returns to Adoption

While IPM has existed as a technology for many years, it is described as a "technology which substitutes knowledge and information (labor) for pesticides (materials and inputs)." (Hall, 1977, p. 267) Any technology that is knowledge or information intensive operates under high fixed costs and falling average costs, since information, once produced, is cheap to reproduce. The information, or R&D costs of IPM are high because the problem that needs to be solved is typically very complex. An IPM program involves several components: identification of the pests to be controlled; definition of the management unit; development of a pest-management strategy (which can demand extensive knowledge of the interactions of plant and pest life cycles); development of reliable monitoring techniques; establishment of economic thresholds; and the evolution of descriptive and predictive models (because controls must be applied before economic damage occurs, which involves making predictions about population dynamics).[12] For any crop, or set of crops, IPM is a technology that involves the development of each of these components, the cost of which must be born before the technology is usable. Once this knowledge is obtained, though, any farmer can use it. Thus the greater the number of users, the lower the average cost.[13]

Part of what makes the development of an IPM program difficult is that any farming system has many interacting components. Rosenberg (1982) argues that any such system will be subject to considerable learning by using. This implies that benefits will increase as the degree of on-farm use increases. In his study of cotton and citrus in the San Joaquin Valley, Hall (1977) finds that "a time trend can be detected suggesting that [IPM] is an improving technology with respect to yield and revenue." (p. 269) If

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[11] Theoretical models of technology choice typically assume that increasing returns are unlimited relative to the size of the market. If strong decreasing returns set in, (pest resistance for example) the theoretical results are mitigated. Results on lock-in due to the reduction of uncertainty are not affected by bounded increasing returns though. See Cowan (1991).

[12] This list is derived from Metcalfe and Luckmann, (1982, p. 3), who cite Apple et al. (1979).

[13] These costs are not typically born directly by the farmer. He does pay them, though, if he buys IPM services from a private firm that has undertaken the R&D. When the R&D is performed in the public sector the expected net benefits (average cost) will clearly play a role in determining whether the research is funded.

learning experiences add to the general knowledge base, benefits from use will increase as more farmers adopt, as in the Arthur model discussed above.

That IPM is a knowledge intensive technology suggests another form of increasing returns, namely network externalities. Because of the importance of information gathering and processing in the implementation of IPM, sources of inexpensive localized information can be crucial. This source is often neighbouring farmers. Allen et al. (1987, p. 64) find that well over half of the farmers surveyed consider their neighbours "preferred or useful" sources of information regarding pest control.[14] This is the type of increasing returns to adoption modelled by Farrell and Saloner.

Other sources of positive externalities exist in the technology itself. The use of predator insects is subject to positive externalities from other users of the predators but negative externalities from users of broad-spectrum insecticides. Pesticide drift from farms using conventional controls can upset the predator/prey relationship in such a way as to make that control difficult to implement.[15] Predators can also migrate to nearby fields, either to be killed by pesticides or to find higher concentrations of prey. (Carlson, 1988, p. 114; cf Hall, 1977, p. 267). "In some cases, use of natural enemies is only feasible if all agricultural producers in the area cooperate to distribute and preserve the benefit of the bio control agent." (Reichelderfer, 1981, p. 411)[16] In reference to the competing technologies literature, the issue is one of coordination. For early adopters of IPM, payoffs to the technology will be low if they have difficulty maintaining the predator-prey balance because their neighbours continue to use chemicals extensively and those chemicals drift. This would not be an issue if all farmers adopted simultaneously.

Pest control, whether conventional or IPM, is subject to Marshall's external economics. For conventional control these stem largely from increasing returns to scale in the chemical industry, and from the importance of information, particularly in the R&D lab. For IPM, as discussed above, information is very important, but there are other sources of external economics as well. Important inputs for IPM are scouting—quite possibly the most important input, and, for some programs, biological inputs such as predator pests. Scouting is done either by the farmer, after a non-trivial investment in human capital, or by a scouting service. The cost of scouting falls if the fixed costs can be

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[14] The proportion varies considerably by crop—from about 75% for alfalfa seed to about 35% for apples.

[15] This became a problem in Israel in the early 1970s, when pesticide drift from nearby cotton fields disturbed the predator-prey balance in citrus groves, counter-acting efforts to control several pests. See below.

[16] This is the point made by the literature on pests as a common property resource; see for example Feder, Lazarus and Dixon, (1979) or Regev et al. (1976).

spread over many users, so scouting services will only exist in areas in which there is a high demand.

Reichelderfer (1981) points out three sources of increasing returns in the production of biologicals. First, "the majority of the total costs required, for the large-scale production of biologicals are fixed costs, the greatest component of which is the rearing facility... Additionally, fixed costs per unit of output fall as the size of the facility increases." (p. 409) Second, there will be learning by doing in the production of biologicals; in the short and medium run at least, the costs of production will fall as producers gain experience with the production process. Finally, increasing returns may exist in the application of biologicals. Here the key is the fixed costs of the equipment, which is specialized and must be clean and uncontaminated. All three of these features of the production and use of biologicals constitute forms of increasing returns to adoption, indicating that farmers' costs will fall as more farmers adopt this type of control.

With IPM, then, we have a technology subject to very high fixed (R&D) costs, increasing returns to scale in the production of some inputs, and important co-ordination effects among potential users of IPM and its competitor technology. All of these combine to cast pest control as a technology that exhibits the features discussed in the competing technologies theory. Theory predicts, then, that a shift from one pest control strategy to another is made difficult by the technologies themselves.

There is another feature of pest control which exacerbates the problems of this technological competition. This is uncertainty surrounding the relative benefits of IPM and conventional control.

Uncertainty

Uncertainty about the relative merits of competing technologies is enough to prevent a technology from attaining a strong market position. This type of uncertainty exists in the minds of many farmers, largely because IPM is seen as a new and relatively unknown technology.[17] For many of the major crops there has not been enough on-farm experience with IPM to be able to make a thoroughly convincing case as to its effectiveness. Of the farmers surveyed by Allen et al. (1987) who had pest problems and an available IPM program, but who had *stopped* using IPM, 40% gave as the reason that they were unsure that IPM works. Much is claimed for both the state and the potential

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[17] Pest control is subject to a second type of uncertainty, namely the variability of income (or yield) inherent in the technology. Though clearly important to a potential adopter, this type of uncertainty is not part of the argument here.

of this technology, but it is difficult to assess these claims, simply because of the lack of experience with it.[18] Chemical control, by contrast, has been extensively used, and as a result farmers have very accurate estimates of its costs and benefits. There is no risk, at least in this sense, in using it. A closely related point is that many farmers seem to be unsure that they can make the technology work. Realising that the technology is knowledge, and therefore human capital, intensive, farmers have doubts that they can acquire the human capital necessary to use the technology effectively.[19]

From the point of view of the farming community as a whole, it would be worth trying the new technology in order to make better estimates of its inherent value.[20] This can only be done, though, by the actual adoption of IPM by practicing farmers. But while the farmers who do "try it out" may get high payoffs if the technology is good (or low if it is bad), they are not compensated for the fact that their experience, good or bad, allows others to form more accurate estimates and make better informed decisions. While a considerable amount of experimentation (through actual implementation) may be socially optimal, no risk-averse farmer has incentive to perform it. Thus an uncoordinated market will under-supply experimentation, and tend to continue using the well-known technology, in this case chemical control.

What this discussion suggests is that there are several sources of increasing returns to pest control technologies, and to IPM in particular. Farmers also see considerable uncertainty about the exact benefits of switching to the new technology. The theoretical literature predicts that under these circumstances, the history of pest control should contain important key events that shift the process onto one or another path (path dependence). It should also be true that as the process develops, the chosen path becomes entrenched, and it becomes difficult to change the system to another technology (inflexibility). Finally, the theory presents the possibility that had the dominant technology been discarded early on, and the other developed, aggregate payoofs to users would be higher (potential regret).

Two Case Studies

To further illustrate the process involved in choosing between competing pest control technologies two case studies will be examined. The first, the citrus fruit industry in Israel, has a long involvement with IPM. This case describes the way a technology is

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[18] Clearly, if farmers see pest control as a form of insurance, as is often suggested, a technology with uncertain properties is not going to be met with a great deal of enthusiasm.

[19] See the section on the Trans Pecos, below.

[20] Trying the new technology would also have the effect of improving it, which would also facilitate its further adoption, but this is part of the previous argument.

built and sustained. It also shows the importance of early successes in sustaining it and persuading people to try it again after switching away. The second case concerns the cotton industry in Texas. This study is made up of three different trajectories that share initial histories but separate into distinctive paths once synthetic pesticides are developed. These cases illustrate the difficulty of switching from one technological trajectory to another.

Citrus Fruit in Israel

The Israeli citrus fruit industry is a well documented example of the successful adoption of IPM. Until 1938 chemical control and IPM had been relatively unexplored. In 1938 the Israeli citrus fruit industry was attacked by a mealybug pest and by 1939 the situation was critical. In May 1939 the industry decided to focus on biological control as the main method of regulating the pest. The chief advocate for this focus was Israel Cohen, director of several insectaries used by the Palestine Farmers Federation (PFF).[21] Although not a trained entomologist himself, Cohen managed to override the opposition of a number of professional entomologists who were against importing parasites or predators for fear of interfering with any native parasites or predators. The PFF shipped various parasites from Japan to Israel for study, and the parasite *P. comstocki* was cultured and released in 1940. The results were phenomenal. By late 1941 the mealybug had been completely controlled.[22] It is important to note that at the same time experiments were undertaken using oil sprays and insecticides but neither of these alternatives generated encouraging results.

The specific circumstances surrounding Cohen present an example of a small event that changes the path of history. Cohen was a strong advocate of biological control only because he happened to be in California in 1928 when it's citrus industry suffered an outbreak of a similar mealybug pest. This pest was completely controlled by a parasite introduced from Australia and the episode left a strong impression on Cohen.[23]

The choice of parasite with which to control the mealybug was crucial to the success of the biological control program. Without Cohen's experience in California it would have been extremely difficult for any individual to have isolated this parasite, at least quickly and at little cost. Even had the parasite been known, it is unlikely it would have been imported without Cohen's determination and position of authority. The

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[21] The PFF constructed several insectaries from 1924 to the late 1930s to conduct experiments in biological control.

[22] See DeBach and Rosen (1991).

[23] For further detail about this incident and the history of pest control of the Israeli citrus fruit industry see DeBach and Rosen (1991), Huffaker and Messenger (1976), Rosen (1967) and Rosen (1990).

native parasites and predators preferred by the entomologists proved ineffective. Had they been relied on for biological control the expected payoff of IPM would have been noticeably reduced.

The success of IPM and the failure of pesticides against the mealybug reduced uncertainty about the relative merits of the two technologies in favour of IPM. This outcome determined the response of the Israeli citrus fruit industry to it's next serious pest, the Florida red scale, in 1956. Cohen, by then head of the Agrotechnical Division of the Citrus Marketing Board of Israel (CMBI), pushed for biological control even though synthetic pesticides developed after World War Two were available.[24] The previous success of biological control against the mealybug meant that Cohen faced little opposition. The parasite *Aphytis holoxanthus* from Hong Kong was one of two suitable candidates. Two years after it's release this parasite had gained complete control of the Florida red scale. In 1956, prior to the introduction of the parasite, over 3000 tonnes of oil were used to control the scale every year. By 1959 only 10-20 tonnes were being used with savings of $1 million per year. The cost of selecting, rearing, and releasing the parasite was a few thousand dollars.[25]

These two successful examples of biological control forced the citrus fruit industry to choose between IPM and chemical control in the late 1950s. To ensure the continued success of the parasites meant suspending the use of broad spectrum pesticides. However, the only known method of controlling serious pests such as the Mediterranean fruit fly and the citrus rust mite was by using pesticides.[26] The industry chose IPM over chemical control. The resultant IPM system controlled pests by using their naturally occurring enemies and small targeted amounts of highly selective insecticides. This actually led to better control of some pests since the populations of their natural enemies increased.

The two consecutive serious pest attacks were efficiently controlled using biological control. There was also evidence that relying solely on pesticides was an

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[24] The CMBI was founded by the Israeli government in 1957 and evolved from the PFF and several different citrus fruit ordinances and programs. Before 1940 organisations overseeing the Israeli citrus fruit industry had few legal powers. However, this changed with the 1940 Ordinance of Citrus Fruit Control. After this ordinance the subsequent organisations, including the CMBI, had considerable legal powers with which to control virtually all aspects—including pest control—of the citrus growers if they so wished. For a more comprehensive treatment of the history and powers of the CMBI see Hoos (1979).

[25] It is worth noting that the Israeli citrus industry was the first recorded successful example of biological control of the Florida red scale. As such there was a high degree of uncertainty surrounding the outcome of their search for an effective controlling agent. It is also worth noting that after the Israeli success the parasite was introduced successfully into Florida, Mexico, Brazil, Peru, South Africa and Australia. This demonstrates the public good nature of knowledge inherent in IPM.

[26] At the time they were controlled with non-selective chlorinated hydrocarbon and sulphur preparation insecticides.

inferior technology. These episodes reduced uncertainty about the technologies, especially concerning the payoffs from using each technology, in favour of IPM. This provided enough evidence to the citrus fruit industry to invest resources in refining and improving IPM.[27]

This system of IPM was highly effective until the mid 1960s. But two major changes had affected the citrus fruit ecosystem. A serious problem was pesticide drift from fields adjacent to citrus growers—this was mainly because the cultivated acreages of cotton had increased. This drift had harmful effects on the natural predators used by citrus growers to control pests. Another major problem was the accidental introduction of several new pests which had no natural enemies in Israel.[28] Their populations exploded and caused severe crop damage.

These changes left growers with two choices. They could continue using IPM or switch to synthetic pesticides. There were two major uncertainties surrounding IPM. First, the search for biological control agents to use against the new pests could be lengthy, if they could be found at all. Second, there was no established mechanism for preventing the spray drift from cotton growers. Although synthetic pesticides had been relatively untried by citrus fruit growers they had proven to be very successful in other crops, were cheap, the cost of switching to them was low, and they did not have the degree of uncertainty that surrounded IPM.[29] The time paths of the two technologies were perceived to be divergent with regard to the current 'pressing problems'. Chemical control was perceived as giving a continuing stream of high payoffs and IPM low payoffs for the first couple of years with uncertain payoffs after that. These factors resulted in a general switch to chemical control in the late 1960s.

By 1973 the path of chemical control had deviated from that expected. Chemical control proved to be highly effective initially but it's benefits declined as pests acquired resistance and as naturally occurring predators and parasites were adversely affected. Increases in pesticide costs also lowered the payoffs to chemical control.

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[27] While financial amounts are not readily available, the industry introduced 45 exotic parasites and predators and investigated many more from 1956 to 1966. It also conducted a series of studies of over 60 indigenous parasites. Information on pest recognition and mortality evaluations was provided to growers and a comprehensive extension service was established. Many pesticides were also studied to determine their effects on pests and their natural enemies.

[28] These pests include the spirea aphid citrus whitefly, Japanese bayberry whitefly and in the early 1970s the citrus flower moth and Mediterranean black scale.

[29] It is also likely that there was a new generation of growers who did not experience the earlier successes of IPM and hence were less familiar with IPM. This would have increased uncertainty about the benefits of IPM. Although this new generation of growers would have seen IPM in action they would not have witnessed the crises of the industry and the effective response offered by IPM.

These events saw the merits of chemical control fall relative to those of IPM and the industry switched back to using IPM as it's pest control technology. The problem of pesticide drift was eliminated by legislation enacted by the Israeli government in the late 1960s, sponsored by the CMBI, which prohibited aerial spraying of non-selective pesticides within 200m of a citrus grove. The industry also resumed it's development of biological control. By the early 1980s the majority of the introduced pests were controlled by parasites, or in one instance by a pheromone trap. Other innovations to IPM consisted of better scouting techniques and a post harvest rinsing device that removed scale insects and their damage which raised the population threshold for economic damage from scale insects.

A key factor in the switch back to IPM had been the favourable experience of IPM early on. The two early successes of IPM ensured that the industry assigned it relatively higher payoffs than it may otherwise have done. It also caused the industry to invest resources in the further development of IPM between 1930 and 1950 which lowered subsequent switching costs. The CMBI, and subsequently the Ministry of Agriculture, also provided considerable extension services to growers. These services lowered the costs of switching back to IPM by lowering the costs of acquiring human capital. Most importantly, these services reduced grower uncertainty about the merits of IPM.

That IPM has ended up as the technology of choice for the Israeli citrus fruit industry is due to a number of factors. The early ongoing successes of IPM, most likely due to historical accidents, ensured that it was viewed favourably and developed further. This meant the industry was able to respond relatively quickly to new problems. The PFF and later the CMBI were also important in their role as coordination mechanisms. They alleviated the problems stemming from the public-good nature of the information produced, the negative externalities of spray drift, and mitigated excess inertia in switching to IPM in the mid 1970s.

Cotton in Texas

This case study involves three different trajectories in the adoption of pest management technologies.[30] Initially the three trajectories share a similar history of pest control but diverge in response to changing pest conditions. This allows us to observe the factors behind the different courses of action and how they relate to the environment within which choices between competing technologies are made.

[30] There are three distinctive cotton growing regions in Texas: the High Plains of Texas; the Trans-Pecos; and what we refer to as the rest of Texas.

Until 1890 the cotton industry in the United States was free from any major pests. In the early 1890s, however, the boll weevil moved into Texas from Mexico and by the late 1890s was established as a major pest. In February 1898 the Agricultural and Mechanical College of Texas (now Texas A&M University) was ordered to find a means of controlling it.[31] In 1899 a series of cultural procedures based on a shortened cotton production season were proposed.[32] When the pink bollworm migrated to Texas in the 1920s and 1930s similar cultural methods were devised. Both sets of cultural practices proved highly effective.

During the early 1940s a number of synthetic organic insecticides were developed. Several factors induced growers to switch from IPM to chemical control. First, the costs of switching from IPM to pesticides were low. Second, pesticides were perceived to give an almost constant stream of high crop yields (payoffs) compared to lower and more variable yields (payoffs) inherent in IPM. Third, government policy moved to an agricultural system based on chemical control. Government programs, such as set-aside acreage payments were based on yields rather than on profitability. Concern with yield rewarded high input growers, thus contributing to the neglect of pest control based on cultural methods in favour of chemicals.[33] It also caused growers to switch to high yield varieties which were less resistant to pests. Moving to these varieties of cotton made growers extremely susceptible to pests and so lowered their pest damage thresholds. This reinforced the adoption of chemical control. A final factor is that cultural control, which was an integral component of IPM, is subject to substantial network externalities since many cotton pests are powerful flyers and can travel large distances. As growers switched to chemical control it reduced the benefits of cultural control to existing growers thereby making it more likely that they too would switch.

Initially the insecticides proved miraculous, reaffirming growers' beliefs that chemical control was superior to IPM. The growers' experiences, however, soon diverged from expectations as pests acquired resistance to insecticides, and naturally occurring enemies were adversely affected. A new range of pesticides was developed and introduced. The pests also acquired resistance to these and by the late 1960s the cotton

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[31] For further details about the history of pest control in the Texas cotton industry see Debach and Rosen (1991), Huffaker and Messenger (1976), Leslie and Cuperus (1993), Metcalf and Luckman (1982) and OTA (1979).

[32] These procedures included early planting, destruction of cotton stalks after harvesting to deny food to overwintering boll weevils, and selecting cotton varieties that would fruit rapidly.

[33] For example cotton growers in the Mississippi River Delta had per acre yields twice that of Texan High Plains growers. However, pesticide costs per acre of the River Delta growers were five times that of the High Plains growers. Other inputs such as fertilisers were also used more extensively by the River Delta growers than those in the High Plains. See Flint and van den Bosch (1981).

industry faced pests that were resistant to all known insecticides, with no foreseeable replacements in the offing.[34] What happened after these events depended crucially on switching costs and network externalities.

High Plains of Texas

The High Plains of Texas is an area where pesticide use is low. This area is subject to only an occasional invasion by migrant pests. Since the boll weevil has not been allowed to establish itself in the High Plains, growers can rely almost completely on naturally occurring predators and parasites to control their pests. Pesticides are only occasionally used when pests escape the constraints of their natural enemies and then only in small targeted amounts.

The boll weevil has been unable to establish itself in the High Plains area because of the High Plains Boll Weevil Suppression Program initiated in the Rolling Plains region which borders the High Plains area.[35] Producers have agreed to uniform delayed planting of the crop so that most boll weevils emerge from diapause and die before food is available. This method of cultural control dramatically reduced the use of insecticides and thus maintained the populations of natural enemies of the two secondary pests. It has also prevented the boll weevil from moving into the High Plains area for over 30 years.

A study of Fisher and Jones counties in the Rolling Plains region showed the effectiveness of this method.[36] Cotton is of the short season type allowing delayed planting. Producer benefits, through yield increases and reduced pesticide costs, were estimated to range from $3.4 million to $5.5 million per annum.[37]

Growers in the Rolling Plains of Texas were quick to switch back to IPM once pests became resistant to insecticides. The ecosystem was relatively simple and an IPM technology had previously been developed. This lowered the costs of switching. Any problem with migrant pests was taken care of with targeted insecticide applications. Finally, legislation passed by the state government, empowering applicable state regulatory agencies to force cotton growers in any region to adhere to planting and

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[34] There are six major cotton pests. The primary pests are the boll weevil, the cotton fleahopper and the pink bollworm which all have the ability to severely damage a crop. Secondary pests are the tobacco budworm, cabbage looper and cotton bollworm which only cause significant damage when the populations of their natural enemies are reduced.

[35] For further details see Bottrell (1973) and Leslie and Cuperus (1993).

[36] See Flint and van der Bosch (1981) for a review of this study.

[37] A variety of short season cotton is Tamcot SP37 which is harvested within 135 days of planting - about 1 month ahead of normal harvesting. This has the same yield as standard commercial varieties grown in a conventional system. It uses 1 pound per acre of nitrogen fertiliser compared to 100 pounds per acre for standard varieties, requires 50% less water and needs only 1/5 to 1/3 the insecticide treatments of standard varieties. See Masud, Lacewell, Taylor, Bendict and Lippke (1981) and Bottrell and Adkisson (1977).

harvesting schedules, was acted upon in this region. This alleviated any problems from externalities in the decision of growers to switch to IPM.

Trans Pecos

The Trans Pecos is an intensive user of insecticides. This region is not subject to serious key pests but sustains damaging populations of secondary pests which have been unleashed through the intensive use of insecticides. Growers in the Trans Pecos region have not, in general, switched back to IPM. This is in spite of several grower and government organisations, including Plains Growers Incorporated, the Texas Pest Management Associated, Cotton Incorporated, and the United States Department of Agriculture (USDA), developing IPM programs, and providing educational and extension services on how to implement them.[38]

A typical district within the Trans Pecos is the Pecos Valley. Working in this area USDA researchers developed an IPM program to control the three main pests: the tobacco budworm; the boll weevil; and the pink bollworm. The normal practice of growers is to apply insecticides on the basis of physical crop damage. This was found by the USDA researchers to be premature and usually led to damaging outbreaks of the tobacco budworm. The IPM program consisted of supervised insect control, regulated fertilisation and irrigation of cotton, and maintenance of crop diversity. This program almost eliminated the need for insecticides. Crop yields were either maintained or slightly above average for the area. The USDA researchers were, however, unable to persuade cotton growers in the Pecos Valley to adopt the IPM program.[39]

The employment of a local extension entomologist in the area by the state government in 1971 and growing resistance of the tobacco budworm to pesticides saw several local growers switch back to IPM. Following implementation of the IPM program the growers saw a large fall in their pesticide use and costs and a reduction in crop losses relative to their previous experiences relying on pesticides. Even with these results the majority of growers continued using pesticides as their pest control technology. Most growers in this district report they did not implement IPM because they thought IPM was too complex. In contrast, pesticides were simple to use, as applications were based on calender timetables or signs of physical damage.

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[38] See Leslie and Cuperus (1993) for further details.

[39] In this particular example the legislation passed by the state government which gives state regulatory agencies the power to ensure growers adhere to planting and harvesting schedules is ineffective. The IPM program for growers in this region encompasses a number of cultural practices with planting and harvesting schedules being only one of them. More comprehensive legislation would be required before it could act as a coordination mechanism.

The Bakersfield district presents an interesting contrast to the rest of the Trans Pecos. This district consists of an isolated irrigation scheme of 1100 acres of cotton owned by five growers. After switching to the IPM program in 1971 the growers used no insecticides, thereby reducing pesticide costs from $70 to $0 per acre. Yields doubled in the first year of the program and have not declined since. The growers switched to the scheme only after two entomologists were employed by the state though. Growers reported that without the entomologists they would not have switched to IPM as they lacked confidence in their ability to implement the IPM program.[40]

In the two instances where growers switched back to IPM in the Trans-Pecos region—in Bakersfield and the few growers in the Pecos Valley—switching involved relatively low research and development and human capital accumulation costs. In both instances the government not only formulated an IPM program for growers, but also employed entomologists as surrogates for the accumulation of human capital and as a form of subsidised training for the growers in using IPM. It is also noteworthy that the state legislation was not used in this region. This is not surprising since the regulatory agencies only implemented the legislation when a majority of growers wanted to switch to IPM.

The Rest of Texas

The final region includes the rest of Texas which is perennially threatened by severely damaging outbreaks of key pests. A typical case is the Lower Rio Grande Valley. Until 1945 cotton pests were controlled using traditional cultural methods such as delayed planting and maintenance of crop diversity. After World War Two, however, growers switched to chemical control. From the early 1940s until the late 1950s pests were controlled using insecticides such as DDT. By the late 1950s the pests had developed resistance and cotton growers converted to the newly developed organophosphorous insecticides. By 1968 these too began to fail.

At the end of the 1960s growers switched back to IPM as their pest control technology. The resistance of cotton pests to insecticides and destruction of beneficial insects in this region lowered the payoffs from chemical control. Switching costs were lowered through government research that improved the previous IPM technology by augmenting traditional techniques with new varieties of short season cotton. The pink bollworm and boll weevil were controlled through a shortened growing season. Where necessary, selective use of insecticides controlled outbreaks of the pests. Growers were legally required to adhere to the short growing season as the state legislation was acted

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[40] See Corbet and Smith (1976).

upon. This alleviated the problem of excess inertia. Yields were maintained at normal levels and the number of insecticidal treatments fell 50% with a corresponding fall in costs. USDA-recommended threshold levels for spraying other pests, such as the cotton fleahopper, were raised to account for the negative effects of spraying on the predators of the tobacco budworm.[41]

Although counter factual examples are generally difficult to give, in this case one exists. Adjacent to this part of Texas is north-east Mexico with identical growing conditions to the Lower Grande Valley. Growers in this part of Mexico were suffering the same problems as their United States counterparts. Mexican growers responded by increasing pesticide use rather than using a different control technology, even though the IPM program used by the Lower Rio Grande Valley growers would have been just as applicable there. The result was the virtual elimination of the cotton industry in north east Mexico with the area planted decreasing from around 700,000 acres in the 1950s and 1960s to 1000 acres by 1970.[42] The only significant, and crucial, difference between the two regions was the lack of a coordination mechanism in north east Mexico.

The history of pest control in the Texas cotton industry highlights several features of competing technologies. The Lower Rio Grand Valley and High Plains of Texas are examples of the importance of coordination mechanisms in overcoming excess inertia. The Trans Pecos demonstrates the effects of uncertainty about a technology's payoffs and the presence of learning-by-using in technologies. It also indicates the importance of government policy, in these cases in the form of subsidised human capital accumulation, to alleviate the effects of these two facets of competing technologies.

Implications

The above analysis suggests that there are several factors militating against a general switch to IPM. Early adopters have two disincentives. Their adoptions take place when little is known about concrete applications of the technology, and so their experiences are used to gather information about it. This provides a valuable service to potential future adopters, but the early adopters are not compensated for undertaking the risk that the payoff is small. Early adopters also have to wait for others to adopt before they get the benefits of increasing returns to adoption. Thus unless there are particular individuals with very strong desires to use IPM (for whatever reason) the adoption process will not get off the ground.

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[41] The threshold was raised from 25 to 50 insects per 100 plants since damage inflicted by the cotton fleahopper was less than the damage caused by the tobacco budworm when it's natural enemies were adversely affected by spraying for the cotton fleahopper. See Huffaker and Messenger (1976).

[42] See Debach and Rosen (1991) and Adkisson (1972)

The first disincentive faced by potential early adopters stems from the fact that IPM is not a mature technology. For many crops the knowledge necessary to design an effective pest control program does not exist. For others, the knowledge exists but there has been little practical application of it. The costs of thoroughly developing an integrated pest management strategy are often very high, and there is currently available a technology that controls most pests very effectively. This implies that there may be several years of relatively low payoffs for any agent contemplating developing an IPM strategy. Discounting will act to make that development unprofitable. Even in cases where IPM has been developed at research stations, at the farm level the uncertainty surrounding the technology can be severe. Farmers know neither how good it is nor how good it will become, nor how best to use it. By contrast, they have extensive experience with chemical controls. In this type of situation, if farmers try IPM and have bad luck with it in the first few trials, whether the low payoffs arise from the technology itself or from random factors that would affect any pest control technology, a switch back to chemical controls will be largely irrevocable. Due to early experiences, IPM will be thought to be a worse technology than chemical control, and because it is not being used it has no way to disprove this claim. The second disincentive faced by early adopters stems from the fact that pest control technologies are subject to increasing returns to adoption. This suggests that there is a critical co-ordination problem. If every farmer in a region were to shift to IPM, all would be better off, assuming the first problem mentioned has been overcome. But if he is the only one to switch, a single farmer faces high costs, both through direct costs of implementation, and through indirect negative externalities from neighbouring farmers who continue to use chemical controls. Thus no one is willing to start the ball rolling—the problem here is the lack of coordinating mechanism.[43]

The existence of these two factors imply that pest control demonstrates what Arthur refers to as inflexibility. Small policy adjustments will not suffice to shift farmers from one technology to another. To any farmer the cost of switching is sufficiently large that small changes in relative costs (either through taxes, subsidies or extension services) will not be enough to overcome technological inertia.

If policy is to contribute to a shift from one technology to another it must be aimed at significantly reducing the switching costs. This can happen in several ways.

For many crops Integrated Pest Management techniques have not been developed. For other crops IPM techniques exist but have had little use and so have not

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[43] In many of the successful IPM programs (cotton in Texas and North and South Carolina; citrus in Israel; rice in Indonesia) coordination is provided by government (or marketing board in Israel) legislation.

been improved through the accumulation of learning by using. The former implies an important need for research and development. The several components of an IPM program discussed above must all be well understood before we can hope to have farmers switch. The latter underlines the need for practical experience with the technology. The nature of the technology requires a thorough understanding of an entire farming system before an IPM strategy can be optimized. This suggests that there will be considerable learning by doing and learning by using at the farm level, and so on-farm experience will be crucial to the development of the technology. Policies to encourage this sort of experimentation, and the sharing of the information the experiments provide, are appropriate.

Any farmer who switches to IPM will suffer from a period of lower payoffs. There is often a biological transition effect, such as the transition into a crop rotation. One of the benefits of rotating crops is that crop specific pests will not be carried over from one season to the next. Clearly, to enter a rotation in the middle, so to speak, the history is lacking and so benefits will not be entirely felt for the first few seasons. The effects are largely biological, and with more knowledge about the biology of these effects, better transition strategies—the use of pesticides, particular rotations and cultural techniques, for example—may be developed.

Farm-level learning is another source of rising payoffs. The adopter of any complex technology spends time learning exactly how it works and modifying it to fit his precise needs. This will certainly take place for several years after a farmer switches to IPM, and we would not expect to see large increases in benefits in the first few years. Policy can help here through extension services.[44] The extension services must be very localized, though, in order to provide the detail needed to facilitate this learning.

One of the features emphasized above was the existence of externalities among geographically nearby users of pest control strategies. One effect of these externalities is that payoffs to an individual farmer increase if more of his neighbours use the same technology as he does. This clearly suggests that farmers will be more likely to switch to IPM if there is a large scale shift among nearby farmers.[45] This has an important implication for policy. The allocation of scarce resources should be geographically concentrated. Relatively small areas, by national standards, should be targeted for increased extension services, and prior to that research and development efforts, in an

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[44] Currently the chemical control strategy is well-served in this regard by the field representatives of chemical companies.

[45] Even in those cases where the decreasing returns have forced a shift away from chemical controls to IPM, often large-scale co-ordination, and the formation of more or less compulsory pest control groups takes place.

attempt to precipitate a large-scale shift in that area. Once effected, the target should be moved to another area. This has the negative effect of leaving some areas with relatively poor services, but it would concentrate resources in such a way that the initial big push is possible, which it is not if resources are geographically dispersed.

The final role for policy is to mitigate what appear to be the negative features of IPM while the market works out its own mechanisms to deal with them. It is often claimed that use of IPM results in a higher variability of yield. Clearly, insurance is a way of solving this problem, but it may take time for the market to gather enough information to offer insurance efficiently. Another problem noted by many users of IPM is the difficulty in educating bank managers of the feasibility and reliability of IPM. (See for example Stover et al. (1985).) *Short term* intervention can overcome these problems.

The existence of increasing returns and uncertainty with regard to the payoffs of Integrated Pest Management suggest that agricultural pest control strategies will be subject to the forces described in the theoretical literature on competing technologies. A tendency for a technology to become entrenched and very difficult to dislodge is one of the main effects of these forces. Many argue that IPM represents a superior technology, and yet it has had relatively little acceptance to date. Any policy aiming at changing this state of affairs is faced with the difficult problem of overcoming the forces tending to reinforce the status quo. This paper suggests that the problem is not insurmountable, but that it may be important to focus policy interventions, in order to concentrate attention on small geographic areas. In this way the intervention may be large enough to force a switch in that area.

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