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School of Social Sciences

Essays in Environmental Policy, Biotechnology and Non-point source Pollution

by

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ABSTRACT

FACULTY OF SOCIAL SCIENCE

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ESSAYS IN ENVIRONMENTAL POLICY, BIOTECHNOLOGY AND NON-POINT SOURCE POLLUTION

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This thesis provides an economic analysis of issues relating to genetic modification (GM) and non-point source pollution (NPS). The type of GM considered is the modification of crops to protect them against pests. Such modification may adversely affect biodiversity. Our analysis shows that, to ensure the optimal level of biodiversity, intervention in the GM R&D market to reflect its social cost is necessary. In some instances, a subsidy to non-GM crops may also be required.

In a separate analysis we examine how the potential for pests to develop resistance to GM technology affects the relative incentives to carry out R&D. This analysis highlights the underlying factors determining the incentives to invest in R&D when such a possibility exists.

In relation to NPS we provide a theoretical overview of the literature and an empirical analysis of nitrogen taxation in the Kennet catchment. By linking an economic model to a hydrological model, we can evaluate the environmental effectiveness of taxation. Although we find a significant impact on land-use decisions in response to the tax, this effect is not reflected in reductions in stream-water nitrate concentrations.

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Chapter 1

Introduction

At its most general level, this thesis is about incentives. In Chapters 2, 4 and 5 we examine the role of incentives in bringing about desired policies, whereas, in Chapter 3 we take a different perspective and study how natural phenomena might affect firms' incentives to carry out R&D. In terms of the environmental issues they address, Chapters 2 and 3 are set in the context of the Genetic Modification (GM) of agricultural crops, a relatively recent technological development with which farmers, consumers and policymakers are currently grappling. Chapters 4 and 5 deal with the problem of pollution, specifically non-point source pollution. Although not a new problem, what makes non-point source pollution interesting is that, the usual policy prescriptions suggested for point source pollution do not apply. Thus, both GM and non-point source pollution are currently 'hot' topics and are very policy-relevant today.

GM technology throws up many new and interesting problems but we concentrate on two: the impact on biodiversity and the potential unsustainability of this technology due to the development of pest resistance to the technology. The type of GM technology we consider is the modification of crops for protection against pests. Thus, the biodiversity impact will be through the loss of food for insects and hence, will affect also the predators of those insects. The emergence of resistance in pests/pathogens to the technology developed to eradicate them will undermine its value to the user and to society. To the extent that pest susceptibility to technology is a public good, it will be undersupplied in the market, i.e. the progression of resistance in pests will be too rapid. The US EPA (Environmental Protection Agency) has recognised this public good nature of pest susceptibility and has mandated the set-aside of refuge areas when GM crops are cultivated (Laxminarayan and Simpson, 2000). Refuge areas promote the delay of pest resistance by encouraging breeding between susceptible individuals supported by the refuge area and resistant individuals from the GM crop area. Such interbreeding dilutes the resistance gene in the pest population because the resistant gene is often recessive, i.e. offspring will be resistant only if both their parents are. The problem of emerging biological resistance to human intervention is already occurring in the pharmaceutical sector with the problem of pathogen resistance to antiobiotics and in the agricultural sector with the unrelenting development of pest resistance to each new generation of pest control measures that have preceded GM technology. It is this past experience, which alerts policy-makers to the high probability that the problem of resistance will also accompany GM technology. Rather than examining the optimal depletion of susceptibility which may be viewed in a similar way to any natural resource depletion problem, we turn our attention to how this pest effect may affect the relative incentives to carry out R&D.

We will first address the potential adverse impact of GM technology on biodiversity. In Chapter 2 we construct a dynamic optimisation model to solve for the socially optimal level of crops. There are three categories of crops: GM only, non-GM and crops grown as a mixture of GM and non-GM. The key problem with GM as mentioned above, is that it eliminates crops as a source of food. Of course, from the farmers' perspective that is exactly the outcome they desire as their yields will increase and incomes will rise. However, from society's point of view, restricting the source of food for insects will have implications for the sustainability of ecosystems because it may lead to ripple effects further up the food chain. This beneficial function of non-GM crops as a source of food is highlighted in Sianesi and Ulph (1999), where they argue that these crops should be subsidised. However, no further intervention in the R&D market was deemed necessary. In our model, we employ a key assumption regarding the relationship between species diversity and the availability of food. Rather than assuming that insects can instantaneously change their diet when their usual source of food supply disappears, we argue that insects are more specialised in their feeding habits. Elimination of their food source implies the disappearance of their species. This characterisation of feeding habits turns out to be crucial in determining whether intervention in the growing of crops alone is sufficient to maximise welfare. We find that it is not and, in addition to controlling the growth of GM crops, policy-makers should also intervene in the R&D market for developing GM technology.

Since our focus is on the GM-biodiversity link, we abstract from consumers' attitudes towards GM technology. Although we recognise the importance of consumer attitudes, especially in view of the recent Government strategy report (Strategy Unit, 2003), which stated that the future of GM crops depended on consumer acceptance and in the light of its current absence, it concluded that GM crops are not economically viable, at least in the short to medium term. As stated above, our justification for ignoring this issue is our desire is to focus on the biodiversity issue. However, it could also be stated that the starting point of our analysis is the *a priori* acceptance of GM technology. Having established this starting position, the issue is how to address the potential adverse impact on biodiversity which is externalised by crop growers.

Due to our assumption of specialised feeding habits, we require policy intervention in the form of a subsidy to ensure that a critical amount of non-GM crops are grown and intervention in the R&D market to reflect its social cost. The optimal amount of GM-only crops is determined by the comparison between a general value function which captures society's valuation of biological diversity and the subsidy payment required to support the critical amount of non-GM crops. The incentive to carry out R&D will naturally depend on its return and in the private market case, R&D would be carried out until its private marginal benefit is zero. In the socially optimal case, the social cost of biodiversity reduction has to be accounted for in determining the socially optimal level of R&D. Our analysis determines a number of possible steady states characterising the optimal growth of GM-only crops and the optimal proportion of crops for which GM technology is made available. The appropriate intervention for each of the possible steady states is presented.

In Chapter 3, we extend the analysis of GM technology to examine how the possibility of the evolution of resistance to the technology affects the incentives to invest in R&D. Although, the analysis is set in the context of GM pest protected crops, we note the wider applicability of this analysis. As stated above, resistance in target organisms affects both the pharmaceutical and the agricultural sectors. In the pharmaceutical industry, ignoring this problem promotes the sub-optimal use of antiobiotics. In agriculture, inadequate care of how we implement GM technology will undermine the value of this technology. To prolong the long-term effectiveness of GM technology, several strategies have been suggested. We choose one which, on the surface at least, appears to offer the promise of an effective control of the development of resistance in pests. This strategy, termed pyramiding or gene-stacking, involves the transfer of multiple toxin producing genes into a single cultivar. The rationale for this method of pest control is that, even if a pest were to develop resistance to one of the toxins, it is unlikely to be able to simultaneously develop resistance to other toxins.

We explore the impact of including the potential for pest resistance on firms' decisions relating to innovation within a game-theoretic framework. Some of the literature on the link between firms' incentives to carry out R&D and market structure subscribe to the Schumpeterian view of the process of technological change, i.e. firms replace each other as monopolists in a process of 'creative destruction'. Other contributions predict persistent dominance with the same firm exerting market power. In both of these outcomes there is persistent monopoly. We know that, since a monopolist cannot appropriate all the benefits from innovation, the pace of innovation will be suboptimal. Thus, the welfare issue (which we do not address) in our analysis does not arise because there is a monopoly but whether the identity of the monopolist matters. Probably not, unless the leader establishes such a lead over the follower that the follower gives up. In this scenario, the incumbent reduces its R&D effort because of the absence of a competitive threat and the pace of innovation may be slower still.

In the standard R&D literature concerned with tournament models, firms compete against each other in a patent race. They increase the probability that it is they, rather than their rival, that succeeds by investing in innovation. In the analysis presented in Chapter 3, firms face a second threat - the potential for pests to develop resistance and hence, erode the value of their technology. To combat this threat, firms can invest in increasing the probability that their technology will survive. In this way, firms have two strategies which they can use to ensure their presence in the market. So the analysis in Chapter 3 differs to the usual patent race model.

The key question addressed in the analysis in Chapter 3 is, whether the threat of pest resistance promotes persistent dominance or 'creative destruction'. It is clear that the development of resistance will reduce the period over which firms earn profits and hence, reduce the incentive to innovate. What is not so clear is, how this will affect the relative incentives to innovate given that the starting positions of the two firms are different. In the standard R&D literature, we see that incumbency can confer a disadvantage in the race to innovate because it acts as a disincentive to carry out R&D. The problem is that, by increasing the probability of winning the race, the incumbent reduces the period for which it earns current profits. By eroding current profits, pest resistance can reduce the opportunity cost of investing in R&D and hence, increase the incentive to innovate. On the other hand, if the entrant is successful and the innovation is not sufficiently cost-reducing so as to drive the incumbent out of the post-innovation market, the progressive undermining of the incumbent's technology holds the promise of the entrant being able to capture the entire market. This increases the entrant's incentive to innovate. The impact of pest resistance on profits becomes more complex when firms can reduce the probability of pests developing resistance to their technology. The ability to modify their technology in such a way may offset the damage due to pest resistance and hence act as incentive to carry out R&D. Broadly, our results show that, when innovation is sufficiently radical, so that, the winner captures the entire post-innovation market, the incumbent's incentive to invest in R&D is lower than the entrant's. When the post-innovation market is shared between the two firms, the results are not so clear-cut. There will be parameter values for which persistent dominance will result and other parameter values for which action/reaction or alternating monopoly will be the outcome.

We also establish the relationship between both types of investment, i.e. in winning the race and modifying the technology, and find that these incentives work in the same direction. Thus, if the incumbent spends more on modifying the technology so as to improve the ability of the technology to withstand pest attack, it also spends more on trying to win the race for the patent. Thus, both incentives tend to reinforce each other. Thus, depending on the view held regarding whether monopoly or competition favours innovation, efforts to promote innovation in terms of the number of technologies developed may promote or hamper innovation in terms of the degree of innovation encompassed within each technology. For example, if policy is aimed at promoting competition in the R&D market the downside of such a policy may be to discourage larger innovations.

In Chapter 4 we break with the theme of GM and address the problem of creating appropriate incentives to control non-point source pollution. Non-point source pollution is interesting because it provides a classic example of production in teams, i.e. production of ambient pollution by multiple sources. It is difficult or too costly to observe individual emissions and uncertainty makes it impossible to infer individual contributions of each of the polluters from the ambient level of pollution. The approach to tackling this problem has been to design group incentives or to apply the usual 'point source' instruments to observable bases, such as inputs, whose use is correlated with emissions production.

Chapter 4 provides a review of the literature on non-point source pollution. Segerson (1988) was the first to recognise non-point source pollution as a problem of moral hazard in teams. Moral hazard arises because the link between a polluter's action and the ambient level of pollution is unobservable. Hence, there is an incentive to free ride on the actions of others. To eliminate this incentive, Segerson designed an ambient tax/subsidy scheme, which achieved the socially optimal ambient level of pollution. However, the assumptions made in deriving the Segerson ambient tax/subsidy scheme lead to problems of implementation of the scheme. Herriges et. al. (1994) and Xepapadeas (1995, 1999) addressed the assumption of risk neutrality. Xepapadeas (1995) presented a combined instrument involving an effluent tax as well as an ambient tax/subsidy which he argued can overcome the potential unacceptability of a scheme which can potentially punish compliant polluters. Cabe and Herriges (1992) and Xepapadeas (1992) highlighted the importance of polluters' expections in designing the appropriate ambient tax/subsidy scheme. Thus, knowledge of polluters' expections regarding the transmission mechanism from source to receptor is key in setting the appropriate level of the ambient tax/subsidy rate. Byström and Bromley (1998) argued that by allowing side-payments between polluters a uniform penalty is efficient.

Other schemes examined in chapter 4 are point/non-point trading regimes, input taxes and standards and voluntary agreements. The attraction of point/non-point trading schemes is the promise they offer of lowering abatement costs. The reason for this is that they provide a means of switching abatement from higher cost point sources to lower cost non-point sources. However, there are issues to be addressed in applying the traditional tradeable permit scheme to the non-point source problem. In traditional schemes the trading base is emissions which is not appropriate in the non-point source context as individual emissions are unobservable. So, alternative trading bases have to be found as well as the appropriate trading ratio between point and non-point sources.

Optimality requires the same number of taxes/standards as the product of the numbers of inputs and sources, imposed at a rate/level reflecting the marginal damage of each input. Thus, the transactions costs of introducing optimal taxes and standards are considerable, leading policy-makers to adopt less ambitious measures such as, focusing on a subset of inputs and imposing a uniform tax rate/standard on each one. The potential welfare loss involved in pursuing such a second-best policy has been explored in the literature. The findings are mixed, with some contributions concluding that the welfare loss is small or negative, especially when the transactions costs of imposing a first-best policy are accounted for and others asserting that targetted instruments perform best.

It is clear from the theoretical analysis that any of the possible approaches to address non-point source pollution present difficulties when it comes to their implementation. Policy-makers have opted for watered down versions of trading regimes, input taxes and standards whereas to date ambient tax/subsidy schemes have not been implemented. It is accepted that they are information demanding, requiring knowledge of abatement costs, damages from ambient pollution and estimates of how each polluter's action affects the distribution of ambient levels but substantial information is also required to implement any optimal scheme. The study of ambient tax/subsidy schemes is relatively new to the environmental economics literature and it may be that policy-makers are not familiar enough with them to consider them as potential alternatives to long standing approaches of standards and taxation. Hence, they are not implemented in practice which means that there is no data available on potential responses to such schemes. In view of this absence of data experimental studies are being carried out to assess in the laboratory the responses to these schemes and investigate whether these responses are transferable to the real world (Spraggon, 2002, Cochard *et. al.* 2003, Vossler *et. al.* 2003). In addition to reviewing some of the experimental evidence on ambient tax/subsidy schemes, we also examine actual practice to curtail non-point source pollution, specifically nitrate pollution.

Chapter 5 carries out an empirical analysis of the effectiveness of one of the instruments reviewed in Chapter 4 in reducing one category of non-point source pollution. The analysis carried out in Chapter 5 contributes to a larger EU-wide study of the applicability of a generic model to capture the nitrogen dynamics in a range of catchment types across Europe. Of the 23 catchments included in the study only 3 experienced a significant anthropogenic contribution towards the nitrogen loading in stream-water. Data availability led us to focus on the Kennet catchment located in the UK as the study catchment for carrying out the economic analysis. Concern with nitrates stems from possible adverse health effects and ecosystem damage. Limiting the maximum allowable concentration to 11 mg per litre within the EU has ensured that the contribution of excessive nitrate concentrations towards health problems has diminished quite considerably. The last recorded case of methaemoglobinaemia (blue baby syndrome) in the UK was in the 1970s. However, it has been recognised that ecosystem damage can occur at much lower nitrate concentrations. The source of this damage is eutrophication caused by the excessive discharge of nitrates into water bodies in the presence of sufficient supplies of phosphorous. The substantial increase in nutrient availability supports the proliferation of algae which eventually use up all the available oxygen and prevent sunlight from penetrating the lower depths. Although inland waterways tend to be phosphorous limited and so eutrophication is less of a problem here, the accumulation of nitrogen discharges along the length of the river has led to excessive levels of nitrates in estuaries and coastal waters where phosphorous is not limited. Recognition of the increasing deterioration in the quality of coastal waters led to the passing of the Oslo Paris (OSPAR) Convention to set in place measures to address this problem.

In view of the significant transactions costs associated with employing optimal taxes as observed in Chapter 4, we choose to examine a single input tax on nitrogen fertiliser. To assess how a fertiliser tax affects the nitrate concentration in the River Kennet, we construct an economic model which provides output to be used in an hydrological model called the **I**ntegrated **N**itrogen model for European **CA**tchments (INCA). This model, which was developed from an earlier version of the model limited to the UK context produced by the Aquatic Environments Research Centre at the University of Reading, simulates the flow of nitrogen through the environment. We employ a frequently used approach in the agricultural economics literature to assess how policy affects farmers' behaviour. This approach is to model farm activity within an optimisation framework, specifically linear programming. Before we can use the model to assess nitrogen policy, we calibrate the model to base year data. The procedure used to do this is Positive

Mathematical Programming (PMP), a relatively recent innovation in the agricultural economics literature. The changing redistribution of land-uses together with the fertiliser applications associated with five different nitrogen tax rates are inputted into INCA to assess how taxation policy translates into changing nitrate concentrations in the Kennet River.

Finally, Chapter 6 contains concluding remarks and outlines directions for future research.

Chapter 2

Biodiversity and Optimal Policies towards R&D and the Growth of Genetically Modified Crops

2.1 Introduction

Despite a steadily decreasing population growth rate, the absolute level of population is rising (UN, 1998) and thus ever-increasing supplies of food are required - especially in regions where environmental degradation compromises the ability to produce food. The prospect that genetically modified (GM) crops might greatly enhance yields is probably the single greatest argument in favour of genetic engineering of plants (Reiss and Straughan 1996). One major cause of reduced crop yields is due to crop pests. Worldwide, around a third of all potential crop production is lost through pests (Reiss and Straughan 1996). The potential for increased crop yields arises from the reduction of crop losses due to pests. Indeed, according to Reiss and Straughan (1996) the most immediate source of increased crop yields will be through enhanced pest resistance. Enthusiasts argue that genetic pest resistance will lead to enhanced yields, reduce the use of conventional pesticides and result in reduced consumer prices. However, there is a concern that GM crops may pose a threat to the environment. In this chapter, we limit our analysis to the question of possible impacts on biodiversity caused by a reduction in the availability of food for organisms due to the transfer of a pest resistant gene into agricultural crops. The observed magnitude of the impact on biodiversity will obviously be influenced by how biodiversity is measured. We utilise the most simple and the most standard representation of biodiversity - species richness (the number of species per unit area).[1] We do not believe that the central message of our analysis and its policy implications will differ qualitatively if we use a different measure of biodiversity as long as it based only on the number of species.[2]

The central question we shall address in this chapter is whether policy on GM crops should be directed towards the growth of the crops themselves or the adoption of the technology for growing GM crops or both. Obviously, this is not the only issue to be addressed, but we focus on this issue because it is not an issue that has been much addressed in the environmental economics literature. Most economists' intuition would be that if, as we shall assume, it is the growth of GM crops rather than the undertaking of GM R&D *per se* which damages the environment[3], then one only needs to regulate the growing of GM crops. Such regulation may indirectly affect the rate of R&D that is done, but that is a consequence of the policy not a direct target of the policy. This intuition is reflected in the literature which looks at how different forms of environmental regulation may affect incentives for the adoption of cleaner technologies, where it is assumed that the R&D market operates efficiently, but inefficiencies in environmental regulation can have

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[1] Other measures of biodiversity are Simpson's Index, Shannon-Weiner Index and Evenness. Species Richness, Simpson's Index and Shannon-Weiner Index base their measure of biodiversity on the number of species. Evenness is based on similarity of abundance of organisms across different species groups. An even spread amongst species groups indicates a higher biodiversity.

[2] If the chosen measure also takes into consideration the abundance of species (e.g. Evenness), our model would also have to take into account abundance of species and explicitly model whether a reduction in the supply of food would increase or decrease similarity in abundance across species groups.

[3] Of course this is a strong assumption, and we make it on the basis that even if GM R&D involves growing some GM crops (perhaps as trials), this is unlikely to be on such a scale as to be a real threat to the environment, and that the real threat to the environment comes only if full-scale growing of GM crops takes place.

adverse effects on innovation and adoption of new cleaner technologies.[4] There is another strand of literature in which there may be inefficiencies in the R&D market, for example because of strategic behaviour by firms in imperfectly competitive markets, where, for standard second-best reasons, environmental policy design needs to deal with both the externality and the R&D failures.[5] Goeschl and Swanson (1999) use an endogenous growth framework to model the different incentives facing industry and the social planner in preserving land which acts as an input in the production of genetic resources. These genetic resources are used to develop more resistant crops as each generation of crops becomes more susceptible to pests. As well as facing the problem of pest resistance which undermines future profits from innovation, firms face competition from other firms in the R&D market. The essence of their conclusion is that genetic resources provide information on potentially superior ways to promote resistance in crops. Since such information is a public good it will be undersupplied in the market, hence, firms will invest less in land reserves dedicated to the preservation of genetic resources than a social planner. They do not explore the policy implications which might follow from such a conclusion.

In this chapter, we shall assume that there are no failures in the GM R&D market and that policy-makers use efficient environmental policy instruments, but show that there is a need to intervene both in the decisions about growing crops and in decisions about adoption of GM technologies. In a closely related paper, Sianesi and Ulph (1999) address the same question but reach a very different conclusion, namely that the only intervention that is warranted is the decision about whether to grow GM or non-GM varieties of crops, and there is no need to alter the normal incentives to do R&D or adopt GM technologies. However, we will argue that these conclusions follow from a very specific model of how it is believed that GM crops affect the environment. Like us, Sianesi and Ulph (1999) are concerned solely with the potential threat that growing GM crops will pose to the

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[4] See for example the classic papers by Orr, 1976; Magat, 1979; Downing and White, 1986; Malueg 1989.

[5] See for example Carraro and Soubeyran (1996).

diversity of species. In their model, species diversity is directly related to the total supply of non-GM crops that is grown. The externality in their model is thus that the growing of non-GM crops generates an external benefit in terms of species variety. Thus, if left to market forces a suboptimal level of non-GM crops results. Therefore, the policy required is to subsidise the growing of non-GM crops. So, in their model irrespective of whether GM technology is available or not, a subsidy to non-GM crops is necessary. This subsidy is sufficient to implement both the optimal mix of GM and non-GM crops and achieve the optimal level of GM R&D investment.

The reason for the different policy conclusions between Sianesi and Ulph (1999) and ourselves is the different assumptions about how GM crops affect biodiversity. In their model, there is no link between the number of crops grown as either GM or non-GM varieties and the number of species. In the limit, if a sufficient quantity of only one crop in the non-GM variety is grown, with all other crops grown as GM varieties, then one could sustain any level of diversity desired. In other words, their model assumes that species are polyphagous, i.e. that they can feed on many sources of food and if one source disappears they can easily switch to another. This seems to us an implausible characterisation of the feeding habits of different species. Even if species are generalists in terms of their feeding habits, their ability to switch will depend on there being an alternative source of food which is readily accessible as well as a sufficient amount of time to discover the new source and adapt to it. Recent evidence from the Farm Scale Evaluations carried out in the UK found a significant adverse impact on biodiversity from the introduction of GM herbicide tolerant oilseed rape and sugarbeet (Firbank cited in Connor, 2003). To date there have been no studies carried out to assess the impact of pest resistant GM crops on the same scale as that for herbicide tolerant GM crops but Birch *et. al.* (1997) discovered that the modification of potatoes to resist aphids which were subsequently fed to ladybirds reduced the lifespan of ladybirds by half.

In the absence of widespread evidence regarding the biodiversity impact of GM pest resistant crops, the precautionary approach of assuming specialisation in feeding habits demands that a variety of crops is maintained. Thus, we follow most of Sianesi and Ulph (1999) model but modify the assumption about the link between GM crops and species diversity. Hence, we adopt an equally simple, but very different view of the relationship between species diversity and crops. In our approach, the variety of animal and insect species that survives is directly linked to the variety of crops, for which at least some minimum threshold quantities of non-GM varieties is grown. With this characterisation of the link between GM crops and biodiversity we get rather different policy conclusions. There will be outcomes where there is no need to directly intervene in the decisions about which crops to grow, although in other possible steady states of our model it will be necessary to subsidise the growing of the minimum threshold levels of non-GM varieties for some, but not all crops. The need to intervene in the decision about whether to grow crops as GM or non-GM varieties arises only because of the existence of GM technology. This is in direct contrast to Sianesi and Ulph (1999) and arises because of the different way in which species dependence on food supplies is modelled. More importantly, we will show that because the number of crops for which GM technology is available negatively affects social welfare, irrespective of whether there is any intervention in the growing of crops, it is now necessary to intervene in the R&D decision, essentially by taxing the profits that would be earned from the adoption of new GM technologies, in order to reflect the social costs imposed on society by making available GM technology to a wider range of crops.

The format of the chapter is as follows. In Section 2.2 we set out the model. Section 2.3 analyses the social planner's problem, which can be decomposed into three elements: the optimal amounts of GM and non-GM crops to be grown, the optimal proportion of GM-only crops, and the optimal level of R&D. This allows us to derive the policy implications. Concluding remarks are contained in Section 2.4.

2.2 The model

We shall stick as closely as possible to the model by Sianesi and Ulph (1999) and modify it only with respect to the link between GM crops and biodiversity. We assume that there is a continuum of possible crops that can be grown denoted by the interval [0,1]. Although crops grown are inherently different from each other, we shall assume that the model is symmetric with respect to different crops, in a sense that will become clear as we proceed. For each crop it is possible to grow a non-GM variety at a unit cost k. If and only if the GM technology has been discovered for a particular crop, it will be possible to grow a GM variety of that crop at a unit cost c, which is the same for all crops. To make the problem interesting, we assume $c < k$. If $c \geq k$ there is no private incentive to develop GM crops and hence no externality can arise. The advantage of GM technology therefore is simply to lower the unit cost of growing crops. However, crops are sufficiently different from each other, that developing the technology to grow a GM variety of one crop does not give one the technology to grow GM varieties of other crops, and so one has to continuously invest in GM R&D if one wishes to expand the range of crops for which GM technology is available. Specifically we assume that at time t, for fraction p_t of all crops, GM technology has been developed, and that if one carries out GM R&D at the rate $g_{t,}$ then the proportion of crops for which GM technology is available can be expanded at the rate $\dot{p} = g_{t.}$

As shown by Sianesi and Ulph (1999), without loss of generality, we shall assume that $p_0 = 0$. The cost of carrying out the R&D is given by $\gamma(g_t)$, where $\gamma' > 0$, $\gamma'' > 0$ for all g_t; in particular $\gamma'(0) > 0$, so that there are strictly positive and increasing marginal costs of doing GM R&D, even for the very first unit of R&D. This assumption, which is standard in the R&D literature, is made to ensure that the objective function in the maximisation problem is strictly concave so that the solution is a global maximum.

Now obviously on the proportion $(1-p_t)$ of crops for which there is no GM technology available, it is only possible to grow non-GM varieties of those crops, and we denote by z_t, the amount of the non-GM variety grown for each of these crops (although crops are different, everything in the model is symmetrical so if it pays to grow z_t of one crop with no GM technology it will pay to grow z_t for all crops for which there is no GM technology). For the proportion of crops p_t for which GM technology has been discovered at time t we do not assume that only GM varieties need be grown. We assume that on a proportion $q_t \leq p_t$ of crops only GM varieties are grown, and the amount of GM variety of each crop grown we denote by w_t. On the remaining proportion $(p_t - q_t) \geq 0$ of crops we assume that both GM and non-GM varieties of each crop are grown, and we denote by x_t the amount of GM variety of each crop grown, and y_t the amount of non-GM variety of each crop grown. Now in Sianesi and Ulph (1999) it was just assumed that $\forall\, t$, $q_t = p_t$, so that once GM technology is available for a crop only the GM variety of it would be grown. It turns out that for their model, such an assumption is justified, at least in steady-state, but because of the different way we model the link between GM crops and biodiversity it is essential that we maintain the possibility of growing both GM and non-GM varieties of the same crop. We now turn to the different models of the GM-biodiversity link.

In Sianesi and Ulph (1999) the number of bird/insect species, S_t is related to the total food supply of non-GM crops, denoted by

$$f_t \equiv (1 - p_t)\, z_t$$

through the equation

$$\dot{S}_t = \phi(f_t/S_t)S_t$$

But this implies that even if $q_t = p_t \approx 1$, provided z_t is made large enough one can achieve, over time, whatever level of variety of species one desires. So species of insects (and hence birds) which may have fed on the non-GM variety of one crop, which is subsequently made insect resistant through GM technology, are assumed to be able to switch to feeding on the non-GM varieties of other crops. Insects are assumed to be able to switch instantaneously to an alternative source of food. As stated above, this seems to us biologically a very strong assumption.

So in this chapter, we adopt an equally simplistic but radically different assumption about the link between species diversity and crops. We assume that there is a direct link between the variety of species of insects and birds and the variety of crops which are not GM, provided that for those species that feed on a particular crop at least $\overline{y} > 0$ of the non-GM variety of that crop is grown, otherwise the species is driven to extinction. Now, assuming that the only rationale in our model for growing non-GM varieties of crops for which GM technology is available will be to ensure the survival of the insects/birds which depend on that crop, it will turn out that for the proportion of crops $(1 - q_t)$, we require that $y_t \geq \overline{y}$, i.e. the amount of non-GM crops is at least as large as the threshold requirement. We shall therefore simply identify the variety of species of insects/birds dependent on crops by $S_t = (1 - q_t)$. Since it will also turn out in our model that $\dot{q}_t \geq 0$ (see Result 2), this implies that once a crop is grown as GM-only, the associated species of insects and birds which depend on that crop are irreversibly lost.

Society's instantaneous preferences for species variety is captured in the value function $V(1 - q_t)$ with the properties $V' > 0$, $V'' \leq 0$, $V'(0) = \infty$, so that there is a strictly positive but diminishing marginal benefit to a given variety of species, and an infinite marginal disutility associated with the loss of the last species.

Finally, we consider the benefits obtained from consuming crops. In terms of consumption benefits, we assume that consumers are completely indifferent to whether they consume the GM or non-GM variety of a crop[6], but that they have a preference for consuming a variety of crops. This is captured by the usual Dixit-Stiglitz C.E.S. preferences,

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[6] Of course consumers' concerns about the impact of GM crops on biodiversity are already reflected in the preference for biodiversity function V. We are ignoring any concerns of consumers about possible health effects of GM crops, essentially because they are not relevant to the point we seek to make in this chapter. Such concerns could be introduced in a straightforward way without affecting our main conclusions. For example, if consumers are worried about the health effects of GM crops, then producers would need to sell GM varieties at a lower price, *ceteris paribus*. But then we could just interpret c as the cost of producing GM crops including the cost of any discount needed to make consumers indifferent between GM and non-GM varieties and the rest of our analysis goes through unaffected.

so that at any moment of time, consumer benefits are given by:

$$U(p,q,w,x,y,z) \equiv q\frac{w^{1-\beta}}{1-\beta} + (p-q)\frac{(x+y)^{1-\beta}}{1-\beta} + (1-p)\frac{z^{1-\beta}}{1-\beta};\ \beta > 0, \beta \neq 1$$

Let $\varepsilon = \frac{1}{\beta}$ be the elasticity of substitution between crops and obviously with $\beta > 0$ crops are imperfectly substitutable. As in Sianesi and Ulph (1999) denote by:

$$B(\alpha) \equiv \max_{x} \frac{x^{1-\beta}}{1-\beta} - \alpha x \qquad (2.1)$$

the maximum social surplus (ignoring environmental effects) from a having a crop produced at unit cost α. Carrying out the maximisation yields $x = \alpha^{-\varepsilon}, B(\alpha) = -\frac{1}{1-\varepsilon}\alpha^{1-\varepsilon}$ so that $B'(\alpha) < 0$.

We assume that $\overline{y} < k^{-\varepsilon}$; as we will see this implies that if one grew only the non-GM variety of a crop at unit cost k and chose to grow the amount of that crop which maximises social surplus, then one would grow enough of it to meet the minimum threshold amount of the crop to allow the insects and birds that depend on that crop to survive. So, in the absence of any GM technology, there would be no reason to intervene in the growing of crops.[7]

2.2.1 The social planner's problem

The problem facing the social planner is to choose w_t, x_t, y_t, z_t, g_t and q_t to maximise:

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[7] The reason for such an assumption is to omit externalities bar the one we are interested in, which is the reduction in species diversity caused by growing GM crops.

$$\int_0^\infty e^{-\delta t}\left\{ q_t \frac{w_t^{1-\beta}}{1-\beta} - q_t w_t c + (p_t - q_t)\frac{(x_t + y_t)^{1-\beta}}{1-\beta} - (p_t - q_t)(cx_t + ky_t) \right.$$

$$\left. +(1-p_t)\frac{z_t^{1-\beta}}{1-\beta} - (1-p_t)kz_t - \gamma(g_t) + V(1-q_t) \right\} dt \qquad (2.2)$$

subject to:

$$\dot{p}_t = g_t;\quad y_t \geq \overline{y};\quad q_t \leq p_t;\quad p_t \leq 1;\quad p_0 = 0$$

The current valued Hamiltonian for the problem contained in (2.2) is:

$$H = q_t \frac{w_t^{1-\beta}}{1-\beta} - q_t w_t c + (p_t - q_t)\frac{(x_t + y_t)^{1-\beta}}{1-\beta} - (p_t - q_t)(cx_t + ky_t) + (1-p_t)\frac{z_t^{1-\beta}}{1-\beta}$$
$$-(1-p_t)kz_t - \gamma(g_t) + V(1-q_t) + \pi_t g + \mu_t(y_t - \overline{y}) + \lambda_t(p_t - q_t) + \omega_t(1-p_t)$$

where π_t is the costate variable and μ_t, λ_t and ω_t are the Lagrange multipliers. The first-order conditions are:

$$\frac{\partial H}{\partial w_t} \ :\ w_t^{-\beta} \leq c; \qquad w_t \geq 0 \qquad (2.3)$$

$$\frac{\partial H}{\partial x_t} \ :\ (x_t + y_t)^{-\beta} \leq c; \qquad x_t \geq 0 \qquad (2.4)$$

$$\frac{\partial H}{\partial y_t} \ :\ (x_t + y_t)^{-\beta} \leq k - \mu_t; \qquad y_t \geq 0 \qquad (2.5)$$

$$\frac{\partial H}{\partial z_t} \ :\ z_t^{-\beta} \leq k\ ; \quad z_t \geq 0 \qquad (2.6)$$

$$\frac{\partial H}{\partial g_t} \ :\ \pi_t \leq \gamma'(g_t); \qquad g_t \geq 0 \qquad (2.7)$$

$$\frac{\partial H}{\partial q_t} \ :\ [B(c) - (B(c) - (k-c)y_t) - V'(1-q_t)] \leq \lambda_t; \qquad q_t \geq 0 \qquad (2.8)$$

$$\dot{\pi}_t \ = \ \delta\pi_t - [B(c) - B(k) - (k-c)y_t + \lambda_t - \omega_t] \qquad (2.9)$$

where equation (2.9) is the first-order condition associated with the state variable p_t and is arrived at by setting $\frac{\partial \pi}{\partial t} = - \frac{\partial H}{\partial p_t}$. We use the definition of maximum social surplus as given in (2.1) to simplify the first-order conditions (2.8) and (2.9). We also write down the complementary slackness conditions associated with y_t, q_t and p_t.

$$(y_t - \overline{y})\mu_t = 0 \tag{2.10}$$

$$\lambda_t(p_t - q_t) = 0 \tag{2.11}$$

$$\omega_t(1 - p_t) = 0 \tag{2.12}$$

We analyse these conditions in three stages.

2.2.2 Optimal amounts of crops grown

In this subsection we take as given p_t and q_t and determine w_t, x_t, y_t and z_t. Assuming interior solutions, using (2.3) and (2.6) it is straightforward to see that, $\forall\ t$,

$$w_t = c^{-\varepsilon}; \quad z_t = k^{-\varepsilon}; \quad w_t > z_t$$

Thus, when only GM or non-GM varieties are grown, the socially optimal amount to grow coincides with the amount that would be chosen in a private market, i.e. the amount that would be demanded if the crop was sold at its marginal (unit) cost of production, and so there is no need for policy intervention.

However, in the absence of any policy, farmers would never grow a mixture of GM and non-GM crops, since it is always cheaper to grow GM crops. The social planner will set y at the constraint level. To see this, using (2.4) we have $x_t + y_t = c^{-\varepsilon}$ and from (2.5) we get $x_t + y_t = (k - \mu_t)^{-\varepsilon}$ which implies $\mu_t = k - c > 0$ since $k > c$ by assumption. Hence from equation (2.10) we obtain $y_t = \overline{y}\ \ \forall\ t$. Substituting $\overline{y}$ for y_t in equation (2.4) we must have $x_t = c^{-\varepsilon} - \overline{y} > 0\ \ \forall\ t$ since by assumption $\overline{y} < k^{-\varepsilon} < c^{-\varepsilon}$. What this means is that, where both GM and non-GM varieties of the same crop are grown, the total amount of the crop grown is the same as would be the case if only the GM variety had been grown, so consumers will get the same benefit from the 'mixed' case of GM and non-GM varieties as from the pure GM-only case. But out of the total, the minimum amount of non-GM variety is grown ($\overline{y}$) to sustain the existence of the species of insect and birds which depend on these crops. To induce the 'mixed' case which includes the required levels of non-GM crops, all crops in the mixed category are sold at a price equal to the unit cost of producing GM crops and the shortfall in profits from producing non-GM crops is made good by the government which grants a subsidy equal to the difference in the costs of production, $(k-c)$ for each unit produced of non-GM crops up to the threshold, $\overline{y}$.

We summarise the above as:

Result 1

For all time periods t, the following pattern of crops is grown:

(i) on a proportion of crops $q_t \leq p_t$, only GM varieties are grown: an amount $c^{-\varepsilon}$ is grown of each crop and sold at price c

(ii) on a proportion $(1-p_t)$ of crops, only non-GM varieties are grown: for each such crop an amount $k^{-\varepsilon}$ is grown and sold at price k :

(iii) on a proportion $(p_t - q_t)$ of crops both the GM and the non-GM varieties are grown: for each of these crops, $\overline{y}$ of the non-GM variety is grown and $(c^{-\varepsilon} - \overline{y})$ of the GM variety is grown: both varieties are sold at price c.

(iv) the only policy required is that on the proportion $(p_t - q_t)$ of crops for which both GM and non-GM varieties are grown, the amount of $\overline{y}$ of the non-GM variety should be subsidised at the rate $(k-c)$ per unit.

2.2.3 Optimal proportion of GM-only crops grown

We now determine the optimal value of q_t taking as given the value of p_t. It is easier to begin with the case where $0 \leq q_t < p_t$, so that from (2.11), $\lambda_t = 0$ and (2.8) becomes:

$$[B(c) - (B(c) - (k-c)\overline{y}) - V'(1-q_t)] = [(k-c)\overline{y} - V'(1-q_t)] \leq 0; \quad q_t \geq 0 \qquad (2.8')$$

The interpretation of (2.8′) is straightforward. An increase in q_t by 'one crop' has three effects. First, for this crop, only the GM variety is now grown, which has a social benefit $B(c)$. Second, the crop will no longer be grown as a mix of GM and non-GM varieties: since this crop was sold at a common price of c, but an amount $\overline{y}$ was subsidised at a rate of $(k-c)$, the net social benefit of growing this crop in a mix of GM and non-GM varieties was $B(c) - (k-c)\overline{y}$. Taking these two effects together mean that the net social benefit of increasing q_t by 'one crop' is $(k-c)\overline{y}$, i.e. it eliminates the need for society to subsidise the growing of $\overline{y}$ level of the non-GM variety of a crop for which the GM technology is available. The third effect of increasing q_t is that it reduces the variety of species and the marginal social cost of this is $V'(1-q_t)$. So, assuming that $q_t < p_t$, the net social gain from an increase in q_t is $(k-c)\overline{y} - V'(1-q_t)$. At an optimum, it must not be possible to vary q_t and obtain a net gain. There are therefore two cases:

(A) $V'(1) \geq (k-c)\overline{y}$. This says that the marginal social cost of the loss of even one species is as least as great as the cost of subsidising the growth of non-GM varieties. If that is the case, then $q_t = q^* = 0 \; \forall \; t$, i.e. one never grows only GM varieties of crops, so all species are retained.

(B) $V'(1) < (k-c)\overline{y}$. Since $V'(0) = \infty$, there must exist a q^*, $0 < q^* < 1$ such that $V'(1-q^*) = (k-c)\overline{y}$. To determine q_t there are two sub-cases depending on the values of p_t and q^*. $(B1)$ If $p_t > q^*$ then $q_t = q^*$. In this case, the proportion q^* of crops will be grown as GM-only, whereas the proportion $(p_t - q^*) > 0$ of crops will be grown as both GM and non-GM. $(B2)$ If $p_t \leq q^*$, then $V'(1-p_t) \leq V'(1-q^*)$, and from (2.8),

$\lambda_t = (k-c)\,\overline{y} - V'(1-p_t) \geq 0$; $q_t = p_t$. In this case, all the crops for which GM technology is available will be grown as GM varieties.

We summarise these results as follows:

Result 2

For any value of p_t, $0 \leq p_t \leq 1$, there are three possible values of q_t :

(i) if $V'(1) \geq (k-c)\,\overline{y}$, $q_t = 0, \lambda_t = 0 \; \forall \; t$

(ii) if $V'(1) < (k-c)\,\overline{y}$, and $p_t > q^*$, where $V'(1-q^*) = (k-c)\,\overline{y}$, then $q_t = q^*$ and $\lambda_t = 0$

(iii) if $V'(1) < (k-c)\,\overline{y}$ and $p_t \leq q^*$, then $q_t = p_t$, and $\lambda_t = (k-c)\,\overline{y} - V'(1-p_t) \geq 0$.

These three possibilities are illustrated in Figure 2-1.

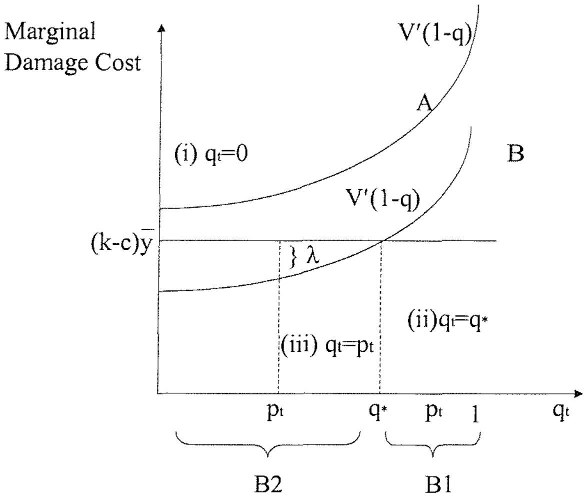

Figure 2-1: Determination of optimal GM-only crops

Note that $\frac{\partial q_t}{\partial t} = 0$ from *(i)* and *(ii)*, and $\frac{\partial q_t}{\partial t} = \frac{\partial p_t}{\partial t} = g_t$ from *(iii)*. Also, $g_t \geq 0$ by equation (2.7). Thus, we get the result that $\dot{q} \geq 0$ in any case, i.e. once a crop is grown as a GM-only variety, it can no longer be grown as a non-GM variety and all species that relied on it for food are irreversibly lost.

2.2.4 Optimal path for GM R&D

Steady State

To find a solution to the optimal path for p_t or equivalently, g_t we begin by considering the steady-state solution. Steady state values are denoted by an asterisk. In steady state $\dot{\pi}_t = 0$ or $\pi_t = \pi^*$. Equation (2.9) becomes:

$$\pi_t = \pi^* \equiv \frac{B(c) - B(k) - (k-c)\overline{y} + \lambda^* - \omega^*}{\delta} \tag{2.13}$$

In addition $\dot{p}_t = 0$ or $p_t = p^*$, so that using (2.7) and (2.13) steady state requires that

$$\frac{B(c) - B(k) - (k-c)\overline{y} + \lambda^* - \omega^*}{\delta} \leq \gamma'(0) \tag{2.14}$$

where $\gamma'(0)$ is the marginal cost of carrying out the first unit of R&D.

It will be useful to define

$$\phi = B(c) - B(k) - \delta\gamma'(0)$$

where ϕ is the instantaneous marginal private net return to carrying out the first unit of research in GM technology, and would be the instantaneous marginal social net return to the first unit of GM R&D in the absence of any concern about the environmental consequence of GM crops (by net return, we mean the marginal gross return net of the marginal cost of doing R&D). The definition of ϕ implicitly reflects the result that in the absence of any concern about environmental consequences of GM, once the GM technology exists for a crop, only the GM variety would be grown. To make the problem interesting we assume $\phi > 0$, otherwise it would never pay to carry out GM R&D even if there was no environmental impact. We can rewrite the condition for steady state as

$$\phi \leq (k-c)\,\overline{y} - \lambda^* + \omega^* \tag{2.15}$$

Now we shall follow Sianesi and Ulph (1999) in arguing that if the steady state value of p^* is strictly positive, then along the approach path to steady state we must have had $g_t > 0$ and hence (2.7) would have held with equality; by continuity (2.15), which is the steady-state version of (2.7), must also hold with equality. However, if $p^* = 0$, so GM R&D is never carried out, then (2.15) could hold as a strict inequality.

There are then three possible outcomes for steady-state.

(i) $\phi \leq \min\left[(k-c)\,\overline{y}, V'(1)\right]$. In this case we argue that $p^* = 0$, and hence $p_t = 0$ $\forall\ t$. From (2.12) $\omega_t = \omega^* = 0$. There are two sub-cases. If $(k-c)\,\overline{y} \leq V'(1)$ then from subsection 2.2.3 (A) $q^* = 0$, $q_t = 0\ \forall\ t$, $\lambda_t = \lambda^* = 0\ \ \forall\ t$. Hence (2.15) holds as $\phi \leq (k-c)\,\overline{y}$. If $(k-c)\,\overline{y} > V'(1)$ then from subsection 2.2.3 (B2) $q^* > 0$, $q_t = p_t = p^* = 0$ $\forall\ t$, $\lambda_t = \lambda^* = (k-c)\,\overline{y} - V'(1)$ and so (2.15) holds as $\phi \leq V'(1)$. These two sub-cases are summarised by $\phi \leq \min\left[(k-c)\,\overline{y}, V'(1)\right]$.

(ii) $V'(1) < \phi < (k-c)\overline{y}$. Define p^* by $\phi = V'(1-p^*)$ and recalling that q^* is defined by $(k-c)\,\overline{y} = V'(1-q^*)$ we have $0 < p^* < q^* < 1$. This implies that $p_t < 1\ \ \forall\ t$, so that from (2.12) $\omega_t = \omega^* = 0\ \ \forall\ t$. From subsection 2.2.3 (B2) since $p^* < q^*$, $q_t = p_t$ $\forall\ t$, $\lambda^* = (k-c)\,\overline{y} - V'(1-p^*)$. Hence (2.15) becomes $\phi \leq V'(1-p^*)$, which from the definition of p^* holds with strict equality.

(iii) $\phi \geq (k-c)\,\overline{y}$. In this case $p^* = 1$. Again there are two sub-cases. Firstly, $(k-c)\,\overline{y} \leq V'(1)$, in which case $q_t = 0\ \forall\ t$, or $(k-c)\,\overline{y} > V'(1)$, in which case in steady state, $q_t = q^* < 1$. In either case, in steady state $q_t < p_t$, and so $\lambda_t = \lambda^* = 0$. From (2.12) we must have $\omega^* \geq 0$, and from (2.15) we must have $\phi = (k-c)\,\overline{y} + \omega^*$, so then $\omega^* = \phi - (k-c)\overline{y} \geq 0$.

These results are summarised in:

Result 3

There are three possible steady-states for the proportion of crops p^* for which GM technology will be developed.

(*i*) If $\phi \leq \min\left[(k-c)\,\overline{y}, V'(1)\right],\ \ p^* = 0$;

(*ii*) If $V'(1) < \phi < (k-c)\,\overline{y}$, p^* is defined by $\phi = V'(1-p^*)$ and $p^* < q^*$;

(*iii*) If $\phi \geq (k-c)\,\overline{y}$, $p^* = 1 > q^*$.

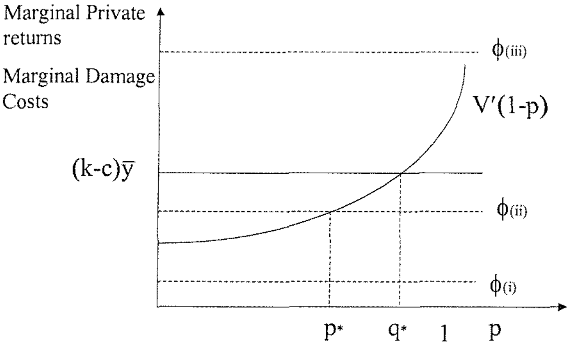

Figure 2-2: Comparison of R&D returns to: non-GM subsidy and social valuation of biodiversity

These three cases are illustrated in Figure 2-2 which shows three different values of ϕ relative to $V'(1-p)$ and $(k-c)\overline{y}$. The interpretation of this result is straightforward. If the marginal private return to GM is less than the minimum social cost of doing GM R&D, defined as the minimum of the subsidy required to ensure the survival of species or the marginal cost of the loss of just one species, then it is never worth doing GM R&D. If the marginal private return is above the marginal cost of the loss of one species, but below the cost of subsidising the growing of non-GM varieties, then there will be some fraction of crops, lying strictly between zero and one, for which it will be worth doing R&D to develop GM varieties. Finally, if the marginal private returns to R&D are higher than the cost of subsidising the growing of non-GM varieties, then it is worth undertaking GM R&D so that all crops have GM varieties.

Approach to steady state and policy implications

The approach to steady state in terms of p_t and q_t is straightforward to describe in the three cases, identified in Result 3.

(*i*) In this case, $p_t = q_t = 0 \;\; \forall \; t$;

(*ii*) In this case $q_t = p_t \; \forall \; t$ and p_t rises as described below until it reaches $p^* < q^*$; so in this case it is never pays to subsidise the growing of the non-GM variety of the crops for which GM technology has been developed;

(*iii*) In this case there are two phases; in the first phase, as in (*ii*), $q_t = p_t$ and both rise until $p_t = q_t = q^*$; in the second phase, p_t continues to rise until $p_t = 1$, but q_t remains constant at q^*; so in this second phase, for all new GM crops that are introduced it will be optimal to subsidise the growing of the minimum amount of the non-GM variety to preserve biodiversity.

We now describe more precisely the way that p_t evolves in cases (*ii*) and (*iii*) above. The optimal path for p_t, equivalently g_t, is described by $p_0 = 0$, $\dot{p}_t = g_t$ where, integrating (2.9), g_t is defined by:

$$\gamma'(g_t) = \pi_t = \int_t^\infty e^{-\delta(\tau - t)} \left[B(c) - B(k) - (k - c)\,\overline{y} + \lambda_\tau - \omega_\tau \right] d\tau \qquad (2.16)$$

(2.16) is just the condition that ensures that R&D is carried out until the marginal cost of doing R&D equals the present value marginal gross social return from R&D. The instantaneous marginal gross social return from GM R&D can be written as $B(c) - B(k) - \theta_\tau - \omega_\tau$ where $\theta_\tau = (k - c)\,\overline{y} - \lambda_\tau$. $B(c) - B(k)$ is the marginal gross private return to GM R&D, and represents the gain in consumer surplus from a reduction in the cost of growing crops. We follow Sianesi and Ulph (1999) in assuming that this private return can be fully captured by those engaged in GM R&D (perhaps in the form of an annual licence fee to grow a GM crop). Of course there are standard reasons why that is unlikely to be the case, but the arguments are not specific to GM R&D, and so we ignore them for the purpose of this paper.

What we are concerned with are the variables θ_τ and ω_τ, which are the policy variables designed to bring the private rate of return on GM R&D in line with the social rate of return. We shall interpret θ_τ as a tax that needs to be levied on the return from GM R&D to reflect the social cost of GM R&D; this can be interpreted as a tax on the annual licence income which R&D firms receive from farmers.[8] We interpret ω_τ as an "operator's licence fee" to undertake any form of GM R&D.[9] From our previous analysis it is straightforward to see what value θ_τ and ω_τ must take for the three cases identified in Result 3.

(i) $\theta_\tau = \min\left[(k-c)\,\overline{y}, V'(1)\right], \omega_\tau = 0, \forall\ \tau$

(ii) In this case, we are always in the region where $p_\tau = q_\tau < 1$, so that $\omega_\tau = 0$, $\lambda_\tau = (k-c)\,\overline{y} - V'(1-p_\tau)$, so that $\forall\ \tau$, $\theta_\tau = V'(1-p_\tau)$, with $\theta^* = V'(1-p^*)$ in steady state.

(iii) In this case there will be three phases. The first phase corresponds to (ii), so that throughout this phase

$p_\tau = q_\tau < 1$, and $\omega_\tau = 0$, $\theta_\tau = V'(1-p_\tau)$. This phase persists until $p_\tau = q^*$. In the second phase, $q_\tau = q^* < p_\tau < 1$, so that $\lambda_\tau = \omega_\tau = 0$, and $\theta_\tau = (k-c)\overline{y}$. Finally, $p_\tau = p^* = 1$, and in this case $\lambda_\tau = 0$, $\omega_\tau = B(c) - B(k) - (k-c)\,\overline{y}$, and $\theta_\tau = (k-c)\,\overline{y}$. Clearly, $\theta_\tau + \omega_\tau = B(c) - B(k)$. We summarise the discussion in the following:

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[8] Of course there are the usual problems of interpretation of tax incidence. An equivalent way of interpreting θ_τ is as a lump-sum tax paid in year τ on the growing of each GM crop that is currently being employed.

[9] As we shall see ω_τ is not really of much policy interest and arises simply from the fact that there is a limited stock of potential crops available for GM innovation denoted by the constraint $p_t \leq 1$. If it is assumed that R&D operators are not aware of this limit, and so might be searching for another crop to modify, then there is a need for an operator's licence fee to be introduced when this limit is reached to choke off any further attempt to develop GM varieties.

Result 4

To secure the optimal investment in R&D the social planner imposes a licence fee to develop crops for GM R&D, ω_T, and a tax to reflect the social cost of GM R&D, θ_T. θ_T and ω_T are determined as follows from each of the three cases in Result 3.

(i) $\theta_T = \min\left[(k-c)\,\overline{y}, V'(1)\right];\ \omega_T = 0$

(ii) $\theta_T = V'(1-p_T);\ \omega_T = 0$

(iii) *Phase* 1 $(0 \leq p_T \leq q^*);\ \theta_T = V'(1-p_T);\ \ \omega_T = 0$

Phase 2 $(q^* < p_T < 1);\ \theta_T = (k-c)\,\overline{y};\ \omega_T = 0$

Phase 3 $(p_T = 1);\ \theta_T = (k-c)\,\overline{y};\ \ \omega_T = B(c) - B(k) - (k-c)\,\overline{y}$

Figure 2-3 illustrates the optimal path of R&D. As stated above, between zero and q^*, $p_t = q_t$ both of which continue to rise until q^* is reached, at which point q_t stops rising and remains equal to q^*. However p_t keeps rising until it reaches 1. This diagram also informs the path of the R&D tax, θ_T. Below q^* the R&D tax is set equal to $V'(1-p_T)$. At q^* the R&D tax is capped at $(k-c)\,\overline{y}$ where it remains. The 'licence fee', ω_T is triggered when p reaches 1.

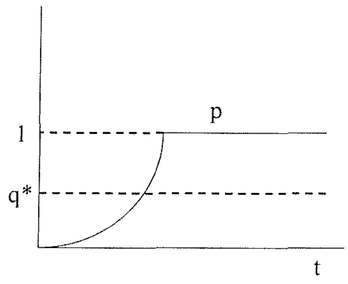

Figure 2-3: Dynamic path of R&D

In terms of policy outcomes, the key point to note is that unlike Sianesi and Ulph (1999), in addition to having to subsidise the growing of the minimum level of non-GM varieties of some GM crops (when $p_t > q^*$), it will now be necessary to intervene in the market for R&D by taxing the return on R&D, by an amount θ_τ, to reflect the social costs of GM R&D. These social costs are either the marginal social costs of the loss of an extra species, for $p_t \leq q^*$, or the social cost of having to subsidise the growing the minimium amount of the non-GM variety of crops for which GM technology has been developed in order to preserve the optimal steady-state level of biodiversity $(1 - q^*)$.

2.3 Conclusion

In this chapter we have attempted to illuminate the debate on whether GM crops should be grown and if so, in what quantity. We have also examined the issue of whether intervention in the GM R&D market is warranted. Unlike Sianesi and Ulph (1999) we found that intervention was indeed necessary. The reason for this difference in policy conclusion stems from the different assumption about how species diversity is related to the growing of GM and non-GM varieties of crops. In Sianesi and Ulph (1999) species diversity is related only to the total amount of non-GM crops grown, where, in terms of environmental impact, the non-GM variety of one crop is a perfect substitute for the non-GM variety of another. A subsidy to the growing of non-GM crops is necessary to address the environmental externality, and this affects the profitability of GM crops and indirectly the incentive to do GM R&D, but once the subsidy is set there is no need for any further intervention in GM R&D. By contrast, we assume that the number of species is directly related to the number of non-GM crops grown at some initial level, so that the non-GM variety of one crop is not a perfect substitute for the non-GM variety of another. In this case, the number of crops for which GM technology is available becomes an important variable and it is necessary to intervene directly in the introduction of GM technologies.

To conclude, this chapter presents a partial analysis of the impact of GM on the environment. The environmental aspect focused upon in this paper is biodiversity. We have chosen an extremely simple model which has produced some policy conclusions. There is no doubt that the model of species reliance on resources does not capture all the nuances in the relationship between species and their food sources. However, from our point of view, the pertinent question is whether introducing a greater degree of complexity in this relationship adds anything in terms of policy. We are not sure that it does. For example, in an attempt to concentrate on the potential impact of GM on species diversity we have omitted the possibility of intertemporal spillovers in the R&D process. Such spillovers could be important since there appears to be a lot of similarity in the genetic make-up of species. This similarity, referred to as synteny, enables specific useful genes identified in a well-studied species to be localised to the corresponding genomic site in other species that have not been studied in the same detail (de Vincente and Hodgkin, 2000). Thus, as the sequence of incorporating the insect resistant gene in successive crops proceeds, the process becomes progressively easier. At first glance, it would appear that returns to R&D may increase and the steady state value of p_t will move closer to 1. Such spillovers represent one of the many reasons why in practice, R&D firms may not be able to capture the full social returns to R&D and hence, provides a further reason why there may be a need to intervene in the R&D market. But since such intertemporal spillovers are not unique to GM R&D, we believe their introduction would not detract from the basic message of this paper - the need to model carefully the links between adoption of GM technologies and biodiversity in order to draw appropriate policy conclusions.

Chapter 3

The Role of Resistance in Biotechnology R&D Investment Strategy

3.1 Introduction

The primary aim of the biotechnology industry is to develop solutions which protect against and offer cures for diseases in both the pharmaceutical and agricultural sectors. The implementation of these solutions encourages the development of resistance in pests/pathogens, thereby, undermining their success in combatting disease. Resistance develops as an evolutionary response to the introduction of antiobiotics/pesticides. Although the technology succeeds in killing most of the individuals within the pest/pathogen population, there will be some individuals who possess a resistance gene to that drug/pesticide. Those individuals that survive will reproduce, thereby, passing on their genetic defence mechanism to their offspring. In this way drugs/pesticides select in favour of resistant individuals.

The topic of resistance in pest/pathogens has received a lot of interest recently. In a paper by Goeschl and Swanson (2003), the social and private incentives to invest in reserve lands are compared. Reserve lands provide two functions. Firstly, they act as an epidemiology buffer, which helps to prevent organisms from evolving in a specific way that would enable them to adapt immediately to human intervention (Weitzman, 2000). Secondly, they are a source of genetic material, both in terms of the information they provide on past patterns of evolution and as a resource input into the R&D process. Goeschl and Swanson find that the incentive for the private firm will be to under-invest in reserve lands because of the different way in which private firms react to the evolution of resistance from the social planner. As pest/pathogen adaptations occur more frequently, the incentive for the social planner will be to devote more resources to preserve reserve lands as it can capture the full benefit of reduced resistance in the future. On the other hand, the effect of resistance is to lower profits from innovation and hence, it will reduce the incentive of private firms to invest in reserve lands.

Laxminarayan and Weitzman (2002) examine the optimal choice of drugs in treating infectious diseases when there is the potential for the development of resistance among pathogens. They note that the standard treatment, which is to treat patients uniformly with the most cost-effective drug, is not necessarily the optimal strategy when the possibility of resistance is considered and its proliferation is positively related to the use of the drug. This is because relying too heavily on a single drug produces a selection pressure which encourages the development of resistance to the drug amongst the target pathogen population. Ignoring this resistance externality implies that the single drug treatment will be overused.

In this paper we wish to examine the relative incentives of firms to carry out R&D when there is the possibility of the development of pest/pathogen resistance. Given that we are examining resistance and we have already identified the development of resistance as being a problem within the pharmaceutical and agricultural industries, our analysis applies equally well to both of these sectors. The type of technology considered is Genetic Modification (GM) technology. Although, currently gene transfer is confined to crops and animals, there may yet come a time when this will take place in humans as well. However, as this has not occurred yet, we will set the context in terms of genetically modified pest protected crops.

In Section 3.2 we describe the nature of the GM technology considered and the possible resistance management techniques that might be employed to delay the evolution of resistance in the pest population. To relate this chapter to previous literature, Section 3.3 outlines the relevant contributions in the R&D literature. Section 3.4 establishes the link between pest resistance and R&D investment strategy. In this section, we surmise how the incorporation of the possibility of pest resistance may affect the R&D investment strategies of firms. The model is presented in Section 3.5. Section 3.6 sets out the analytical results. Some simulation results are discussed in Section 3.7. Finally, Section 3.8 concludes.

3.2 GM and resistance management

The most widespread form of GM is based on products derived from *Bacillus thuringiensis* (Bt), a bacterium that produces proteins which are toxic to pests such as lepidoptera (moths), coleoptera (beetles) and diptera (mosquitos). Although still used as a microbial spray, its lack of persistence in the environment and incomplete coverage reduces its efficacy in killing pests. However, by incorporating the Bt gene within the plant's genetic structure, it can be expressed throughout the life of the plant, thereby, offering constant protection. Other attractive features of Bt include its high specificity towards target pests, low registration costs and lack of pollutant residues.[1]

Despite the promise of significant benefits, the threat of pest resistance will undermine the value of this technology (Tabashnik, 1994). The very attribute that makes this form of GM successful as a form of pest control in the short-run - constant expression within the plant, could jeopardise its ability to achieve long-run success. Unlike pesticides which

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[1] Although, Bt does not directly affect non-target pests, it can affect the quantity or quality of food (i.e. susceptible pests) causing the natural enemies of that pest to starve or emigrate (Tabashnik, 1994). The previous chapter offered an economic analysis of this problem.

are applied only at certain times, the Bt gene is present throughout the life of the plant controlling pests even when the size of the economic threat is small. Hence, possible selection for resistance may be more intense than with any other pesticide (Fitt and Forrester, 1998).[2] The threat of induced resistance to Bt has generated considerable concern, especially in the US, where the uptake of GM has been much more widespread (Roush, 1997).[3] Substantial efforts are being devoted to preserve the efficacy of pest resistant GM technology.

The goal of resistance management is to delay resistance for as long as possible. There are several possible methods which could be used to potentially delay resistance. These are: temporal and spatial variability of gene expression in the plant; high dose strategies; sequential deployment; seed mixes; and pyramiding.[4] Fine-tuning the degree of gene expression within a plant is beyond technical feasibility at present. The success of seed mixes, where GM and non-GM varieties of the same or different crop are mixed together, rely on very specific conditions which are not always present.[5] High dose strategies involve killing the maximum number of individuals that carry the resistant gene. Combined with this strategy, the use of refuges (adjacent areas of non-GM crops) is required, which provide a pool of susceptible individuals to mate with any survivors from GM crops so as to dilute the resistance gene in the population.[6] Sequential deployment of GM mirrors the pattern of use of chemical pesticides, which has failed to effectively eradicate pest

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[2] In fact, several major pest species have demonstrated the ability to resist Bt toxins in the laboratory with one species, the diamondback moth having developed widespread resistance in the field (McGaughey and Whalon, 1992; Tabashnik, 1994).

[3] The majority of transgenic crop cultivation has been in the US, with 70 million acres out of 98 million acres worldwide located there (NRC, 2000).

[4] Cross-resistance can undermine the success of all strategies. Cross-resistance occurs when a single gene within a pest can confer resistance to more than one toxin. To minimise the likelihood that cross-resistance will occur, genes used simultaneously as in pyramiding or sequentially should be as unrelated to each other as possible. Although all currently available Bt crops are single toxin cultivars, there does appear to be at least two candidate toxins which could be incorporated into crops for each of the major pest species (Roush, 1997).

[5] To be effective, seed mixes require that major damage to the crop occurs at the larval stage of the pest and that the mobility of the larva is low. In the absence of these conditions, seed mixes can in fact exacerbate the development of resistance in the pest (Roush, 1996).

[6] In the US, the Environmental Protection Agency (EPA) requires that the area set aside as a refuge be 20% of the GM crop area sown if insecticides are used or 4% if they are not (Roush, 1997).

resistance. Pyramiding involves the transfer of multiple genes into a single cultivar - it is also referred to as gene stacking. Deploying multiple toxin producing genes within the plant is more effective than using a single gene (Roush, 1998). Even if it is assumed that the probability of a particular pest developing resistance to one toxin is not too small, the chances of the pest developing resistance to two toxins can be considered to be much smaller, with the probability diminishing to zero as more and more toxins are incorporated within the plant.[7] Roush (1998) shows that pyramiding can offer the potential for superior delays in resistance with smaller and more acceptable refuge sizes.[8]

3.3 R&D literature

We confine ourselves to considering the literature relating to market structure and the relative incentives to carry out R&D. Early contributions to this literature include Schumpeter (1947), Arrow (1962) and Kamien and Schwartz (1982). These studies aimed at showing a causal link between industry concentration and the pace of technological change. Schumpeter argued that monopoly encourages more technological progress than a competitive market structure. In his view, there would be a succession of temporary monopolies as each new monopoly supercedes the last one, a process known as 'creative destruction'. Conversely, Arrow stated that a competitive market structure was more conducive to innovation than a monopolistic one. Kamien and Schwartz asserted that industry concentration encourages innovation up to a threshold level of concentration, after which, the pace of innovation tends to diminish. Scherer (1967) was the first to set the analysis within a game-theoretic framework. Rather than assume a particular market structure, later contributions examined how the relative incentives to carry out R&D

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[7] Presumably, there is a limit to the number of toxins that can be incorporated into a single cultivar, both in terms of the availability of suitable genes and the preservation of genetic integrity of the crop. We assume that firms have not reached this limit.

[8] Large refuge areas can be costly to farmers in terms of forgone yields and do not necessarily offer an environmental benefit because often the practice of using conventional pesticides on these areas is continued at the same level of intensity as on non-refuge areas.

might affect market structure. These models found that both outcomes of persistent dominance or 'creative destruction' are possible. To give a flavour of what assumptions drive which outcomes we will briefly outline some of these contributions.

To begin with, we consider the paper by Gilbert and Newbery (1982). In their model they assume that innovation is deterministic, i.e. a firm knows that if it spends a sufficient amount on R&D it is assured of success. There are two firms: an incumbent and a potential entrant or challenger both bidding for a patent that will confer unlimited protection on their innovation. The firm that bids the most wins the patent. They show that if entry reduces industry profits, the incumbent will preempt entry by bidding an amount equal to the maximum pay-off to the entrant in the event that the latter is successful. Hence, the net pay-off of winning for the incumbent is equal to the monopoly profits it enjoys minus its bid amount, and the net pay-off to winning in the case of the entrant is the duopoly profits it earns. Because of the assumption of entry reducing industry profits, the former is necessarily greater than the latter, which means that the incumbent's incentive to innovate is greater than the entrant's. Entry is likely to reduce industry profits unless the duopolists engage in joint profit-maximisation. Hence, monopoly in the hands of the incumbent will persist.

Reinganum (1983) obtains the opposite result when innovation is allowed to be a stochastic process, i.e. increased expenditure on R&D increases the probability of innovation but does not guarantee it. Again, there are two firms, with the incumbent enjoying current monopoly profits. She shows that the existence of these current monopoly profits acts as a disincentive to the incumbent to innovate. As the incumbent spends more on R&D, it stochastically shortens the period of time for which it earns current monopoly profits. The entrant faces no such disincentive. She assumes a single innovation which is sufficiently radical so that the innovator succeeds in capturing most of the post-innovation market. Hence, the prize for winning is essentially the same for both firms. Thus, the only difference between the firms' incentives to innovate is the incumbent's prospect of replacing itself, which dampens the incumbent's incentive to innovate. Hence, in Reinganum's model there will still be a persistent monopoly, but in her case it will alternate between the firms.

These two papers highlight two opposing forces acting on the incentive to innovate. In Gilbert and Newbery (1982) the 'efficiency effect' spurs the incumbent to undertake more investment in R&D than an entrant. The 'efficiency effect' arises because monopoly profits exceed duopoly profits as it is unlikely that the duopolists will engage in joint profit maximisation. Thus, the incumbent has a greater incentive in the form of higher profits from retaining the monopoly than if it allows entry and earns duopoly profits instead. The 'replacement effect' arises out of the assumptions of initial incumbency and technological uncertainty as in Reinganum (1983). By spending more on R&D, the incumbent increases the probability of winning and thus probabilistically reduces the period for which current profits are earned. Tirole (1988) states that whether the incumbent invests more or less than the entrant depends on which of these two effects dominate.

Reinganum (1983) assumes a single innovation model, whereas her 1985 paper introduces the possibility of a sequence of innovations. The possibility of future innovations introduces the likelihood that what happens in the current period affects incentives to do R&D in future periods and hence, the outcome predicted by models that allow for multiple innovations over time might differ from those predicted by single innovation models. In Reinganum (1985) there are multiple periods with firms carrying out R&D in each one. The period ends when one of the firms wins the patent and the process begins again with the start of the next period. So, although she models dynamic innovation, her model can be reduced to a single innovation model since the process is restarted at the beginning of each period with both firms beginning the next race as if it were the first one. Hence, her finding of action/reaction, i.e. monopoly alternating between firms, has nothing to do with her sequential structure (Beath *et. al.* 1987).

Unlike Reinganum (1985), Vickers (1986) assumes deterministic innovation and allows previous history to affect the potential gains from carrying out R&D. Thus, the form of competition in the R&D market is of a bidding nature as in Gilbert and Newbery (1982).

In Reinganum (1985) innovation is *drastic*, i.e. the innovation is sufficiently radical to drive out all competition in the post-innovation market, whereas, in Vickers innovation is *non-drastic*, i.e. two technologies can co-exist in the market with a firm's current profit level depending on the most recent patents owned by the firms. Interestingly, Vickers finds that the outcome in the R&D market is inextricably linked to what happens in the product market. Paradoxically, he discovers that the more competitive the product market, the less competitive the R&D market will be and vice versa. He reaches this conclusion because, in deriving a sufficient condition for persistent dominance in the R&D market, he finds that the firm which does not possess the latest patent should earn zero profits. This characterises Bertrand competition when there are two firms distinguished by their costs of production, where the low cost firm sets the price equal to the cost of the other firm ensuring that the high cost firm earns zero profits.

All the contributions considered so far relate to process innovations, i.e. cost-reducing innovations. Beath *et. al.* (1987) assume that patents relate to product innovations (quality-increasing) which are auctioned. The more frequently patents are auctioned, the faster is technological progress. They assume that this is an exogenous process. Previous patent history imposes a constraint on the loser's choice of what quality product to produce. It may not necessarily be optimal for that firm to produce the product whose quality is closest to that currently patented, because it may increase its profits by targetting consumers who prefer to pay less for the product (Shaked and Sutton, 1982). In contrast to Vickers (1986), they find that product innovation combined with Bertrand competition in the product market can lead to either persistent dominance or action/reaction. This highlights the necessity of considering process and product innovations separately when considering the link between relative incentives to carry out R&D and the evolution of market structure.

Within the context of a sequence of product innovations, Gruber (1992) derives a sufficient condition based on learning for persistent dominance. In his model, learning is characterised by a reduction in the fixed cost of producing a higher quality product. The prerequisite for learning is that the firm is active in the product market. In this way, there is a first mover advantage which echoes Reinganum's (1985) caveat regarding the potential reversal of her result of action/reaction if a firm possesses an advantage over and above its present incumbent position.

Similarly to Reinganum (1985) and Vickers (1986), Budd, Harris and Vickers (1993) adopt a sequential model to examine whether asymmetry between firms increases or decreases. Unlike Reinganum, they assume non-drastic innovations and in contrast to Vickers, they assume stochastic innovation. In particular, they ask whether the gap between firms, where the gap is defined as the difference between industry share, widens or contracts as firms pursue patents. Similarly to Vickers (1986), they find that the competition evolves in the direction of increasing joint profits and that this occurs as the market share of the leader increases. Hence, the leader works harder than the follower and the gap widens. However, there are other effects at work such as cost effects which produce equilibria in their numerical simulations, where the follower works harder than the leader. In the case of multistage races, where firms can observe their relative positions as the race unfolds, a common result is one of increasing dominance (Fudenberg *et. al.* 1983, Harris and Vickers 1985, 1987, Grossman and Shapiro 1987).

The specification of the cost structure will also affect the incentives to innovate. The two main specifications employed in the literature are contractual, whereby, firms undertake to spend a fixed amount on R&D determined at the outset, and non-contractual where expenditure can vary and ceases once a winner is proclaimed. The effect of increased rivalry can be captured by increasing the number of firms carrying out R&D or increasing the amount each spends on R&D. Whether increasing rivalry increases or reduces the incentives to innovate depends on which specification of costs has been made. In the fixed cost case, R&D expenditure will fall (Loury, 1979). This is because the expected benefit of doing R&D falls as the probability of winning is now reduced but the expected costs remain unchanged. In the case of non-contractual costs, R&D expenditure may rise because both expected benefits and costs fall when the amount of R&D done by others increase, but the fall in costs may exceed the reduction in benefits (Lee and Wilde, 1980).

It is evident from this brief overview of the relevant literature that, although some models provide unambiguous results regarding market outcome, it is difficult to draw an overarching conclusion regarding the relationship between relative incentives to innovate and the outcome in terms of market structure. In an effort to provide an encompassing framework for the various models, Beath *et. al.* (1989a,b, 1995) distinguish between two underlying forces of incentive to innovate: competitive threat and profit incentive. Although as they concede these forces are fairly obvious, it is surprising how well they elucidate the driving assumptions of the various models in the literature. The competitive threat refers to the strategic reason why firms innovate and the profit incentive obviously refers to the desire of firms to increase their profits. The latter exists even in the absence of other firms and it is equal to the gain in profits from innovating. The competitive threat is equal to the difference in a firm's profits when it wins the patent and its profits when it does not. Organising the literature around these two concepts, Beath *et. al.* (1989a) argue that many of the models employ assumptions that effectively rule out one or the other of the forces. For example, in Reinganum (1983, 1985) the assumption of drastic innovation ensures that the competitive threats facing both firms are equal, so that, it is the asymmetry in the profit incentives that drives her result. In models that assume identical firms, possibly all potential entrants as in Harris and Vickers (1985, 1987), the profit incentives are identical and it is the competitive threats that determine who will spend more on R&D. In their analysis of these two concepts, Beath *et. al.* (1989a,b) show that they provide upper and lower boundaries to firms' reaction functions. The profit incentive is defined by the reaction function of a firm when its rival's R&D expenditure is zero, and the competitive threat is defined by the reaction function when the rival firm's R&D expenditure is close to infinity. Whether the profit incentive is greater or smaller than the competitive threat depends on the ease of imitation or how imperfect a patent is. Perfect patent protection implies that the competitive threat is greater, i.e. the firm has a great deal to lose if its rival succeeds in innovating first. In this case, the firms' reaction functions are upward sloping, i.e. firms' R&D expenditures are strategic complements - when the rival increases its expenditure, the firm will respond by increasing its level of expenditure on R&D. Imperfect patent protection implies that there is not much difference between winning and losing the patent. In this case, the competitive threat is smaller than the profit incentive and the reaction functions are downward sloping, i.e. firms' R&D expenditures are strategic substitutes. In response to rising expenditure on the part of its rival, the firm would do best to cut back on its own expenditure, thereby, reducing its costs. When its rival obtains the patent, due to imperfect patent protection, the firm can easily imitate the innovation and obtain the benefits. In this way, it is clear how utilising the concepts of profit incentives and competitive threats can aid the understanding of the relative incentives to carry out R&D.

3.4 Resistance, R&D link

As in Goeschl and Swanson (2003), firms encounter two types of threats to the survival of their technology in the market-place. They face possible replacement in the market place by their rival and the erosion of their profits through the development of resistance in the pest population, which shortens the life of the technology and hence, the period over which profits can be earned. The process occurs as follows. Once a technology is introduced, it will start to select in favour of those pests that are resistant to it. As pests develop resistance to the technology, it will be less effective in controlling these pests. When pests develop complete resistance to it, the technology fails. In our analysis we do not model the dynamics of pest resistance, rather we assume that there is a probability that the pest will develop complete resistance to the technology, at which point, the technology is no longer effective.

To combat these threats from its competitors and pests, firms can undertake two types of investment. They can invest in R&D to increase the probability that it is they, rather than their opponent that wins the patent. They can also invest in increasing the longevity of their technology by undermining the ability of the pest/pathogen to develop resistance to the technology. The chosen strategy to prolong the development of resistance in pests is to pyramid toxin producing genes within a single cultivar.

Although, as we have stated above, the evolution of pest resistance reduces the returns to innovation, it is not immediately clear whether it scales down all profits equally and hence, relative incentives remain unchanged, or whether there is a differential impact on incentives and hence, potentially on market outcome. In the drastic case, where only a single innovation can survive in the market, the impact of pest resistance on the incumbent's profit is to reduce the disincentive to invest. This is because the opportunity cost of innovating in the form of forgone profits due to the replacement of the current technology is lower. From a prospective entrant's point of view, the potential for pests to wipe out the incumbent's current technology presents the entrant with the opportunity of earning monopoly rather than duopoly profits when innovation is of the non-drastic type. Incomplete pest resistance to the current technology may allow the reinstatement of this technology should the entrant's technology fail. The analysis becomes even more complex when firms possess the opportunity to invest in ways to modify the pest effect. The ability to make such an investment may offset the damage to profits due to pest resistance and increase the incentive to invest.

If we employ the concepts of profit incentives and competitive threats, we can see that to the extent that the evolution of pest resistance to innovation reduces profits, it reduces the profit incentive. However, by reducing the profits of all firms, it also reduces the competitive threat offsetting the strategic need for innovation. Hence, we would expect a reduction in the incentive to invest on both counts because of the potential for pests to adapt to technology. However, the question again arises as to whether it affects the profit incentive or competitive threat to a greater or lesser extent, implying a differential effect on both the incumbent's and the entrant's incentives.

3.5 The model

To investigate how the inclusion of the possibility of pest resistance might affect relative incentives to carry out R&D, we adopt a single innovation model in which there are three periods and two firms. In period t_1, the incumbent is in possession of the current technology to resist pest damage to crops and earns per period monopoly profits of Π_c^m. For every period, as long as the technology is being used, there is a probability $q_o \equiv \theta_1$, where $0 \leq \theta_1 \leq 1$, that the pest will develop complete resistance to the technology. The development of pest resistance and the failure to innovate implies zero profits for the incumbent. During the first period, both the incumbent and the entrant invest in R&D to develop a completely *new* and more effective substitute technology to combat a given pest. If successful, they obtain a patent which provides them with infinite protection against another firm being able to use/sell that technology. Note that infinite patent protection also applies to the current technology.[9] The type of innovations we have in mind are process or cost-reducing innovations. Innovations are stochastic so that firms can increase the probability of winning a patent by spending more on R&D, but this probability is reduced by increased R&D expenditure on the part of their rival. Let x (y) be the amount of R&D invested by the incumbent (entrant). At the end of the first period, there are three possible outcomes: the incumbent succeeds in innovating first, the entrant is the successful innovator or neither is successful. The probabilities of these outcomes are, respectively

$$p_I \equiv \frac{x}{1+x+y}; \qquad p_E \equiv \frac{y}{1+x+y}; \qquad p_N \equiv \frac{1}{1+x+y}.$$

where p_I (p_E) is the probability that the incumbent (entrant) is successful and p_N is the probability that neither is successful. If the R&D effort is unsuccessful at the end of this period, then no further R&D investment is made. In the case where the incumbent

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[9] Dasgupta (1986) notes the usefulness of the patent race model in elucidating the relative incentives of firms.

is the first to innovate, the new technology will be introduced superceding the current technology irrespective of whether pests have become resistant to it or not, and the incumbent earns per period monopoly profits $\Pi_n^m > \Pi_c^m$ in the second period t_2.[10] If the entrant succeeds in innovating first, the entrant becomes a monopolist supplier of the new technology or a duopolist depending on whether the innovation is drastic or non-drastic respectively. In the case of a drastic innovation, the new technology is so effective that it drives the current technology out of the market and the entrant earns per period monopoly profits Π_n^m. In the case of a non-drastic innovation, the current technology can survive in the market and the entrant and incumbent earn Π_E^d and Π_I^d respectively, where $0 \leq \Pi_I^d < \Pi_E^d \leq \Pi_n^m$. To save notation, we shall denote the four profit levels by: $\Pi_n^m = \Pi$; $\Pi_c^m = \alpha\Pi$; $\Pi_E^d = \beta\Pi$; $\Pi_I^d = \gamma\Pi$; where $\Pi > 0$; $0 < \alpha < 1$; $0 \leq \gamma < \beta \leq 1$; $\beta + \gamma \leq 1$ and $\alpha \geq \gamma$.

The pest can attack technology in all three periods. In addition to investing in R&D to increase the probability of winning the R&D race, the two firms can also invest in reducing the probability that pests will adapt to the technology. In the absence of this investment opportunity, firms continue to earn period t_2 profits in period t_3 modified by the pest effect. If investment by the firms to reduce the ability of pests to resist the technology is possible, the probabilities that the pest becomes resistant to the new technology after one period for the incumbent and the entrant are denoted respectively by

$$q_I \equiv \frac{\theta_2}{1+u}; \qquad q_E \equiv \frac{\theta_2}{1+v}$$

where u (v) is the investment by the incumbent (entrant) and $0 < \theta_2 < 1$.[11] These

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[10] Under process innovation, it is always the case that the firm will only ever employ the single best technology for which it holds a patent (Beath *et. al.*, 1987).

[11] Expressing the probabilities in this way ensures that if u or v are zero the probability of technology failure is not equal to 1 ($\theta_2 \neq 1$). Certainty of technology failure in the absence of investment to improve the effectiveness of technology against pests appears too strong an assumption. However, in characterising the conditions for optimality, we assume interior solutions, so the problem of zero values of u and v do not arise and θ_2 can equal 1. Nevertheless, we proceed with the more general formulation for the sake of completeness. In addition, we distinguish between θ_1 and θ_2 because there is no reason why these should be the same.

probabilities of the pest becoming resistant to the new technology are independent of the probability of resistance to the current technology. In period t_3, there are four possibilities depending on the outcome of the innovation race and what happens to pest resistance in the two previous periods: (i) both technologies could still be effective; (ii) only the new technology remains effective; (iii) only the current technology remains effective (either because the new technology was never developed or it was but became ineffective); (iv) neither technology is effective (again perhaps because the new technology was never successfully developed). In the case of possibility (i), there will either be a monopoly or a duopoly depending on who is successful and whether the innovation is drastic or non-drastic. Irrespective of the nature of the innovation, there will be a monopoly if the incumbent is successful. However, if the entrant is successful, there will a monopoly if the innovation is drastic and a duopoly if the innovation is non-drastic. Under possibility (ii), either the entrant or the incumbent will be a monopolist depending on who was successful. In the case of possibility (iii), the incumbent will be monopolist. Finally, neither firm earns profits under possibility (iv).[12]

The full decision tree for the case of non-drastic innovation is shown in Figure 3-1. The decision tree for drastic innovation differs only in the branch where the current technology survives for the first period and the entrant innovates. In this case, the second period involves the entrant earning monopoly profits and the incumbent earning nothing. Subsequently, because the current technology must remain effective as it was not used in the second period, there are only two possibilities in the third period: (i) the entrant remains a monopolist if the new technology remains effective; (ii) the incumbent reverts to being a monopolist with the current technology if the entrant's new technology becomes ineffective.[13]

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[12] In Reinganum (1983) and Goeschl and Swanson (2003), the introduction of a new technology renders the previous one obsolete, i.e. both are concerned with drastic innovation. In our model, although we develop an analysis including both drastic and non-drastic innovations, a given technology does not become obsolete unless pest adaptation to it is complete. Failure of a new technology provides the opportunity for the old technology to be used again. The assumption of an infinite patent life ensures that only the incumbent has recourse to the old technology.

[13] Actually, due to the fitness cost of resistance, effectiveness of the technology may recover over the

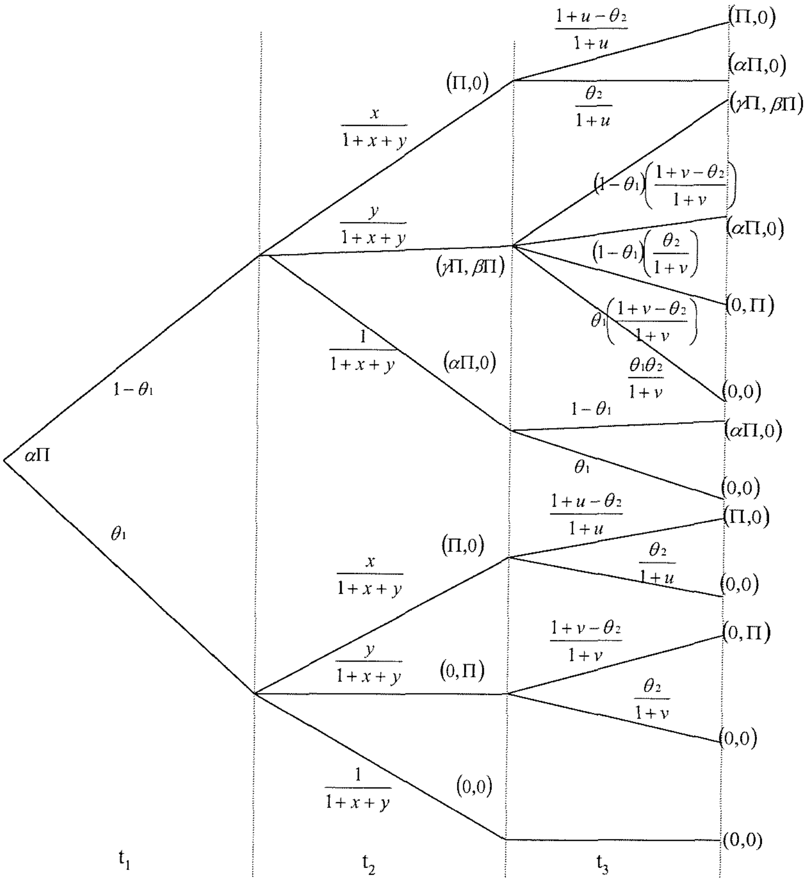

Figure 3-1: Probability tree under non-drastic innovation

Finally, we ignore discounting as it does not make any difference to our results and would just add to the already significant amount of notation in the model.[14] The question we wish to address is, whether firms are more or less aggressive towards their rivals when there is a possibility of pests evolving resistance to technology, thereby, undermining the

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period of non-use. Fitness cost of resistance refers to the situation where resistant strains may be at a comparative disadvantage in the absence of the selection pressure. Absence of resistance prior to the introduction of a technology suggests that resistance may have a fitness cost associated with it. Mathematically, fitness cost is a measure of the rate at which pests regress to susceptibility in the absence of the GM technology (Laxminarayan and Brown, 2001). Hence, in our model the value of θ_1 should decrease following innovation in the drastic case. However, the disadvantage conferred by resistance in the absence of the selection pressure is often small and so we ignore it here (Munro, 1997).

[14] Since the only asymmetry in the model is the initial position of the two firms, discounting does not change the relative net pay-offs of the two firms and so can be disregarded.

flow of benefits from that technology to the firm. To answer this question, firms' investment strategies are determined with and without the pest effect under both drastic and non-drastic innovation. In all cases, V^I represents the expected pay-off for the incumbent and V^E the expected pay-off for the entrant. Note that in the following analysis, we explicitly model strategic competition in the R&D market and model competition in the product market implicitly.

3.6 Analysis

3.6.1 No pest resistance

$(\theta_1 = \theta_2 = 0)$

Here, we explore the relationship between the two firms' equilibrium investment rates when there is no pest problem. We consider possible outcomes both when innovation is drastic and non-drastic. These cases are included to provide a benchmark for the analysis that follows when the effect of pests is included. We also employ the concepts used by Beath *et. al.* (1989a,b) to throw further light on the relative incentives of firms to carry out R&D. In Case 1, we spell out how we derive the profit incentive (PI) and competitive threat (CT), so that, when we come to more complex cases it will be clear how we arrived at the expressions for these two forces.

Case 1: Drastic innovation

The expected pay-offs to the incumbent and entrant are shown in (3.1) and (3.2) respectively. The incumbent earns monopoly profits from the current innovation for sure in period t_1. The second term in equation (3.1) represents the incumbent's expected profits in periods t_2 and t_3. From total expected profits over the three periods, we subtract the cost of R&D to arrive at an expression for the expected profits for the incumbent V^I. Expected profits for the entrant V^E is equal to profits earned in periods t_2 and t_3 minus its R&D cost because it does not earn profits in period t_1.

$$V^I = \alpha\Pi + 2\Pi\left(\frac{x}{1+x+y} + \frac{\alpha}{1+x+y}\right) - x \tag{3.1}$$

$$V^E = 2\Pi\left(\frac{y}{1+x+y}\right) - y \tag{3.2}$$

The first-order conditions are:[15]

$$\frac{\partial V^I}{\partial x} : 2\Pi\left[(1+y) - \alpha\right] = (1+x+y)^2 \tag{3.3}$$

$$\frac{\partial V^E}{\partial y} : 2\Pi\ (1+x) = (1+x+y)^2 \tag{3.4}$$

Letting the solutions equal (x_0, y_0) and equating the two first-order conditions (3.3) and (3.4), we see that $y_0 - \alpha = x_0$, which immediately shows that $x_0 < y_0$ because $\alpha > 0$ by assumption. Table 3.1 shows the competitive threats and profit incentives of the two firms. Recalling that the profit incentive is equal to the difference between future profits when the firm is successful in innovating and when it is not, we see that the incumbent earns Π in each of the periods t_2 and t_3 if successful, otherwise, it earns $\alpha\Pi$ in each of these periods. Hence, the incumbent's profit incentive (PI^I) is equal to $2\Pi(1-\alpha)$ as shown in the table. With the assumption of drastic innovation, the successful innovator obtains a monopoly in the post-innovation market. Earlier we defined the competitive threat to be the difference in profits between winning and losing the patent. Thus, the profits of the incumbent when it succeeds first is 2Π, its monopoly profits for each of the periods t_2 and t_3, and its profits when the entrant is successful are zero, yielding a

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[15] It is worthwhile pointing out that the second-order conditions for a maximum were checked in all cases. It was found that $\frac{\partial^2 V^I}{\partial x^2} < 0$ and $\frac{\partial^2 V^E}{\partial y^2} < 0$ in Cases 1, 2, 4 and 5 satisfying the second-order condition for a maximum. For Cases 3 and 6, the Hessian matrix was constructed and the first and second determinants were $|H_1| > 0$ and $|H_2| < 0$ also satisfying the second-order condition for a maximum.

competitive threat for the incumbent (CT^I) equal to 2Π. We derive the entrant's profit incentive (PI^E) and competitive threat (CT^E) in a similar manner.

Table 3.1: PI and CT under drastic innovation and no pest resistance

	Incumbent	Entrant
PI	$2\Pi(1-\alpha)$	2Π
CT	2Π	2Π

Table 3.1 clearly shows that it is the asymmetry of the profit incentives of the two firms that drives the result that the incumbent invests less than the entrant because the competitive threats are equivalent. Since by assumption $1-\alpha<1$, the profit incentive is greater for the entrant giving the result that $x_0 < y_0$. As Beath *et. al.* (1995) state, it is the assumption of drastic innovation that is crucial to this result. Thus, using first-order conditions and the concepts of profit incentive and competitive threat, both produce an unambiguous result. When innovation is drastic and firms do not have to worry about pests, the incumbent invests less than the entrant, giving rise to the conclusion that monopoly will alternate between the firms.

Case 2: Non-drastic innovation

As in Case 1, the firms do not have to worry about the development of resistance in pests. However, in the situation where the entrant succeeds in innovating first, there is a duopoly rather than a monopoly as before. The expected pay-off to the incumbent is the combination of the certain monopoly profits in period t_1 from the current technology and the expected profits over periods t_2 and t_3, which depend on whether innovation is successful or not, minus its expenditure on R&D. The expected pay-off to the entrant is the duopoly profits it earns if it is the first to innovate minus its R&D cost.

$$V^I = \alpha\Pi + \frac{2\Pi}{1+x+y}(x+y\gamma+\alpha) - x \tag{3.5}$$

$$V^E = \frac{2y\beta\Pi}{1+x+y} - y \tag{3.6}$$

The first-order conditions are:

$$\frac{\partial V^I}{\partial x} : 2\Pi\left[(1+y)(1-\gamma)-(\alpha-\gamma)\right] = (1+x+y)^2 \tag{3.7}$$

$$\frac{\partial V^E}{\partial y} : 2(1+x)\beta\Pi = (1+x+y)^2 \tag{3.8}$$

Equating the first-order conditions and expressing y_0 in terms of x_0 we get:

$$(1+y_0)(1-\gamma) = \beta(1+x_0) + (\alpha-\gamma) \tag{3.9}$$

which reduces to Case 1 when $\beta = 1$ and $\gamma = 0$. Note that, if $\beta \geq 1-\gamma$, then $y_0 > x_0$. However, since we assume that $\beta + \gamma \leq 1$, there are parameter values for which $x_0 > y_0$. In terms of competitive threats and profit incentives the outcome is similarly ambiguous.

Table 3.2: PI and CT under non-drastic innovation and no pest resistance

	Incumbent	Entrant
PI	$2\Pi(1-\alpha)$	$2\beta\Pi$
CT	$2\Pi(1-\gamma)$	$2\beta\Pi$

In Table 3.2 we have $\mathrm{PI}^I \lesseqgtr \mathrm{PI}^E$ because $1-\alpha \lesseqgtr \beta$. Since by assumption $\beta \leq 1-\gamma$, we also have $\mathrm{CT}^I \geq \mathrm{CT}^E$. This leads us to conclude that it is possible to have $x_0 < y_0$ or $x_0 > y_0$.

To summarise, in the case where there are no pests, the assumption of drastic innovation produces the result that the incumbent invests less than the entrant. This is the same result obtained by Reinganum (1983) when innovation is drastic and uncertain. When innovation is assumed to be non-drastic the outcome is ambiguous. In the subsequent analysis, we investigate whether the incorporation of pest resistance alters the relative incentives of firms to invest in R&D.

3.6.2 Exogenous risk of pest resistance

$(\theta_1 = \theta_2 = \theta > 0;\ u = v = 0)$

Case 3: Drastic innovation

We now introduce the possibility of pest adaptation into the analysis. The effect of the pest is exogenous, i.e. firms cannot invest in modifying the technology to slow down the progression of genetic resistance in the pest. Expected profits are now

$$\begin{aligned} V^I &= \alpha\Pi + \frac{\Pi}{1+x+y}[x(2-\theta+\alpha\theta(1-\theta)) + y\,(1-\theta)\,\theta\alpha \\ &\quad +\alpha\,(1-\theta)\,(2-\theta)] - x \end{aligned} \tag{3.10}$$

$$V^E = \frac{y(2-\theta)\Pi}{1+x+y} - y \tag{3.11}$$

The expected pay-off to the incumbent is comprised of expected profits from the current technology and expected profits from three possible outcomes: (i) when it is the first to innovate; (ii) when the entrant succeeds first but its technology fails; (iii) when neither firm innovates but the old technology survives. Unlike the incumbent, the entrant's expected pay-off is solely determined by its probability of being the first to innovate minus its investment cost. The first-order conditions are:

$$\frac{\partial V^I}{\partial x} \quad : \quad \Pi\left[(1+y)(2-\theta) - 2\alpha(1-\theta)^2\right] = (1+x+y)^2 \tag{3.12}$$

$$\frac{\partial V^E}{\partial y} \quad : \quad \Pi(1+x)(2-\theta) = (1+x+y)^2 \tag{3.13}$$

Equating the two first-order conditions yields the following:

$$x_1 = y_1 - \frac{2\alpha(1-\theta)^2}{2-\theta} \tag{3.14}$$

where (x_1, y_1) are the equilibrium investment rates when the problem of pest resistance exists. We know that $\alpha(1-\theta) < 1$ because $1 > \alpha > 0$. If $\theta = 1$, then $\alpha(1-\theta) = 0$, otherwise $\alpha(1-\theta) > 0$. Summarising, $1 > \alpha(1-\theta) \geq 0$. If $\theta = 0$, this case collapses to Case 1. If $\theta = 1$, then $x_1 = y_1$. This is to be expected because the effect of complete pest resistance is to wipe out the incumbency effect and to put both the incumbent and the entrant on an equal footing, so that, both invest at the same rate. Thus, for $0 \leq \theta \leq 1$, $x_1 \leq y_1$. As the probability of induced resistance in the pest rises, the incumbent's incentive to invest also increases. When failure of technology is certain, the incumbent's incentive to invest matches the entrant's but never rises above it. This can also be seen from the following. Rewriting (3.14) as follows:

$$|x_1 - y_1| = \frac{2\alpha(1-\theta)^2}{2-\theta}$$

we see that

$$\frac{\partial\,|x_1 - y_1|}{\partial\theta} = \frac{2\alpha\,(1-\theta)\,(\theta-3)}{(2-\theta)^2} < 0$$

so that the gap between x_1 and y_1 diminishes as θ increases.

As before, we investigate by analysing a firm's profit incentive and competitive threat whether its investment rate will be higher or lower when faced with the prospect of pests adapting to its technologies. As the profit incentive for the incumbent is a little more involved, we will explain how we arrive at the expression for it.

If the incumbent is successful, then it earns monopoly profits Π from the new technology in period t_2 and in period t_3 it earns either (i) monopoly profits Π from the new technology if it survives or (ii) monopoly profits $\alpha\Pi$ from the current technology if the new technology fails but the current technology survives or (iii) zero profits if both technologies fail. On the otherhand, if the incumbent is unsuccessful, then it earns monopoly profits $\alpha\Pi$ from the current technology in each of periods t_2 and t_3 if it survives up to that period. Thus, recalling that the profit incentive is the potential increase in future profits from successfully innovating (i.e. it is the difference between the profits a firm receives if it is successful in innovation and the profits it receives if it is not), the expression for the incumbent's profit incentive is as given in Table 3.3.

Table 3.3: PI and CT under drastic innovation and exogenous pest resistance risk

	Incumbent	Entrant
PI	$(2-\theta)[\Pi-\alpha\Pi]+\alpha\Pi\theta(3-2\theta)$	$(2-\theta)\Pi$
CT	$(2-\theta)\Pi$	$(2-\theta)\Pi$

Since the competitive threats are identical for the incumbent and the entrant, the relative size of x_1 and y_1 depends on the relative size of the profit incentives for the two firms. It is straightforward to show that the incumbent's PI can be rewritten as $(2-\theta)\Pi - 2\alpha\Pi(1-\theta)^2$ and so is less than the entrant's PI, which implies $x_1 < y_1$. However, it is interesting to note that relative to Table 3.1 all terms in Table 3.3 are scaled down by the factor $\frac{2-\theta}{2}$, where the expression for the incumbent's PI also involves the addition of a positive term. From this we can conclude that $y_1 < y_0$. However, it is not obvious that $x_1 < x_0$ because, although both the incumbent's PI and CT are scaled down, there is also the additive term in the incumbent's PI. Nevertheless, the relative gap between the profit incentives in this case is smaller than in Case 1, leading us to expect that $\frac{y_1-x_1}{x_1} < \frac{y_0-x_0}{x_0}$.

Case 4: Non-drastic innovation

As in Case 3, there is an exogenous pest effect which reduces the pay-off either firm can expect from successful innovation. The incumbent's pay-off from its current technology in period t_1 is $\alpha\Pi$. The incumbent's pay-off in period t_2 is either (i) monopoly profits Π from having been the first to innovate or (ii) duopoly profits $\gamma\Pi$ if its current technology survives and the rival succeeds or (iii) zero profits if the current technology fails and the rival succeeds or (iv) a continuation of monopoly profits $\alpha\Pi$ if its current technology survives and neither firm is successful. In period t_3, depending on what occurred in the previous period, the incumbent can expect to earn either (i) monopoly profits Π if it succeeds and the new technology survives or (ii) monopoly profits $\alpha\Pi$ if the current technology survives and either no-one is successful or the new technology fails (irrespective of the identity of innovator) or (iii) duopoly profits $\gamma\Pi$ if the entrant is successful and both technologies survive or (iv) zero profits if the current technology fails and either no-one is successful or the new technology fails (irrespective of the identity of the innovator). Thus, the incumbent's expected pay-off is as given in (3.15). Using a similar reasoning, the entrant's expected pay-off is given by the expression in (3.16).

$$\begin{aligned} V^I &= \alpha\Pi + \frac{\Pi}{1+x+y}\{x\left[(2-\theta)+\theta\alpha(1-\theta)\right] \\ &\quad +y(1-\theta)\left[\gamma+(1-\theta)^2\gamma+\theta(1-\theta)\alpha\right] \\ &\quad +\alpha(2-\theta)(1-\theta)\} - x \end{aligned} \tag{3.15}$$

$$V^E = \frac{\Pi y}{1+x+y}\left\{(1-\theta)\left[\beta+(1-\theta)^2\beta+\theta(1-\theta)\right]+\theta(2-\theta)\right\} - y \tag{3.16}$$

If $\beta = 1$, the pay-offs to the entrant are identical under drastic and non-drastic innovation. However, when $\gamma = 0$, the pay-offs to the incumbent differ by $(1-\theta)$ on the y term. In the non-drastic case, since the incumbent's technology remains on the market when the entrant is successful, it is vulnerable to pest attack as reflected in the $(1-\theta)^2$ term.

In the drastic case, the current technology is eliminated in the second period when the entrant innovates and so it is not subject to pest attack for that time as reflected in the $(1-\theta)$ term (see (3.10)). The first-order conditions are:

$$\begin{aligned}\frac{\partial V^I}{\partial x} &: \Pi\left\{(1+y)\left(2-\theta-(1-\theta)\left[\gamma+(1-\theta)^2\gamma-\theta^2\alpha\right]\right)\right. \\ &\left.-(1-\theta)(\alpha-\gamma)\left[1+(1-\theta)^2\right]\right\} = (1+x+y)^2\end{aligned} \tag{3.17}$$

$$\begin{aligned}\frac{\partial V^E}{\partial y} &: (1+x)\,\Pi\left\{(1-\theta)\left(\beta+(1-\theta)^2\beta+\theta(1-\theta)\right)+\theta\,(2-\theta)\right\} \\ = \;& (1+x+y)^2\end{aligned} \tag{3.18}$$

Rewriting equations (3.17) and (3.18) we obtain:

$$\varepsilon(1+y)-\chi=(1+x+y)^2$$

and

$$\eta(1+x)=(1+x+y)^2$$

where

$$\varepsilon=\Pi\left\{(2-\theta-(1-\theta)\left[\gamma+(1-\theta)^2\gamma-\theta^2\alpha\right]\right\};$$

$$\eta=\Pi[(1-\theta)[\beta+(1-\theta)^2\beta+\theta(1-\theta)]+\theta(2-\theta)];$$

$$\chi=\Pi(1-\theta)(\alpha-\gamma)[1+(1-\theta)^2];$$

where $\chi \geq 0$ because $\alpha \geq \gamma$ by assumption. Therefore we can write:

$$\varepsilon(1+y_1)\geq\eta(1+x_1)$$

where as before x_1 and y_1 are the optimal investment rates when firms face the problem of induced pest resistance. If $\eta > \varepsilon$, then $y_1 > x_1$, otherwise there can be parameter values for which $x_1 > y_1$.

The profit incentive for the incumbent is as in Case 3. The profit incentives together with the firms' competitive threats are shown in Table 3.4.

Table 3.4: PI and CT under non-drastic innovation and exogenous risk of pest resistance

PI^I	$(2-\theta)\left[\Pi-\alpha\Pi\right]+\alpha\Pi\theta\left(3-2\theta\right)$
CT^I	$(2-\theta)\left(\Pi-\gamma\Pi\right)+(1-\theta)\,\theta^2\alpha\Pi+\theta\left(3-3\theta+\theta^2\right)\gamma\Pi$
PI^E	$(2-\theta)\,\beta\Pi+\theta\left(\Pi-\beta\Pi\right)\left(3-3\theta+\theta^2\right)$
CT^E	$(2-\theta)\,\beta\Pi+\theta\left(\Pi-\beta\Pi\right)\left(3-3\theta+\theta^2\right)$

To check the relative sizes of the firms' profit incentives and competitive threats, we find the following:

$$PI^I-PI^E=2\Pi\left(1-\alpha-\beta\right)\left(1-\theta\right)^2+\theta^2\Pi\left(1-\beta\right)\left(1-\theta\right)>0 \quad \text{if } \alpha+\beta<1$$

and

$$CT^I-CT^E=\Pi\left(1-\gamma-\beta\right)\left(\left(1-\theta\right)+\left(1-\theta\right)^3\right)+\theta^2\left(1-\theta\right)\alpha\Pi>0$$

which allows us to conclude that $x_1>y_1$ if $\alpha+\beta<1$. Recalling that in the non-drastic case with no pest resistance problem we had

$$PI^I-PI^E=2\Pi\left(1-\alpha-\beta\right)>0 \quad \text{if } \alpha+\beta<1$$

and

$$CT^I-CT^E=2\Pi\left(1-\gamma-\beta\right)\geq 0$$

and we see that the direction of the relationship between the incumbent's and the entrant's investment rates remains unchanged from the case where there are no pests.

To summarise the results obtained so far, we find that the incumbent invests less than the entrant in the case of drastic innovation regardless of whether pests develop resistance or not. However, when the possibility of pests developing resistance to the technology is included, the gap between the firms' levels of investment contracts. In the case of non-drastic innovation, the results are ambiguous, both when the possibility of pest resistance is allowed and when it is not. We also find that the incumbent's investment level could exceed or fall short of the entrant's investment level depending on the parameter values. In particular, we concluded that the incumbent invests more than the entrant if $\alpha + \beta < 1$, otherwise the converse could occur.

3.6.3 Endogenous risk of pest resistance

$(0 < \theta_1 < \theta_2;\ u \geq 0;\ v \geq 0)$

Case 5: Drastic innovation

Finally, the situation which we characterise as endogenous risk describes the case where it is possible for firms to affect the acquisition rate of resistance in the pest towards their technology through investment. According to Goeschl and Swanson (2003), by intervening in the biological world, society is committing itself to a continuing race against nature. The assumption that $\theta_1 < \theta_2$ captures this 'catch-up' ability of pests to match each new technology. In Goeschl and Swanson (2003), the more widespread the technology the greater the selection process of resistant individuals within the pest population and therefore, the faster the growth of pest resistance. In their case, to reduce the pace of selection process, the firm reduces the size of the resource allocated to a given technology. In our case, the firm can invest in the technology itself to inhibit the ability of pests to adapt to the technology.

The incumbent's pay-off from its current technology in period t_1 is $\alpha\Pi$. The incumbent's pay-off in period t_2 is either (i) monopoly profits Π if it succeeds or (ii) monopoly profits $\alpha\Pi$ if the current technology survives and neither firm is successful or (iii) zero profits if, either the entrant succeeds or no-one succeeds and the current technology fails.

In period t_3, depending on what occurred in the previous period, the incumbent faces the following possibilities: (i) if it is successful and the new technology survives, it earns monopoly profits Π; (ii) if the current technology survives and either no-one is successful or the new technology fails (irrespective of the identity of innovator), it earns monopoly profits $\alpha\Pi$; (iii) if entrant is successful and either the new technology survives or the current technology fails, it earns zero profits; (iv) if it is successful but neither the new nor the current technologies survives, it earns zero profits; (v) if no-one is successful and the current technology fails, it earns zero profits. The incumbent's cost of investment entails both expenditure to ensure successful innovation before its rival and its investment to reduce the probability of failure of technology as pests develop resistance to it. Thus, the incumbent's expected pay-off is as given in (3.19). Using a similar reasoning, the entrant's expected pay-off is given by the expression in (3.20).

$$\begin{aligned} V^I &= \alpha\Pi + \frac{\Pi}{(1+x+y)}\left\{\frac{x(2+2u-\theta_2+\theta_2(1-\theta_1)\alpha)}{1+u} + \right. \\ &\left. \frac{\alpha(1-\theta_1)\theta_2 y}{1+v} + \alpha(1-\theta_1)(2-\theta_1)\right\} - x - u \end{aligned} \tag{3.19}$$

$$V^E = \frac{y\Pi}{1+x+y}\left[\frac{2+2v-\theta_2}{1+v}\right] - y - v \tag{3.20}$$

This problem is a little more involved because there are four choice variables and it can be seen that the system of first-order conditions is highly non-linear. Assuming interior solutions, i.e. $x > 0$, $y > 0$, $u > 0$, $v > 0$, the four first-order conditions are:

$$
\begin{aligned}
\frac{\partial V^I}{\partial x} &: \Pi\left\{(1+y)\left(\frac{2+2u-\theta_2+\theta_2(1-\theta_1)\alpha}{1+u}-\frac{(1-\theta_1)\theta_2\alpha}{1+v}\right)\right. \\
&\quad \left.-\left(\alpha(1-\theta_1)(2-\theta_1)-\frac{(1-\theta_1)\theta_2\alpha}{1+v}\right)\right\} \\
&= (1+x+y)^2
\end{aligned}
\tag{3.21}
$$

$$
\frac{\partial V^E}{\partial y} : (1+x)\Pi\left[\frac{2+2v-\theta_2}{1+v}\right]=(1+x+y)^2 \tag{3.22}
$$

$$
\frac{\partial V^I}{\partial u} : \frac{\theta_2 x\Pi\left[1-\alpha(1-\theta_1)\right]}{(1+u)^2}=(1+x+y) \tag{3.23}
$$

$$
\frac{\partial V^E}{\partial v} : \frac{\theta_2 y\Pi}{(1+v)^2}=(1+x+y) \tag{3.24}
$$

Note that (x_2, y_2) are the equilibrium investment levels when it is possible to invest in improving the effectiveness of the technologies against pests. Rewriting equations (3.21) and (3.22) we obtain:

$$
\Pi\left[(1+y)\phi-\delta\right] = (1+x+y)^2 \tag{3.25}
$$

$$
(1+x)\Pi\psi = (1+x+y)^2 \tag{3.26}
$$

where $\phi=\frac{2+2u-\theta_2+\theta_2(1-\theta_1)\alpha}{1+u}-\frac{(1-\theta_1)\theta_2\alpha}{1+v}$, $\delta=\alpha(1-\theta_1)(2-\theta_1)-\frac{(1-\theta_1)\theta_2\alpha}{1+v}$ and $\psi=\frac{2+2v-\theta_2}{1+v}$. The analysis of these first-order conditions is relegated to Appendix A. Assuming $\delta>0$, i.e. $\alpha>0$ and $\theta_1<1$, we can derive the relationships between x, y, u and v. The analysis in Appendix A allows us to state the following results: (i) we cannot have $u=v$ or $x_2=y_2$ (unless $\theta_1=1$), but we could have either (ii) $x_2>y_2$ and $u>v$, or (iii) $x_2<y_2$ and $u<v$.

Table 3.5: PI and CT under drastic innovation and endogenous risk

	Incumbent	Entrant
PI	$\left(\frac{2+2u-\theta_2}{1+u}\right)(\Pi - \alpha\Pi) + \theta_1\alpha\Pi\left[3 - \theta_1 - \frac{\theta_2}{1+u}\right]$	$\left(\frac{2+2v-\theta_2}{1+v}\right)\Pi$
CT	$\left(\frac{2+2u-\theta_2}{1+u}\right)\Pi + \theta_2(1-\theta_1)\alpha\Pi\left[\frac{v-u}{(1+u)(1+v)}\right]$	$\left(\frac{2+2v-\theta_2}{1+v}\right)\Pi$

The profit incentives and competitive threats for the drastic case when the possibility of pest resistance is incorporated into the analysis are given in Table 3.5. Table 3.5 shows that, when $\theta_1 = \theta_2 = \theta$, $u = 0$ and $v = 0$, this case reduces to Case 3 where innovation is drastic and the risk of pest resistance is exogenous. When we let $u = v$, since $0 \leq \theta_1 \leq 1$ and $0 < \theta_2 < 1$ by assumption, we obtain the following

$$PI^I - PI^E = -\left(\frac{\alpha\Pi}{1+u}\right)\{(\theta_1 - 1)[(1+u)(\theta_1 - 2) + \theta_2]\} \leq 0$$

and

$$CT^I - CT^E = 0$$

which allows us to conclude that $x_2 \leq y_2$. However, when $u \neq v$, it is difficult to obtain results, i.e. whether $\mathrm{CT}^I \gtrless \mathrm{CT}^E$ or $\mathrm{PI}^I \gtrless \mathrm{PI}^E$.

Case 6: Non-drastic innovation

By using a similar reasoning as in previous cases, we obtain the following expressions for the expected pay-offs of the two firms:

$$V^I = \alpha\Pi + \frac{\Pi}{1+x+y}\left\{\begin{array}{c} x\left(\frac{2+2u-\theta_2+\alpha(1-\theta_1)\theta_2}{1+u}\right) \\ +(1-\theta_1)y\left(\frac{\gamma[(1+v)(2-\theta_1)-\theta_2(1-\theta_1)]+\alpha(1-\theta_1)\theta_2}{1+v}\right) \\ +\alpha(1-\theta_1)(2-\theta_1) \end{array}\right\} - x - u \quad (3.27)$$

$$V^E = \frac{\Pi y}{1+x+y} \left\{ \begin{array}{c} (1-\theta_1)\left(\beta + \frac{1+v-\theta_2}{1+v}\left((1-\theta_1)\beta + \theta_1\right)\right) \\ +\theta_1\left(\frac{2+2v-\theta_1}{1+v}\right) \end{array} \right\} - y - v \qquad (3.28)$$

If $v = u = 0$ the incumbent's pay-off is equivalent to its pay-off in Case 5. When $\beta = 1$, the pay-off to the entrant V^E under the drastic and non-drastic cases are equivalent. Setting $v = 0$ reduces the entrant's pay-off to what it was in Case 5. With $\gamma = 0$, the incumbent's pay-off V^I between the drastic and non-drastic cases are similar except for $(1-\theta_1)$ on the y term in the latter case. This echoes the comparision we made earlier between the incumbent's pay-offs when the risk of pest resistance is exogenous, i.e. Cases 3 and 4. When innovation is non-drastic, the incumbent's current technology remains on the market and hence, is subject to attack by pests as reflected in the $(1-\theta_1)^2$ term. The first-order conditions are:

$$\begin{aligned}
&\frac{\partial V^I}{\partial x} : \Pi\left\{(1+y)\left[\frac{2+2u-\theta_2+(1-\theta_1)\,\theta_2\alpha}{1+u}\right.\right.\\
&-\frac{1-\theta_1}{1+v}\gamma\left[(1+v)\,(2-\theta_1)-\theta_2\,(1-\theta_1)\right]+\alpha\,(1-\theta_1)\,\theta_2\Bigg]\\
&-\alpha\,(1-\theta_1)\,(2-\theta_1) \qquad (3.29)\\
&\left.-\frac{1-\theta_1}{1+v}\left[\gamma\left[(1+v)\,(2-\theta_1)-\theta_2\,(1-\theta_1)\right]\ +\alpha\,(1-\theta_1)\,\theta_2\right]\right\}\\
=\ &(1+x+y)^2
\end{aligned}$$

$$\frac{\partial V^I}{\partial u} \ : \ \frac{x\theta_2\Pi\{1-\alpha\,(1-\theta_1)\}}{(1+u)^2}=(1+x+y) \qquad (3.30)$$

$$\begin{aligned}
\frac{\partial V^E}{\partial y} \ : \ &\Pi(1+x)\left\{(1-\theta_1)\left[\beta+\frac{1+v-\theta_2}{1+v}\left(\beta\,(1-\theta_1)+\theta_1\right)\right]\right. \qquad (3.31)\\
&\left.+\theta_1\left(\frac{2+2v-\theta_2}{1+v}\right)\right\}=(1+x+y)^2
\end{aligned}$$

$$\frac{\partial V^E}{\partial v} \ : \ y\Pi\theta_2\left[\frac{(1-\theta_1)^2\beta+(1-\theta_1)\,\theta_1+\theta_1}{(1+v)^2}\right]=(1+x+y) \qquad (3.32)$$

Equating the expressions in (3.30) and (3.32) we obtain:

$$\frac{x_2}{y_2}\left(\frac{1-\alpha\,(1-\theta_1)}{(1-\theta_1)^2\beta+\theta_1(2-\theta_1)}\right)=\frac{(1+u)^2}{(1+v)^2} \qquad (3.33)$$

When $\theta_1=1$, the coefficient of the term $\frac{x_2}{y_2}$ in (3.33) reduces to 1 and so $x_2 \gtreqless y_2$ as $u \gtreqless v$. A sufficient condition for $v<u$ to imply $y_2<x_2$ is that the coefficient of $\frac{x_2}{y_2}$ be less than 1. If the parameter values of this coefficient are such that it exceeds 1, we cannot rule out $x_2<y_2$. On the otherhand, a sufficient condition for $u<v$ to imply $x_2<y_2$ is that the coefficient of $\frac{x_2}{y_2}$ be greater than 1. Similarly, if in this case the coefficient is less than 1, we cannot rule out $x_2>y_2$.

The firms' profit incentives and competitive threats are contained in Table 3.6. From the table, we can see that the profit incentive for the incumbent is the same as in the previous case of drastic innovation and the entrant's profit incentive and competitive threat are identical.

Table 3.6: PI and CT under endogenous risk and non-drastic innovation

PI^I	$\left(\frac{2+2u-\theta_2}{1+u}\right)(\Pi-\alpha\Pi)+\theta_1\alpha\Pi\left[3-\theta_1-\frac{\theta_2}{1+u}\right]$
CT^I	$\left(\frac{2+2u-\theta_2}{1+u}\right)(\Pi-\gamma\Pi)+\alpha\Pi\theta_2\left(1-\theta_1\right)\left[\frac{v+\theta_1-(1-\theta_1)u}{(1+v)(1+u)}\right]$ $+\theta_1\gamma\Pi\left[3-\theta_1-\frac{2\theta_2}{1+v}+\frac{\theta_1\theta_2}{1+v}\right]$
PI^E	$\left(\frac{2+2v-\theta_2}{1+v}\right)\beta\Pi+\theta_1\left[\Pi-\beta\Pi\right]\left[3-\theta_1-\frac{2\theta_2}{1+v}+\frac{\theta_1\theta_2}{1+v}\right]$
CT^E	$\left(\frac{2+2v-\theta_2}{1+v}\right)\beta\Pi+\theta_1\left[\Pi-\beta\Pi\right]\left[3-\theta_1-\frac{2\theta_2}{1+v}+\frac{\theta_1\theta_2}{1+v}\right]$

When $u=v$ we find that

$$\begin{aligned} CT^I-CT^E &= (\Pi-\gamma\Pi-\beta\Pi)\left(2-\frac{\theta_2}{1+u}-\theta_1\left(3-\theta_1-\frac{2\theta_2}{1+u}+\frac{\theta_1\theta_2}{1+u}\right)\right) \\ &\quad +\frac{\alpha\Pi\theta_2\left(1-\theta_1\right)\theta_1}{1+u} \end{aligned}$$

Since $1\geq\gamma+\beta$ by assumption, $\mathrm{CT}^I>\mathrm{CT}^E$ if the term multiplying $(\Pi-\gamma\Pi-\beta\Pi)$ is positive. Simplifying this term yields $\left(1-\theta_1\right)\left(1-\frac{\theta_2}{1+u}\right)+\left(1-\theta_1\right)$. Hence, since $u>0$, $0\leq\theta_1\leq1$ and $0<\theta_2<1$ by assumption, we find that $\mathrm{CT}^I>\mathrm{CT}^E$ if $\theta_1\neq1$. Similarly, for profit incentives:

$$\begin{aligned} PT^I-PT^E &= (\Pi-\alpha\Pi-\beta\Pi)\left(\left(1-\theta_1\right)\left(2-\theta_1-\frac{\theta_2}{1+u}\right)\right) \\ &\quad +\theta_1\Pi\left(1-\beta\right)\left(\frac{\theta_2\left(1-\theta_1\right)}{1+u}\right) \end{aligned}$$

From this we can see that, if $\theta_1\neq1$, then $\mathrm{PI}^I>\mathrm{PI}^E$ iff $\alpha+\beta<1$. To summarise, $\theta_1<1$ and $\alpha+\beta<1$ imply $\mathrm{PI}^I>\mathrm{PI}^E$ and $\mathrm{CT}^I>\mathrm{CT}^E$, which gives $x_2>y_2$. However, when $u\neq v$, it is difficult to obtain results, i.e. whether $\mathrm{CT}^I\gtrless\mathrm{CT}^E$ or $\mathrm{PI}^I\gtrless\mathrm{PI}^E$.

All the results from the foregoing analysis together with the parameter assumptions are summarised in Figure 3-2.

		No Resistance	**Exogenous Risk**	**Endogenous Risk**
Drastic	**FOCs**	$x_o < y_o$	$x_1 \leq y_1$	$u = v \Leftrightarrow x_2 = y_2$ *if* $\theta_1 = 1$ $u \lesseqgtr v \Leftrightarrow x_2 \lesseqgtr y_2$, *otherwise*
	PI & CT			$u = v, \theta_1 \leq 1$ & $\theta_2 < 1 \Rightarrow x_2 \leq y_2$
Non-drastic	**FOCs**	$x_o \lesseqgtr y_o$	$x_1 \lesseqgtr y_1$	$u \leq v \Rightarrow x_2 \leq y_2$ & $u \geq v \Rightarrow x_2 \geq y_2$ *if* $\theta_1 = 1$ *otherwise*, $u > v \Rightarrow x_2 \lesseqgtr y_2$ & $u < v \Rightarrow x_2 \lesseqgtr y_2$
	PI & CT	$x_o > y_o$ *if* $\alpha + \beta < 1$	$x_1 > y_1$ *if* $\alpha + \beta < 1$	$u = v$, $\theta_1 < 1$ & $\alpha + \beta < 1 \Rightarrow x_2 > y_2$

Figure 3-2: Summary of results

3.7 Some simulations

The analysis of the six cases in the previous section did not allow us to completely analyse the outcome for every case, nor did it allow us to compare results across different cases. So in this section we report on some numerical simulations which we carried out to address these issues.

3.7.1 Drastic innovation

We begin by completing the analysis of individual cases. We know from Cases 1 and 3 that with drastic innovation the entrant always has an incentive to do more R&D than the incumbent. But for the case of endogenous risk, all that we were able to show was that $u \gtreqless v$ implied $x_2 \gtreqless y_2$. So, is it possible that the incumbent has a stronger incentive to do both kinds of R&D than the entrant? To answer this question, we solved the equilibrium values of $\frac{\partial V}{\partial x_2}, \frac{\partial V}{\partial y_2}, \frac{\partial V}{\partial u}$ and $\frac{\partial V}{\partial v}$ for the following range of values of the parameters Π, α, and θ_2: we took values of Π of 10 to 200 increasing in steps of 10; a range of α from .01 to .99 and θ_2 from .1 to .9 in steps of .01 and .1 respectively; a total of 17820 cases. We never found a case for which $x_2 > y_2$ and $u > v$. Obviously, it would be desirable to prove this result analytically.

We now turn to a comparison of the outcomes for drastic innovation across the three different cases. We saw that the introduction of an exogenous risk of pest resistance scaled down both profit incentives and competitive threats, but there was an additional boost to the profit incentive for the incumbent. Could this effect outweigh the general reduction in profits causing the incumbent to do more R&D with an exogenous risk of pest resistance than with no risk? Again the simulations showed that this was not possible. Finally, we asked whether reducing the exogenous risk through the second form of R&D expenditure might allow either the incumbent or the entrant to do more R&D than in the case of no risk of pest resistance, and again the answer was no.

So the conclusion from these results is that, when there is drastic innovation, the basic result of the textbook model that entrants have stronger incentives to do R&D than incumbents under uncertainty is not affected by the introduction of pest resistance, and all that happens is that R&D expenditure is reduced for both types of firms.

3.7.2 Non-drastic innovation

Again we begin by completing the analysis of individual cases and then proceed to make comparisons across cases. For both, we present tables illustrating the frequencies of each of the situations investigated. The analysis of the non-drastic and endogenous risk of pest resistance (Case 6) did not allow us to say whether $x_2 > y_2$ implied that either $u > v$ or $v > u$ and similarly for $y_2 > x_2$. To determine what combinations are possible, we again solved for x_2, y_2, u, and v for the following range of parameters: Π ranged from 10 to 100 in steps of 10, α, β and γ each had 19 values assigned, chosen so that $.75 \leq \beta + \gamma \leq 1$;

$\gamma < \alpha < 1$; $\gamma < \beta$ and $\theta_2 \in [.1, .9]$; a total of 617310 cases. These simulations showed that only $u > v$ and $x_2 < y_2$ is not possible. Table 3.7 shows the proportion of times the other possible combinations of relative incentives occurred.

Table 3.7: Relative incentives under non-drastic and endogenous risk

Incentives	Frequency of Occurrence
$x > y$ and $u > v$	0.0984
$x > y$ and $u < v$	0.8570
$x < y$ and $u > v$	0
$x < y$ and $u < v$	0.0445

We next turned to a comparison across cases. Now, we know that in the cases where there is no risk of pest resistance, we can get either the incumbent doing more R&D than the entrant or vice versa. The first question we asked was whether the pattern of R&D that arose with no risk of pest resistance would be preserved when we introduced pest resistance. The set of results obtained are shown in Table 3.8 which describes each of the cases examined along with the frequencies of their occurrences.

Table 3.8: Comparison across cases for exogenous risk of pest resistance

Relative Incentives across Cases	Frequency of Occurrence
$x_0 < y_0$; $x_1 < y_1$; $x_2 < y_2$	0.0158
$x_0 < y_0$; $x_1 < y_1$; $x_2 > y_2$	0
$x_0 < y_0$; $x_1 > y_1$; $x_2 < y_2$	0.0273
$x_0 < y_0$; $x_1 > y_1$; $x_2 > y_2$	0.0498
$x_0 > y_0$; $x_1 < y_1$; $x_2 < y_2$	0
$x_0 > y_0$; $x_1 < y_1$; $x_2 > y_2$	0
$x_0 > y_0$; $x_1 > y_1$; $x_2 < y_2$	0.0015
$x_0 > y_0$; $x_1 > y_1$; $x_2 > y_2$	0.9056

So, if $x_0 < y_0$, it is possible that $x_1 > y_1$ or $x_1 < y_1$. If $x_0 < y_0$ and $x_1 < y_1$, then $x_2 < y_2$. But if $x_0 < y_0$ and $x_1 > y_1$, we can have $x_2 \gtreqless y_2$. If $x_0 > y_0$, then $x_1 > y_1$ but it is possible that $x_2 > y_2$ or $x_2 < y_2$, although the latter is rare. The essence of these results is that, the introduction of pest resistance can cause an incumbent who had less incentive to do R&D without pest resistance to now do more R&D than the entrant, but the reverse is very unlikely - an incumbent who is ahead with no risk of pest resistance stays ahead. So pest resistance seems to favour incumbents.

Finally, we were interested to know the relative sizes of investment for each firm under the different cases of no pest resistance, exogenous risk of pest resistance and endogenous risk of pest resistance. In Table 3.9 we present the spread of frequencies amongst the most and least likely relationships between each firm's incentives when there is no risk of pest resistance, when the risk of pest resistance is exogenous and when it is endogenous.

Table 3.9: Cross-case comparisons for each firm

Incumbent	Frequency	Entrant	Frequency
$x_0 > x_1 > x_2$	0.0140	$y_0 > y_1 > y_2$	0.0082
$x_0 > x_2 > x_1$	0.1185	$y_0 > y_2 > y_1$	0.0444
$x_1 > x_0 > x_2$	0.0024	$y_1 > y_0 > y_2$	0.0018
$x_1 > x_2 > x_0$	0.0771	$y_1 > y_2 > y_0$	0.0715
$x_2 > x_0 > x_1$	0.3788	$y_2 > y_0 > y_1$	0.3293
$x_2 > x_1 > x_0$	0.4092	$y_2 > y_1 > y_0$	0.5447

A certain symmetry emerged between the pattern of investments for each firm for the most and least frequent cases. For the four most frequent categories of cases, investment under endogenous risk exceeded investments under the other two cases for both types of firm. However, among these cases investment under exogenous risk could be higher or lower than in the case with no pest resistance, with the former occurring more frequently than the latter. Again, this was the case for both firms. The situations where investment under endogenous risk were smaller than investment under either of the other two cases occurred with the lowest frequency. However, in these cases, the relative position of investments with no risk of pest resistance and exogenous risk were interchangeable. This pattern emerged for both the incumbent and the entrant. The conclusion to be drawn from this is that, the possibility of investment in improving the ability of a technology to resist pests increases the incentives to invest in innovation for both types of firms. Hence, there may be a positive spillover in terms of increased frequency of innovation from increased investment in the degree of innovation captured within each technology.

Thus, incentives directed at encouraging firms to invest in larger innovations may also speed up the pace of tecnological advance.

3.8 Conclusion

In this chapter, we have applied the standard game-theoretic model to the biotechnology industry. The specific type of biotechnology R&D considered is the development of pest control solutions through the genetic modification of plants. The key feature of this type of R&D activity is the potential for the target organism to develop resistance to the technology, thereby, eroding the usefulness of the technology. We examined both types of innovation: drastic and non-drastic. We examined cases where the risk of pest resistance was exogenous and firms could not incorporate any measures to mitigate this risk into their investment plans and cases where the risk of pests developing resistance was endogenous. In the latter case, the possibility of investing in measures to mitigate the evolution of pest resistance was available to the firms. The specific type of measure we had in mind was pyramiding, where several toxins are simultaneously incorporated into a single cultivar. Combining toxins in this manner appears to present a more effective way of delaying the progression of pest resistance. The question we posed was whether this feature might alter the relative incentives to do R&D and if so, in what manner might these incentives change and what repercussions might this have for market structure? Armchair reasoning would suggest that the reduction in expected returns to R&D would reduce the incentive to conduct it. However, on closer analysis, we found that there were many strands to this general conclusion. A clear dichotomy of results emerged for the drastic and non-drastic cases. In the drastic case, the results mirrored the standard literature on R&D incentives, although the analysis did reveal opposing forces acting on the incumbent's incentive to invest. As expected, the risk of pest resistance dampens the incentive to invest through lowering both firms' profits. However, the gap between the firms' incentives diminishes, but not by enough for the incumbent's incentive to exceed that of the entrant. The incumbent invests less than the entrant for both types of investment. No clear finding emerged in the analysis of the non-drastic case and so we resorted to simulations. When firms can invest in mitigating the risk of pests developing resistance to their technology, the simulations yielded the result that the incumbent would never carry out more of this type of investment while investing less in ensuring the success of its innovation vis-à-vis the entrant. However, enabling firms to modify their technology increased the incentive to invest in innovation for both types of firms. We also concluded that pest resistance tends to favour the incumbent because, if initally ahead in the absence of the risk of pest resistance, it stays ahead once this risk is included. Even in the case where the incumbent's R&D expenditure was below the entrant's in the absence of pest resistance, we found that it was extremely rare for the incumbent's R&D investment to remain lower when the possibility of pest resistance was introduced.

Chapter 4

Non-point Source Pollution - A Review

4.1 Introduction

In this chapter we present a review of the literature on non-point source pollution (NPS). This literature grew out of a recognition that a large part of pollution is not of the point source variety and therefore cannot be tackled using the regulatory approach developed for this type of pollution. Before we proceed to present the various ways in which the literature has developed to address the problem of NPS, it will be helpful to examine the nature of non-point source pollution. By identifying the features of NPS pollution it can readily be seen why it is comparatively difficult to regulate, as well as, providing a rationale for the various approaches that have been proposed in the literature.

Unlike point source pollution which enters a receptor, e.g. a river at a single point, NPS pollution enters a receptor via multiple entry points. Generally speaking, point source pollution tends to be produced by large and easily identifiable polluters whereas NPS pollution is generated by many polluters, each individually small. On the otherhand, NPS pollution shares many features with point source pollution. In both cases, damages may be uncertain and influenced by the location of the source of emissions. Although natural variability due to weather and technological uncertainty (e.g. emission production functions and pollution pathways) which affect the relationship between emissions and damages, are thought to be more a feature of NPS (Braden and Segerson, 1993 cited in Tomasi *et. al.* 1994) they can also characterise point source pollution. Time lags between discharge of emissions and their contribution towards ambient pollution can exist for both types of pollution. Whether the pollution is of a point or a NPS nature, the regulator faces uncertainty regarding abatement costs of polluters and may encounter strategic interaction between polluters to minimise the impact of regulation on their activities.

However, the key characteristic of NPS that distinguishes it from point source pollution is the issue of observability or ability to monitor sources (Cabe and Herriges 1992, Millock, *et. al.* 2002). Point source emissions are relatively cheap to monitor, whereas NPS emissions involve a very high and possibly infinite cost of monitoring. Even if monitoring technology improves significantly, costs are unlikely to be driven to zero. The reason for this is that factors such as timing of actions and degree of care with regard to the environment are likely to affect environmental impact. The continual monitoring required in these cases would be exorbitant (Weersink *et. al.*, 1998). Hence, the problems relating to regulation of NPS pollution are mainly informational (Xepapadeas, 1999) and it is this distinction between point and NPS pollution that calls for a different regulatory approach. The features described above as being common to both sources of pollution, e.g. time lags, exacerbate the informational problems relating to NPS and hence, compound the difficulty of assigning individual responsibility for ambient pollution.[1] Also, spatial characteristics such as location, soil type and weather which play a role in determining the load entering a receptor and ultimately its contribution towards damages, further impede the ability to link ambient pollution with individual actions. The inability to attribute responsibility amongst polluters or to use regulatory instruments based on emissions, as in the case of point source pollution, requires alternative approaches to control NPS pollution. One possibility is to base policy on estimated emissions produced

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[1] Time lags can vary between 2 - 10 years and 50 - 500 years (Werner and Wodsak, 1995).

by simulation models which link actions with emissions produced. Unfortunately, current models cannot be relied upon to consistently provide accurate estimates of emissions and so can always be legally challenged in the case of a dispute (Weersink *et. al.* 1998). Thus, directly linking regulatory instruments to individual sources of pollution is not possible. The imperfect observability of sources of NPS pollution also raises the issue of the choice of monitoring - what to monitor, where and with what frequency?

Transactions costs include the cost of designing, implementing and enforcing a policy. Given the substantial information requirements necessary to design efficient instruments, the costs of designing appropriate instruments for NPS pollution will be high. Depending on the base chosen, e.g. input use, monitoring costs may still be high especially if there are many inputs to be monitored. High enforcement costs will make the potential for deviation by polluters more likely. The issue of transactions costs is an empirical question and as such, has not been much addressed in the literature.[2] Helfand and House (1995) refer briefly to the issue of transactions costs and state that their inclusion in a comparative analysis of uniform and differentiated taxes may swing the cost-benefit analysis in favour of uniform taxation even where there is large spatial variability in pollution production/damage functions.

Although the literature presented here relates to all types of NPS pollution, to give context to the problem we take the example of agricultural pollution entering surface waters. This mainly involves the discharge of nutrients and/or pesticides into surface waters arising from their application to crops and grass. There are two pathways to surface waters: either as run-off or through leaching (movement of nutrients in solution down through the soil profile into the groundwater zone and ultimately entering surface water through groundwater recharge). Within a particular geographical area, e.g. catchment, there will be many farmers each of whom are potential polluters of the stream-water. Through their choices of production technology, application of fertilisers and pesticides and their location, they will impact on ambient pollution levels to different degrees (Rib-

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[2] An exception is Kampas and White (2002).

audo *et. al.* 1999). The aim of policy is to introduce first-best measures to achieve an optimal reduction in pollution, or in the absence of information required to implement a first-best measure, a second-best instrument which will achieve a target level of pollution reduction at least-cost (Cabe and Herriges 1992, Helfand and House 1995, Fleming and Adams, 1997).

This review will highlight the main policy options that have been put forward in the literature to address NPS pollution. These policies can be direct as in the ambient-based and tradeable permit schemes or indirect as in the input taxation approach and incentives to carry out more environmentally benign practices. Advocates of the former argue that they are efficient whereas supporters of the latter point to their practicality. The direct approach tends to be favoured by economists whereas the indirect approach is more popular amongst policy-makers (Hanley *et. al.* 1990). We focus first on the direct approach as these are more theoretically sound than indirect approaches, however problems related to their implementability will lead us naturally to a discussion of indirect policies which have the advantage of greater applicability. Finally, we present a review of actual practice.

4.2 Ambient Taxes

The key attraction of ambient-based schemes is that they circumvent the need for individual monitoring. They also directly target environmental quality which is what policy-makers are concerned about. The theoretical basis of ambient taxation is drawn from the moral hazard in teams literature. In this literature, a team of workers produce an output through their efforts, where efforts are unobservable. So without monitoring, there is an incentive to shirk because effort is costly to the individual. The moral hazard literature constructs incentive compatible mechanisms or sharing rules that govern the distribution of the output amongst workers, which aim to eliminate the incentive of each worker to shirk or free-ride.

The application of the moral hazard in teams literature to the NPS pollution context can be understood as follows. Individual emissions are produced as a by-product of profit-making activities and hence, are beneficial to the individual polluter. However, these emissions determine the ambient pollution level which produces environmental damages that are harmful from society's perspective. Unless they are controlled, emissions will be excessive and social welfare will be sub-optimal. The first paper set in the moral hazard in teams framework, is the seminal article by Segerson (1988) which we will carefully set out. By describing Segerson's model in some detail, it will be clearer how later contributions extended her model.

As stated above, individual emissions are unobservable and therefore cannot form the basis of regulation. However, by limiting monitoring to receptor sites, it is possible to observe the ambient level of pollution at a significantly reduced cost.[3] Polluters' emissions contribute to the ambient pollution level, but the regulator is unable to infer the contribution of each polluter. In addition to emissions produced by $i = 1, ..., n$ polluters/firms, random factors such as weather events influence pollution concentrations. Thus, the ambient level of pollution is given by $\widetilde{X} = \overline{X} + \epsilon$, with $\overline{X} = \sum_{i=1}^{n} e_i$, where e_i is the level of emissions produced by polluter i, and ϵ is a random variable. It is assumed that $E(\epsilon) = 0$ and $E(\epsilon^2) = \sigma^2$, where E is the expectations operator. In Segerson (1988), firms influence the ambient level of pollution through abatement.[4] We recast her model in terms of emissions to make comparisons with later models more obvious. This does not alter Segerson's (1988) results in any way, and it provides a more intuitive link between pollution produced at source and its contribution towards the ambient level of

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[3] Depending on the type of pollutant, monitoring will have to be carried out more or less frequently. For example, monitoring would have to be more frequent, and hence more costly, the greater the variability in concentration levels and the more undesirable it is for the concentration to exceed a particular threshold level.

[4] Abatement is the reduction of emissions and therefore, it can be thought of as being the opposite to emissions production. Focusing on abatement rather than emissions, we can re-interpret the moral hazard in teams, as applied to the pollution context, given in the text as follows. Abatement is costly for the polluter, but beneficial to society. Because abatement is unobservable, in the absence of control, polluters will choose to minimise their abatement effort, and we are again in a situation of moral hazard in teams.

pollution. In Segerson (1988), the target level of pollution is set at an arbitrary level, however for simplicity and ease of comparison to later models, we assume that the target level is the socially optimal level determined by the following maximisation problem:

$$W^* = \max_{e_1,\ldots,e_n} \sum_{i=1}^{n} \pi_i(e_i) - E\left[D\left(\widetilde{X}\right)\right] \tag{4.1}$$

Total welfare consists of the summation of firms' profits $\pi_i(e_i)$ minus the expected damages due to the ambient pollution level, where D is the damage function. We follow convention and assume convex damages, i.e. $D' > 0$, $D'' > 0$. As emissions are beneficial to the firms, we assume $\pi_i'(0) > 0$, diminishing marginal returns, i.e. $\pi_i'' < 0$ and that there exists a level of emissions $\overline{e}$ such that $\pi'(\overline{e}) = 0$.[5] In Segerson's model, instead of expected damages she includes expected benefits of abatement in W^*. The choice of expected damages arises naturally from choosing emissions rather than abatement as the endogenous variable. Note also that in Segerson's model, firms and the social planner choose output levels but since it does not add anything to her key result, we will simply concentrate on decisions relating to pollution. The socially optimal emissions $e^* = (e_1^*, \ldots, e_n^*)$, are determined by the equality $\pi_i'(e_i^*) = E\left[\frac{\partial D}{\partial \widetilde{X}} \frac{\partial \widetilde{X}}{\partial e_i}\right]$, with the derivatives evaluated at e^*. Since $\sum_{i=1}^{n} e_i^* = X^*$, $E[X^* + \epsilon] = X^*$ is the target level of ambient pollution. Segerson's (1988) instrument takes the form of a constant tax t_i, imposed on polluter i, per unit of deviation in the observed from the target level of ambient pollution. So when the ambient level of pollution is $\widetilde{X}$, the tax/subsidy facing polluter i is $t_i\left(\widetilde{X} - X^*\right)$, and is therefore conditioned on all polluters' actions through the level of ambient pollution. The expected tax payment of/subsidy received by the polluter is $t_i E\left(\widetilde{X} - X^*\right)$ in the event of realised ambient pollution exceeding/falling short of the

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[5] $\overline{e}$ can be thought of as a saturation point beyond which the polluter will have no incentive to go.

target.[6] Thus, given a tax rate t_i for polluter i, the polluter's problem is:

$$P_i^* = \max_{e_i} \pi_i(e_i) - t_i E\left[\widetilde{X} - X^*\right]$$

The first-order condition of this problem yields

$$t_i = \frac{\pi_i'(e_i)}{E\left[\frac{\partial \widetilde{X}}{\partial e_i}\right]}$$

Since $E\left[\frac{\partial \widetilde{X}}{\partial e_i}\right] = 1$ by construction, this is equivalent to

$$t_i^* = \pi_i'(e_i^*) = E\left[\frac{\partial D}{\partial \widetilde{X}} \frac{\partial \widetilde{X}}{\partial e_i}\right]\Bigg|_{e=e^*} \tag{4.2}$$

at the socially optimal level of pollution and is the same as Segerson's ambient tax/subsidy scheme.

The assumptions underlying Segerson's ambient tax/subsidy scheme point to several potential problems in implementing the scheme. Firstly, she assumes that profit functions and the damage function is known, as well as, the link between individual actions and the ambient level of pollution, making the scheme informationally demanding and hence difficult to implement. Her assumption of risk neutrality requires the scheme to be budget-breaking for it to be efficient.[7] She also assumes that expectations are the same across everyone, which if not the case, has implications for the ambient tax/subsidy rate. Finally, we noted that liability is a function of group action and hence, it may happen that compliant polluters are also punished. This feature of the ambient tax/subsidy

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[6] In Segerson's model, in addition to a tax, polluters pay a penalty if $\widetilde{X} > X^*$. Since polluters are assumed to hold Nash conjectures, i.e. they take as given the emissions of other polluters, at the appropriate Nash Equilibrium each polluter is effectively the marginal polluter, and so the ambient tax works in exactly the same way as a pure emission tax and there is no need for a penalty.

[7] This follows from Holmström (1982). Budget-breaking in this context occurs when total tax receipts exceed the social costs of damages and is defined as $\sum_{i=1}^{n} t_i \left(\widetilde{X} - X^*\right) > D\left(\widetilde{X}\right) - D\left(X^*\right)$.

scheme may make it unacceptable to potential participants.

Herriges *et. al.* (1994) and Xepapadeas (1995, 1999) exploit the case where the polluter is risk averse. Assuming risk aversion rather than risk neutrality allows these authors to overcome two problems associated with the Segerson ambient tax/subsidy scheme: non-budget balancing and political unacceptability.[8] [9] Drawing on Rasmussen (1987), Herriges *et. al.* show that a random scheme can implement the socially optimal outcome provided that (i) polluters are sufficiently risk averse or (ii) the fines are sufficiently large. The intuition for this is as follows. Because there is a positive chance of being punished when there is a deviation, with sufficient risk aversion or a sufficiently large fine, each polluter will try and avoid being punished. Thus, each polluter will have an incentive to comply.

By introducing risk aversion and the opportunity to carry out individual monitoring[10] into the Segerson framework Xepapadeas (1995) shows that the polluter may prefer to reveal a portion of its emissions through monitoring, and pay a per unit effluent tax on that portion in return for a lower ambient tax.[11] Thus, the ambient tax rate is a function of the level of monitoring carried out. Then, assuming that the higher the level of monitoring the greater the proportion of emissions observed, it is likely that the ambient tax rate will be a decreasing function of the level of monitoring. Thus, by increasing monitoring, polluters can reduce their ambient tax liability if random effects cause the

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[8] The argument that excess tax revenues can be redistributed as lump-sum subsidies and therefore non-budget balancing of the scheme is not an issue (Aftab *et. al.* 2003), is rather weak for the following reason. If polluters create environmental damage, the polluter pays principle argues that they should pay for that damage. Under a non-budget balancing scheme they may pay more than the social cost of the damage. Then the question is - 'why should this be?' Even if the excess tax revenue is subsequently redistributed as lump-sum subsidies it is bound to affect the overall social welfare. Therefore, if the ultimate objective is to maximise social welfare, which it should be, then the policy-maker should explicitly account for the effect of this redistribution on the social welfare.

[9] To increase the political acceptability of ambient tax/subsidy schemes Romstad (2003) provides polluters with two options (i) face a standard regulatory regime or (ii) face a Segerson type ambient tax/subsidy scheme.

[10] Monitoring is defined as any action, apart from end-of-pipe monitoring, which increases the ability of the regulator to quantify individual emissions. This could be research carried out by the regulator on the physical attributes of the polluter such as location, soil characteristics, production technology, information provided by the polluter itself or the installation of monitoring equipment.

[11] This of course presumes the ability of polluters to know their own emissions.

actual ambient pollution to exceed expected levels. Xepapadeas shows that under certain conditions - risk aversion, a particular parameterisation of the effluent tax and a sufficiently large variance of ϵ, firms will choose a positive level of monitoring (Proposition 3). Since there is an inverse relationship between monitoring and the ambient tax/subsidy level, a positive level of monitoring implies that the Xepapadeas version of the Segerson ambient tax/subsidy rate is lower.

Thus, Xepapadeas (1995) shows that, when monitoring of individual emissions is introduced and firms are risk averse, the opportunity to pay part of their liability for pollution production in the form of an effluent fee acts as a form of insurance for polluters against being penalised by the influence of random effects through an incentive scheme consisting of an ambient tax alone, even though they are in full compliance. The polluter will only avail of this 'insurance' option when there is uncertainty over the relationship between ambient pollution and emissions. When there is no such uncertainty, the optimal level of monitoring will be zero.

Both Cabe and Herriges (1992) and Xepapadeas (1992) introduce the possibility of dissimilar expectations between the regulator and polluters and amongst polluters respectively.[12] When polluters and the regulator hold different beliefs regarding the pollution transport mechanism, the optimal ambient tax will be higher or lower than in Segerson's case. For example, if polluters believe that they have a minimal impact on the ambient level of pollution, the optimal ambient tax rate will be higher. Cabe and Herriges (1992) argue that the ability of the regulator to ascertain and to present polluters with the full impacts of their pollution, is likely to be crucial in designing and implementing the tax.

Rather than taking others' actions as given, polluters may surmise that others will condition their response on the expected level of ambient pollution. For example, if the level of ambient pollution is expected to exceed the target set by the regulator, polluters might reduce their emissions. To illustrate this, Xepapadeas (1992) introduces a conjectural function of the form $e_j = \overline{e}_j + \beta \left(E \left[\widetilde{X} \right] \right)$ where $\beta' < 0$. This implies that

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[12] See also Horan *et. al.* (2002).

polluter i believes polluter j's emissions are made up of a fixed part plus or minus an amount, which depends on whether ambient pollution is expected to be lower or higher than the target respectively. On the basis of this, polluter i might increase its emissions so that polluters' emission levels act like strategic substitutes. In this case, Xepapadeas (1992) shows that the optimal ambient tax would be higher than in Segerson's case. Using Xepapadeas' (1992) conjectural function and assuming symmetry across polluters, expression (4.2) becomes:

$$t_i^{CF} = \frac{\pi'\left(e_i^*\right)}{1+(n-1)\,\beta'\left(E\left(\frac{\partial \tilde{X}}{\partial e_i}\right)\right)} \tag{4.5}$$

So $t_i^{CF} > t_i^*$, because by assumption $\beta' < 0$. This is true whether polluters are risk averse or risk neutral.

Byström and Bromley (1998) argue that the informational requirements of Segerson's (1988) approach can be reduced by introducing a common contract based on ambient water quality for all while allowing side payments between polluters. The contract consists of an identical penalty imposed on all polluters should the level of water quality fall below the desired target or a zero penalty in the case of the ambient water quality meeting the target level. Given the stochastic nature of pollution, the probability of paying the penalty is never zero. Polluters can reduce the probability of having to pay the penalty by undertaking abatement themselves or paying others to do so. When abatement costs differ it may be cheaper for a polluter to pay another to undertake pollution abatement than to carry it out itself. Byström and Bromley argue that by including the possibility of making side payments, the private profit-maximisation problem is converted into that of joint profit maximisation for all polluters. For this reason an identical rather than a farm-specific penalty can be used.

The problem with Byström and Bromley's model is that it implicitly assumes that abatement efforts are verifiable, because to allow side payments to be made in return for abatement efforts, the abatement efforts themselves must be verifiable. A simple example will illustrate the problem. Although, Byström and Bromley assume farmers can observe each others' abatement efforts, it is not the same as saying that the abatement efforts are verifiable in the case of a dispute. For example, suppose Farmer A agrees to pay £100 to farmer B to undertake 10 units of abatement effort. Now, there is nothing to stop farmer B from reneging on his/her abatement effort and still demanding payment from farmer A, by arguing that he/she has indeed undertaken the required abatement effort because when there is a dispute between A and B regarding B's abatement effort, a third party cannot verify it. Byström and Bromley argue that they cater for the situation of farmer B reneging on his/her abatement effort by having a repeated game where farmer B is punished by farmer A not entering into future agreements with him/her and so the future threat is sufficient for them to comply. However, this is a weak argument because we know that such threats in a dynamic situation are not necessarily credible. For example, when the simple Prisoner's Dilemma game is repeated for a finite number of times or repeated infinitely with a sufficiently low discount factor, the cooperative solution is not necessarily sustainable. Observability and verifiability are two distinct concepts with the latter a stronger information requirement than the former. It is non-verifiability of individual actions and not simply unobservability that produces the moral hazard in NPS pollution problems. Thus, if abatement efforts could be verified, albeit at some cost, the problem is no longer of a NPS nature.

Horan *et. al.* (1998) focus on the mistaken observation that Segerson only considers linear taxation and argue that when the number of inputs exceeds two and damages are nonlinear a linear tax will not achieve efficiency. But this argument is not surprising since when damages are non-linear, marginal damages are not constant and policy needs to be directed at the mix of inputs as well as the overall ambient level, i.e. you need as many instruments as the number of inputs. In the linear damage case, marginal damages are constant and the policy-maker need only worry about the ambient level of pollution and single instrument is sufficient. In place of a linear tax, Horan *et. al.* proceed to offer two alternative ambient taxes (i) state dependent linear tax and (ii) non-linear ambient taxes. In case (i) $t_i = \pi_i'|_{e^*}$ where t_i is determined ex post. Profits are evaluated at the ex ante efficient level of emissions and conditional on the realisation of all random variables. Thus, the tax rate and tax base (i.e. ambient pollution levels) are state dependent. However, as in the linear case, the tax rate is applied uniformly on all firms. In case (ii) the general form of the tax rate is given by $T_i(\mathbf{e}) = D(\mathbf{e}, \eta)$ where $\mathbf{e}$ is a vector of emissions η is a random variable. Each firm pays an amount TD and considers the impact of each input on expected damages. The tax rate is again applied uniformly across firms. Horan *et. al.* note that the implementation of state dependent taxes should not be significantly more demanding in terms of implementation than state independent taxes.

4.3 Tradeable Permits

An alternative to the ambient-based scheme to control NPS pollution which has received attention in recent years is point/non-point trading. Point/non-point trading is the bubble idea applied to watershed management (Letson, 1992). Increases in individual emissions are permitted as long as they are offset by reductions elsewhere so that the aggregate level of emissions leaving the bubble does not increase. In practice, it enables point sources such as municipal sewage treatment works to obtain reductions in non-point sources such as farm holdings rather than achieve further reductions themselves. The rationale for the emergence of point/non-point trading as a possible option for the control of NPS pollution is based on the observation that point sources have been relatively tightly controlled in the past, whereas non-point sources have not, so that further reductions in point source emissions can only occur at significantly high marginal abatement costs. Reallocation of abatement away from point sources to non-point sources could potentially offer significant cost savings.

Due to the nature of NPS pollution, i.e. unobservability of individual emissions the trading base cannot be emissions. Several alternatives have been suggested in the literature. These schemes involve point sources trading emissions for restrictions in pollution generating inputs, e.g. fertiliser or for estimated reductions in emissions loading (Letson 1992, Weersink *et. al.* 1998 and Horan *et. al.* 2001). Alternatively, Pan and Hodge (1994) has suggested land-use permits, whereby, the number of permits required for each land-use depends on the extent of nitrate leaching associated with that land-use. Apart from having to modify the trading base, the appropriate trading ratio at which trades between point sources and non-point sources take place would also have to be determined. The trading ratio gives the number of units of reduction that a non-point source must achieve in order for a point source to avoid reducing its own emissions by one unit. The choice of a trading ratio in excess of one is because of the uncertainty of the conversion of actions to reduce emissions by a non-point source polluter into actual emissions reduction. A conservative trading ratio (i.e. in excess of one) reflects the desire to ensure that the overall aggregate level of emission loading does not increase. However, there is a trade-off between potential cost savings and reliability of meeting an environmental target implicit in the choice of the trading ratio. A high trading ratio will increase the reliability of meeting the target but discourage trading because of higher reductions required of non-point sources. Limited trading means that cost savings are not fully exploited. A high degree of uncertainty in the relationship between non-point source actions and emission reductions could mean that an appropriate trading ratio which gives rise to cost savings does not exist. Thus, the potential for point/non-point source trading regimes is greatest in watersheds where the appropriate trading ratio implies a favourable trade-off between cost savings and reliability which will occur when the following factors are present: (i) low levels of uncertainty regarding the relationship between NPS actions and actual emissions reduced (ii) similarity between point sources and NPS in terms of type and timing of pollution (iii) pollutants accumulate (iv) adequate number of potential traders and (v) redistributive impacts are acceptable. With regard to (iii), pollutants that decay over time require a modification of the trading ratio to reflect this because timing and location of discharge are just as important as the quantity of discharge when considering NPS pollution (Letson, 1992). Thus, degradeability of pollution increases the complexity of the trading scheme increasing its monitoring and enforcement costs. Lack of similarity between the two sources of pollution also increase the costs of implementing a trading regime. Too few participants and the market for permits will be too thin with potential anti-competitive behaviour by dominant parties which reduce cost-savings. A system where permits are initially auctioned would result in the significant transfer of funds to the exchequer. Acceptability of the scheme can be increased if permits are initially granted free of charge. Absence of any of these factors will mitigate against the success of point/non-point source trading schemes and may explain why there are a limited number of these schemes in place.

4.4 Input taxes

The difficulties of basing regulation on emissions have led policy-makers to focus on those inputs involved in the generation of emissions. The assumption here is that while emissions cannot be observed, the inputs linked with those emissions may well be. To illustrate input taxes we present a simple derivation of an efficient input tax following Griffin and Bromley (1982). The underlying rationale of this approach is that inputs are observable. In addition, they assume that the functional relationship between inputs and emissions is known by both the polluter and the regulator. To link the analysis with the approach described above, we do not present their model exactly, but rather a simplification of it as well as retaining the same notation where appropriate. As we will see, efficient input taxation require taxes to be differentiated across inputs and sources of pollution. Griffin and Bromley (1982) adapt the Baumol and Oates (1975) framework for point source pollution to the NPS context. They introduce an emissions function $e_i = h(x_{i1}, ..., x_{im})$ for each firm/polluter i, where x_{ij} denotes the j^{th} input used by firm i. They assume that the emissions production function, which is strictly increasing in emissions and strictly concave, is the same across firms. If damages are known, they will enter the regulator's objective function. As above, we might assume that emissions enter the damage function additively, i.e. $D\left(\sum_{i=1}^{n} e_i\right)$. Griffin and Bromley (1982) assume that damages are unknown, and instead the regulator has a particular target level of emissions which it deems as desirable or acceptable to obtain. For the purpose of comparison with the preceding analysis, we will show the derivation of the input tax in both cases. Griffin and Bromley (1982) assume a similar construction for the input tax as in the case of the ambient tax scheme adopted by Segerson (1988). A particular input level $\overline{x}_{ij}$ is chosen for each i and each j such that if actual j^{th} input used by firm i is above this particular level, polluter i pays a tax per unit of j^{th} input exceeded and if j^{th} input use is below this level, polluter i receives a subsidy. In the Griffin and Bromley model, there is no uncertainty but it would be quite straightforward to incorporate it along the same lines as in the section on ambient taxes. Polluter i's problem is

$$\begin{aligned} P_i^I &= \max_{x_{i1},\ldots x_{im}} \pi_i(e_i) - \sum_{j=1}^{m} t_{ij}\left(x_{ij} - \overline{x}_{ij}\right) \\ & \qquad \text{subject to: } e_i = h\left(x_{i1}, \ldots, x_{im}\right) \end{aligned}$$

and the first-order condition is

$$\pi_i' \frac{\partial h}{\partial x_{ij}} - t_{ij} = 0 \qquad \forall\ j, \ldots, m$$

The regulator's problem is

$$\begin{aligned} W^I &= \max_{x_{i1},\ldots,x_{im},\ldots,x_{n1},\ldots,x_{nm}} \sum_{i=1}^{n} \pi_i(e_i) - D\left(\sum_{i=1}^{n} e_i\right) \\ & \text{subject to: } \; e_i = h\left(x_{i1}, \ldots, x_{im}\right) \qquad \forall\ i = 1, \ldots, n \end{aligned}$$

Solving this we obtain

$$\pi' \frac{\partial h}{\partial x_{ij}} - D' \frac{\partial h}{\partial x_{ij}} = 0 \qquad \forall\, i = 1, ..., n; \quad \forall\, j = 1, ..., m$$

Hence, the socially optimal input tax rates are $t_{ij} = D' \frac{\partial h}{\partial x_{ij}}$, which is the familiar result for point source pollution, i.e. per unit tax equal to marginal damages, except in this case, the marginal damages are with respect to inputs and the tax is imposed on inputs rather than emissions.[13]

Alternatively, as in Griffin and Bromley (1982), the regulator may maximise welfare subject to an environmental constraint, which sets E as the maximum level of overall emissions permitted.

$$\begin{aligned} &W^{II} = \max_{x_{i1},...,x_{im},...,x_{n1},...,x_{nm}} \sum_{i=1}^{n} \pi_i \left(e_i \right) \\ &\text{subject to:} \\ &e_i = h \left(x_{i1}, ..., x_{im} \right) \quad \forall\, i = 1, ..., n \\ &\sum_{i=1}^{n} e_i \leq E \end{aligned}$$

The optimal tax rates when the regulator is faced with such a problem are $t_{ij} = \mu \frac{\partial h}{\partial x_{ij}}$ where μ is the shadow price of the environmental constraint.

The key feature of Griffin and Bromley's analysis is that, they have replaced an unobservable emission by an emission production function which is assumed to be known by polluters and the regulator alike. All linkages between inputs and pollutants are accounted for in deriving the set of efficient input taxes. The question that arises is, whether this information is more obtainable than knowledge of individual emissions. In the absence of uncertainty, if we can observe inputs then we can infer individual emissions - the two are equivalent and the problem is no longer of an NPS nature. Under uncertainty, individual emissions may no longer be inferable from the observed inputs.[14]

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[13] The input targets $(\overline{x}_{i1}, ..., \overline{x}_{im})$ are equal to the socially optimal input levels that solve the regulator's problem.

[14] Shortle and Horan (2001) introduce uncertainty into the emissions production function and show

In this case, taxing inputs becomes a way in which to shift the burden of risk from the polluters to the regulator if polluters are risk averse. This echos Xepapadeas' (1995) approach of enabling risk averse polluters to switch to a tax based on their own individual emissions in lieu of a higher ambient tax, which is conditioned on the actions of others and random effects. However, if polluters are risk neutral, then the benefit of taxing inputs rather than ambient pollution disappears.

The information requirements to implement a Griffin and Bromley input tax are quite substantial - the regulator is assumed to be able to observe all inputs that play a role in generating emissions, as well as, the relationship between that set of inputs and emissions. As shown above, optimal input taxation requires taxes to be differentiated by source and input. The implementation of such taxes may be highly costly at best, or simply impractical at worst. For example, pricing fertiliser use according to its contribution towards ambient pollution is not feasible, unless there are separate markets. Without separate markets, buyers facing low prices will sell to individuals facing high prices and a single price will emerge through arbitrage, thereby, eroding the optimality of the tax scheme (Helfand and House, 1995). Instead, second-best instruments such as uniform taxes on a subset of inputs have been proposed. We discuss some of the results of empirical studies which assess the trade-off in implementing second-best policies.

The regulator is unlikely to have perfect information regarding the emissions production function. Biophysical models such as the Integrated Nitrogen model for European Catchments (INCA) (INCA is discussed in the next chapter), which simulates the flow of emissions from source to receptor, help in identifying the relationship between inputs and emissions, i.e. h. In addition to enabling the taxation of inputs, biophysical models can contribute to the task of evaluating taxation policy as the response of ambient pollution levels to changing tax rates can be estimated. Alternatively, knowledge of the

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how the introduction of uncertainty affects the optimal input tax. Depending on how increased input use affects the variance of ambient pollution, and hence, damages the tax rate will be lower or higher than in the absence of uncertainty. If damages are convex, as we have assumed, then the additional term reflecting the effect of risk in the expression for the tax rate will be positive, thus increasing the tax rate.

emission function means that taxes can be imposed on estimated emissions. However, as stated already, there is still the problem of verifiability. If there is a dispute about the polluter's tax liability, the tax scheme breaks down because the polluter's emissions cannot be verified by a third party in a court of law. This is because biophysical models simulate emissions and do not measure actual emissions. Even if it could be decided which model is best, it could always be open to dispute.

Griffin and Bromley's (1982) analysis assumes that the regulator can observe inputs to the production process. In the absence of this knowledge, direct use of input taxes is ruled out. If in addition to the unobservability of emissions - the moral hazard problem, there is also unobservability of inputs (or any characteristic which affects emissions and is private information to the polluter), then the problem is also one of adverse selection.[15] To illustrate the adverse selection problem, the optimal solution when there is adverse selection and the implementation of the optimal solution, we will extend Griffin and Bromley's model. Uncertainty is a separate issue to the adverse selection problem which is one of incomplete information, so we will retain the assumption of no uncertainty. In this section, we will draw on Xepapadeas (1997) quite closely.

There is a continuum of polluters, each characterised by a parameter β belonging to the interval $\left[\underline{\beta},\overline{\beta}\right]$. The regulator has a prior distribution function $F(\beta)$ on $\left[\underline{\beta},\overline{\beta}\right]$ with a strictly positive probability density function $f(\beta) > 0$. Rewriting the emissions function given above to take account of the role of β in determining emissions we get

$$e(x,\beta) = h(x) - \beta \tag{4.6}$$

where $h' > 0$ and $h'' < 0$. Note that, unlike the analysis based on Griffin and Bromley's model, we assume a single input per polluter. The emissions function characterised

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[15] Unlike moral hazard in teams, the theory of adverse selection is not restricted in its application to the problem of non-point source pollution. Spulber (1988) examined the problem of adverse selection in the context of point sources, where the adverse selection variable was the abatement costs of firms. Similar to moral hazard in teams, the theory of adverse selection has a long tradition outside environmental economics, starting with Akerlof's (1970) model of the market for lemons.

in (4.6) implies that polluters with a higher β produce less emissions, i.e. they are more efficient in producing less emissions for a given input level. The revelation principle allows the regulator to design an incentive compatible direct regulation mechanism $\left\{t\left(\widehat{\beta}\right), x\left(\widehat{\beta}\right)\right\}$ that specifies for any announcement $\widehat{\beta} \in \left[\underline{\beta}, \overline{\beta}\right]$ by a polluter, a tax $t\left(\widehat{\beta}\right)$ and an input level $x\left(\widehat{\beta}\right)$ which induces the polluter to reveal its true type. As in Xepapadeas, we make the simplifying assumption that the tax and input for each polluter depends only on that polluter's response and not on the responses of other polluters.

Given an incentive compatible direct mechanism $\{t(\beta), x(\beta)\}$ by using (4.6), the corresponding ambient level is given by

$$E = \int_{\underline{\beta}}^{\overline{\beta}} \left[h(x(\beta)) - \beta\right] f(\beta)\, d\beta$$

Assuming that the damage function is known and is linear in the ambient level, we have $D(E) = \alpha E$ with $\alpha > 0$. In addition, following Xepapadeas (1997), we also assume that the social price of public funds exceeds one and is equal to $1+\lambda$ with $\lambda > 0$. This captures the distortionary effect of imposing taxes. Thus the regulator's problem is

$$W^A = \max_{x(.),t(.)} \int_{\underline{\beta}}^{\overline{\beta}} \left\{\pi(h(x(\beta)) - \beta) - \alpha\left[h(x(\beta)) - \beta\right] + \lambda t(\beta)\right\} f(\beta)\, d\beta$$

subject to:

$$\beta \in \arg\max_{\widehat{\beta}} \left[\pi\left(h\left(x\left(\widehat{\beta}\right)\right) - \beta\right) - t\left(\widehat{\beta}\right)\right] \qquad \forall\, \beta$$

$$\pi(h(x(\beta)) - \beta) - t(\beta) \geq 0 \qquad \forall\ \beta$$

where the first constraint is the incentive compatibility constraint, which requires each polluter to report its true type, and the second constraint is the participation constraint, which requires non-negative profits for each firm.

Denote the socially optimal incentive compatible mechanism, which solves the regulator's problem, by $\left\{t^A(.), x^A(.)\right\}$. Then by using a similar technique as in Xepapadeas (1997), we can show that x^A and t^A are strictly increasing. At the social optimum, the least efficient polluters emit the same level of emissions as in the complete information case[16], and all other polluters with $\beta > \underline{\beta}$ emit more pollution as compared to the complete information case. Furthermore, at the social optimum, the participation constraint is satisfied in such a way, that the most efficient polluter obtains a rent equal to zero while other polluters obtain a positive rent. The intuition for this is as follows. Since less efficient polluters have the incentive to mimic the more efficient polluters, to prevent them from doing so and to induce them to truthfully reveal their type, they are allowed to retain a positive rent.

Obviously, the socially optimal incentive compatible direct mechanism requires polluters to report their types which may not be easily implementable. However, the regulator does not have to rely on polluters reporting their types. Since we have now established a monotonic relationship between type and input use, it is possible to employ an input tax schedule (which may be more readily implementable) to achieve the same outcome as the incentive compatible direct mechanism. Since $x^{A\prime} > 0$, we can invert the x^A function to give a function $\beta^A(x) = x^{A-1}(x)$, which can then be used to derive an input tax schedule $T^A(x)$ as follows: for each x, $T^A(x) = t^A\left(\beta^A(x)\right) = t^A(\beta)$ with $\beta = \beta^A(x)$. This is made more explicit in Figure 4-1.

Figure 4-1 illustrates the transformation from the direct mechanism to the input tax schedule. Panels (a) and (b) depict the incentive compatible direct mechanism. By choosing a level of input x, we can trace out the tax schedule $T^A(x)$ in panel (c). We

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[16] In the case of complete information, the regulator chooses $e(\beta)$ to maximise $\int_{\underline{\beta}}^{\overline{\beta}} [(1+\lambda)\pi(e(\beta)) - \alpha e(\beta) - \lambda P(\beta)] f(\beta)\, d\beta$

subject to: $P(\beta) \geq 0$

which gives $\pi'(e(\beta)) = \frac{\alpha}{1+\lambda} \ \forall \ \beta$

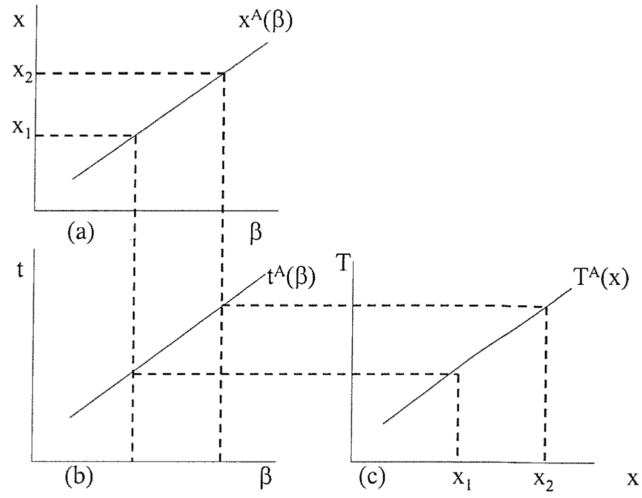

Figure 4-1: Derivation of input tax schedule

demonstrate this for two input levels, x_1 and x_2.

So the regulator simply announces a tax schedule $T^A(x)$ and each polluter chooses an input level and pays the corresponding tax. However, because of the way in which the input tax schedule has been derived from the optimal direct mechanism, the regulator knows that a polluter with characteristic β will choose its optimal input level $x^A(\beta)$ and pay the tax $T^A(x^A(\beta))$ which will be equal to its optimal tax $t^A(\beta)$.

Wu and Babcock (1996) describe how incentive payments can be made to farmers in return for the provision of environmentally-friendly services. They also use an adverse selection model to design an incentive compatible mechanism to induce truthful reporting of type by the farmer. In their paper, type refers to environmental characteristics which affect agricultural production and pollution. If we reinterpret environmentally-friendly services as pollution reducing inputs, so that $h' < 0$, and instead of $\{t^A(.), x^A(.)\}$, our socially optimal incentive compatible mechanism is given by $\{s^A(.), x^A(.)\}$, where $s^A(.)$ refers to the subsidy provided to the farmer as compensation for using pollution reducing inputs, their analysis follows through.

4.5 Standards

It is well known that regulators have favoured regulation over the use of economic incentives to control pollution (Hanley *et. al.*, 1990). Within the regulatory approach, the standards applied are generally uniform across polluters as this is perceived to be fairer by polluters than if they face different restrictions on emissions. In this section, we will show the rationale behind the use of management standards and how they are implemented in general. The use of management standards in NPS pollution consists of restrictions on those inputs responsible for generating emissions or instructions to polluters to employ less polluting technology. In contrast to incentives, polluters have no flexibility in meeting the standard.

Optimal standards restrict all inputs that have a role in producing emissions. Following the framework above, we show how optimal standards on inputs are derived. Given input standards $(\overline{x}_{i1}, ..., \overline{x}_{im})$ for polluter i, the polluter solves the following profit maximisation problem:

$$\begin{aligned} P_i^S = & \max_{x_{i1},...,x_{im}} \pi_i \left(e_i \left(x_{i1}, ..., x_{im}\right)\right) \\ & \text{subject to: } x_{ij} \leq \overline{x}_{ij} \qquad \forall\, j = 1, ..., m \end{aligned}$$

Let $\widehat{e}_i \left(\overline{x}_{i1}, ..., \overline{x}_{im}\right)$ be the emission level that maximises polluter $i's$ profits at the standard $\left(\overline{x}_{i1}, ..., \overline{x}_{im}\right)$. Then, given an ambient target E, the regulator's problem of setting the optimal input standards is given by

$$\begin{aligned} W^S \; = & \max_{\overline{x}_{i1},...,\overline{x}_{im},...,\overline{x}_{n1},...,\overline{x}_{nm}} \sum_{i=1}^{n} \pi_i \left(\widehat{e}\left(\overline{x}_{i1}, ..., \overline{x}_{im}\right)\right) \\ & \text{subject to: } \sum_{i=1}^{n} \widehat{e}_i \left(\overline{x}_{i1}, ..., \overline{x}_{im}\right) \leq E \end{aligned}$$

However, similar to the input taxation approach, the cost of monitoring and enforcing standards on the entire range of inputs linked to pollution will be very high and instead, a less costly option would be to restrict standards to a subset of inputs. In this case, standards should take account of the possibility that polluters switch to inputs which are not controlled, but are also linked to pollution, i.e. unregulated inputs should be those for which the marginal product of emissions with respect to those inputs is small.

4.6 Review of Actual Practice

The ambient tax/subsidy scheme has not been implemented in practice (Shortle and Horan 2001, Romstad 2003). The primary reason for this appears to be the substantial informational requirements to implement such a scheme, as well as, its potential political unacceptability (Xepapadeas, 1999).[17] This absence of real world data on how firms would respond to such a mechanism has prompted researchers to use experimental studies to guage the likely success or otherwise, of these schemes in practice (Shortle and Horan, 2001). Vossler *et. al.* (2003) examine three instruments: a group fine which is imposed when the actual level of ambient pollution exceeds the optimal level; a per unit tax/subsidy based on the deviation between ambient pollution and the optimal level; and a combined instrument composed of a group fine and a per unit tax/subsidy. According to Weersink *et. al.* (1998) and Shortle and Horan (2001), the potential for successful implementation of ambient tax/subsidy schemes is higher if confined to watersheds where the number of polluters are small and relatively homogenous, water quality is readily monitored and there are short time lags between the discharge of pollution and its contribution towards the ambient level.[18] Vossler *et. al.*'s (2003) study involves the assessment of ambient schemes under such circumstances. Additionally, they allow for

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[17] Of course, the informational requirements of any efficient regulatory regime will be high which explains why we do not see the implementation of optimal taxes for example. Also, rather than arguing that the ambient tax/subsidy scheme does not achieve political acceptability ex post, the political unacceptability factor should enter the welfare maximisation problem explicitly as a constraint in deriving the ambient tax/subsidy scheme.

[18] Presumably the number of polluters is still too large to monitor individually.

the possibility that communication can occur between the polluters and that there is an incentive for polluters to communicate their abatement strategies to each other to reduce their payment under the scheme. The effectiveness of the schemes depends on whether communication is allowed or not. In the absence of communication the tax/subsidy instrument achieves the pollution target, whereas the group fine and combined instrument result in excess pollution. The reason put forward is that, under the tax/subsidy instrument polluters face the correct marginal incentives, whereas in the case of the other two instruments they do not if pollution is far from the optimal level. When communication is permitted, the strategy of the different groups facing the three different instruments is to maximise profits, which is suboptimal from society's perspective because in all cases profits are maximised at output levels less than the socially optimal level of output and hence, pollution. The results of the study show that apart from the groups facing the combined instrument, the other groups were successful in implementing the optimal group strategy. This suggests to the authors that under the combined instrument the profit maximising strategy is less transparent and hence, the outcome is closer to the socially optimal one.

Although not widespread, there are an increasing number of point/non-point source trading schemes being implemented, albeit confined to the US. The two earliest schemes are the Dillon Reservoir in Colarado and the Tar Pamlico River Basin in North Carolina which where introduced in 1986 and 1989 respectively. Although feasibility studies carried out prior to the introduction of these schemes suggested that the scope for cost savings was significant (Apogee Research Inc. 1992 cited in Malik *et. al.* 1994, Letson 1992) these have failed to materialise. In the case of the Dillion scheme, municipal sewage treatment facilities can obtain credits by funding controls to reduce loadings from urban sources. A trading ratio of 2:1 was established to provide a margin of safety given the stochastic relationship between actions undertaken by urban sources and actual emissions produced. Improved tertiary treatment technology at the municipal sewage treatment facilities greatly reduced their emissions and hence, need for credits. This has discouraged these facilities from engaging in trades limiting actual cost savings. In the case of Tar Pamlico, a coalition of municipal and industrial dischargers were allocated a discharge allowance and required to make a monetary contribution into a NPS fund that is used to implement agricultural best management practices. A trading ratio of 3:1 was set in place. Despite little evidence that predicted cost-savings have been realised, Letson (1992) is still optimistic about the future of such schemes. He notes that any incentive scheme devised to control NPS pollution will have to overcome similar problems as experienced by trading schemes. According to Letson, the success of point/non-point source trading schemes relies on finding applicability to a wider range of pollutants, improved policy design and better enforcement.

Much more widespread, is the use of standards and input taxes to control non-point emissions. The theoretical description of input taxes and standards given above informs us that to be optimal, these instruments should be differentiated across inputs and source. However, it was also stated that the costs of implementing differentiated taxes and standards would be significant, potentially undermining the efficiency gains of implementing such systems. Hence, there is a trade-off between efficiency and cost-effectiveness in deciding the degree to which input taxes and standards implemented should mimic their theoretical versions. The efficiency gains from careful targetting are a major source of empirical research (Shortle and Horan, 2001).

To assess the welfare loss associated with following a second-best policy, Helfand and House (1995) conducted a study of lettuce production which uses two inputs - nitrogen and water. Farmers are distinguished by the location of their farm. They essentially fall into two distinct regions, one with relatively more permeable soil than the other, i.e. we can think of the population as consisting of two farmers $i = 1, 2$. Leaching is positively related to permeability. Farmers know their own soil type and take decisions regarding fertiliser usage and irrigation accordingly. Thus, leaching rates will differ not only because of different soil types s_i, but also because of the different rates at which the inputs are used, hence, $e_i = h(w_i, n_i, s_i)$ where w_i and n_i refer to water and nitrogen use by polluter i respectively. They estimate this relationship using the Erosion/Productivity Impact Calculator (EPIC). They considered uniform input taxes levied simultaneously on water and nitrogen and on water and nitrogen separately, as well as, simultaneous uniform percentage restrictions on water and nitrogen and uniform individual restrictions. The target reduction in leaching is set at 20% below the baseline. Of the four policies examined, the water tax, the policy of uniform input taxes and the uniform reduction in both inputs are nearly as efficient as the use of taxes differentiated across inputs and farmers. Regulating or taxing nitrogen alone resulted in the largest loss of welfare relative to the social optimum. To encourage a sufficient reduction in nitrogen use, the tax rate has to be set very high. The required low levels of nitrogen use to achieve the target of a 20% reduction in the leaching rate has a dramatic effect on yields, thereby, reducing income substantially. They also found that if both inputs are taxed, the levels of taxation are much lower than relying on a single input to control leaching. Furthermore, farmers located on the more porous soil are taxed more heavily. Helfand and House (1995) conclude that second-best policies do not necessarily lead to large losses in welfare, an argument that is further strengthened if the relatively high transactions costs of imposing first-best policies are factored into the analysis.

Similarly to Helfand and House (1995), Moxey and White (1994) use the EPIC model to generate nitrogen response and nitrate emission coefficients for the different production activities located on each land-use type. To convert total nitrate emissions into average nitrate concentration at a receptor point they use historical discharge data provided by the Institute of Hydrology which allowed them to obtain a rough estimate of the conversion ratio. Both Moxey and White (1994) and Mapp *et. al.* (1994) confine their analysis to the assessment of quota restrictions on nitrogen. In the case of the former, three instruments are examined: catchment level nitrate emission quota, catchment level nitrogen input quota and nitrogen input quotas targetted at individual land classes. In the absence of appropriate information to impose a first best nitrate emissions tax or tradeable land class specific emission quotas, the targetted quota performs best. Mapp *et. al.* consider four policies: (i) total restriction on nitrogen (ii) per acre restriction on nitrogen (iii) nitrogen restriction confined to porous soil and (iv) nitrogen restriction targetted at that production system associated with relatively higher leaching rates. Their findings corrorobate Moxey and White's. Although broad policies resulted in greater reductions in total nitrogen, they also had a significant impact on incomes. Targetted policies were more cost-effective than broad policies, because although they gave rise to smaller reductions in total nitrogen leached, the nitrogen reduction per dollar of income reduced was greater.

Fleming and Adams (1997) concur with the conclusion reached by Helfand and House (1995). Similar to the previous studies, the empirical focus of their model is agriculture in the US. To assess the relative increased costs of imposing a uniform tax on nitrogen versus a spatial tax that takes account of heterogeneity of land characteristics, specifically soil type, they compared the impact on farmers' incomes of each tax type. The tax scheme considered is a per unit tax on nitrogen. The land area is divided into four zones based on soil type. In the case of the non-uniform tax policy, different zones face different taxes but farmers within zones pay the same tax. They used an integrated modelling framework: economic optimisation model; soil water transport model; and a groundwater solute transport model. The economic optimisation model allows a comparison of the costs of meeting a standard through different tax policies. The biophysical models provide the environmental link to assess whether a policy is achieving its objective or not. A feedback mechanism allows the tax to be set iteratively until the ambient standard is achieved. In the uniform tax case, the tax rate is altered until the ambient standard for every monitoring point within the region is reached. In the spatial tax case, the tax rate is increased if the ambient level of pollution exceeds the target level set for that zone. They find that the impact on crop choice is more severe under the uniform policy, as farmers have to substitute more lucrative but more polluting crops with less polluting but also less financially rewarding land-uses to a greater extent. Hence, the uniform tax reduces income by more than the non-uniform tax. Although their results agree with the argument made by Abrams and Barr (1974) and Russell (1986) that, targetting incentives outperform uniform measures when the location of sources relative to monitoring points matters, they find that the cost differential between the two policies is small. Thus, they argue that the relative cost-effectiveness of a policy that takes into account the location of polluters would be easily offset by the cost of implementing such a policy.

Similarly to Helfand and House (1995), Aftab *et. al.* (2003) consider the role of irrigation water both in crop production and nitrate pollution. In both processes, nitrogen fertiliser and irrigation water act as complements. They study the effectiveness of an input tax in the presence and absence of river flow restrictions and find that the tax rate required to achieve a given reduction in nitrate pollution is lower when river flow restrictions are in place. However, due to the complementarity between irrigation water and nitrogen fertiliser in crop production lower levels of nitrogen are required and hence crop yields fall reducing profits by a greater margin than if the tax alone was implemented. They also assess the effectiveness of various instruments under average and high rainfall levels. They find that economic instruments that target inputs are more effective than management approaches when average rainfall levels are considered, a ranking which reverses under very wet years. The explanation offered by the authors is the difference in economic incentives provided by each instrument. A nitrogen tax or quota reduces fertiliser application per hectare while a land retirement or setaside policy removes land from production so that no nitrogen is applied to that portion of land. In the former case, the potential for leaching from that land is still present, exacerbated under very wet conditions whereas, in the latter case it is not.[19] The importance of this study is to show how the interaction between different inputs, i.e. water and nitrogen, into the nitrate pollution production process may affect policy. Also, in the light of climate change producing wetter years in the future, the study also suggests the possibility that best management approaches may become superior to the economic incentive approach in curtailing nitrate pollution.

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[19] Of course there may be some nitrogen leaching due to historic applications of fertiliser.

An example of a single input tax which has been introduced in countries to curtail nitrogen leaching is the tax on nitrogen fertiliser. These countries include Finland (1976), Sweden (1984), Austria (1986), Norway (1988) and Denmark (1998).[20] Rougoor *et. al.* (2001) carried out a study evaluating the effects nitrogen taxes in Finland, Sweden and Austria. Across the three countries the tax rate varied between 10% and 72% of the price of fertiliser. In all three cases, the use of nitrogen fertiliser did decrease which led the authors to assume that a reduction in the nitrogen load to the environment had occurred although, the empirical data to justify this claim was not available. A later study on the impact of the nitrogen tax in Sweden states that while the tax has had a minimal impact on the use of nitrogen fertiliser, it has helped to reduce the level of nitrogen leaching from arable land by 1,500 tonnes of nitrogen per year. Its introduction has also increased the awareness of farmers of the link between nitrogen application and the problems associated with nitrogen leaching.[21]

More frequently policy-makers have opted for standards or codes of practice to achieve their objective of limiting nitrogen leaching. An example of such standards are the rules governing farming practices within areas designated as either exceeding or likely to exceed the EU nitrate limit of 50 mg per litre.[22] These zones termed Nitrate Vunerable Zones (NVZ), implemented under the EC Nitrate Directive 91/676/EEC, require mandatory measures to control nitrogen leaching from fields. These mandatory measures are judged to be in accordance with good agricultural practice and thus do not attract compensation. These requirements consist of measures to restrict the quantity and timing of applications of nitrogen fertilisers and livestock manure, as well as, minimal requirements concerning manure storage capacity. Under the scheme, member states have to report every four years on their progress in meeting the objective of reducing nitrate leaching in these areas. The most recent report on progress to date, concludes that on balance, the nitrate concentration in groundwaters in Europe has stabilised or worsened, whereas surface and

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[20] Both Austria and Finland abolished their nitrogen taxes prior to joining the EU in 1995.

[21] source: http://finans.regeringen.se/propositionermm/sou/pdf/sou2003_9a.pdf

[22] This limit was set down in the 1980 EC Drinking Water Directive.

coastal marine waters have shown some improvement.[23] In terms of implementation of the requirements, i.e. the setting up of codes of good agricultural practice and/or action plans, member states were initially slow to fulfil their commitments. However, the report also states that there has been a real improvement in the awareness of member states of the nitrate issue in recent years. Member states have transposed the directive, set up codes of good practice, put monitoring networks in place and designated their vulnerable zones.[24]

Increasingly, voluntary approaches to encourage improvements in environmental performance in all sectors are being considered. In a survey article on voluntary approaches to regulating the environment, Khanna (2001) concludes that voluntary agreements work best when there are few firms which are relatively homogenous, abatement costs are lower than under mandatory regulation, the social costs of public funds are low and there is a weak regulatory structure. This would suggest that voluntary agreements are not suited to the agricultural industry, which is characterised by numerous heterogenous farms. Despite this, regulation within the agricultural sector has tended towards the voluntary approach. A possible argument for this tendency is the strength of resistance to the introduction of mandatory measures by a strong agricultural lobby. According to Piccinini and Loseby (2001) the move towards voluntary agreements with payments is also a way to lower costs of monitoring and enforcement as the burden of proof is shifted from the regulator to the farmer. In a mandatory system the regulator would have to demonstrate non-compliance to implement a penalty/charge. Wu and Babcock (1999) provide an analysis of the relative efficiency of the voluntary approach versus the mandatory option. They derive a sufficient condition for the voluntary programme to be more efficient: the social cost of public funds incurred from raising tax revenue to fund compensatory payments should be less than the sum of the difference between private and public costs of government services and the implementation costs of the mandatory programme. They

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[23] COM (2002)

[24] With the exception of Ireland.

find that this condition is more likely to be satisfied when the social cost of public funds are low, government services tend to be non-rival, the costs of government services relative to the costs incurred if farmers carried out these activities themselves are lower, the land area covered by the programme is greater and the costs of implementation under the mandatory programme are higher.

An example of a voluntary measure used in agriculture is the Nitrate Sensitive Areas (NSA) scheme which was introduced to limit nitrate leaching in areas where the nitrate concentration exceeded or was at risk of exceeding the EU limit of 50 mg per litre. Whereas NVZs were designated as a result of the implementation of the Nitrates Directive and measures undertaken within these areas were to be mandatory, NSAs were launched under the EC Agri Environment Regulation No. 2078/92 and actions undertaken within these areas were of a voluntary nature and hence, subject to compensation. The NSA scheme which was launched in 1994 and ended in 2003 was comprised of three types of voluntary measures: conversion of arable land to grassland; extensification of intensively managed grassland; and low nitrogen arable cropping.[25] The Ministry for Agriculture, Fisheries and Food (MAFF) carried out a survey of participants in the NSA scheme to assess uptake of the scheme and its cost-effectiveness (MAFF, 1998). The results of the survey led them to conclude that although uptake had been good, the scheme did not achieve a significant change in farmers' attitudes towards the nitrate problem. The basis of this conclusion was that just under half of the sample participants were unaware of which farming practices contributed most to nitrate leaching and those that were aware, stated that they would be unlikely to continue with the recommendations of the scheme unless offered compensation to do so.[26] The report stated that the NSA scheme was cost-effective, although, they judged that the payments made for certain types of land conversion had been too generous and their reduction would offer improvements in the cost-effectiveness of the scheme. Although the survey did not address the extent

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[25] source: www.defra.gov.uk/erdp/schemes

[26] It is unlikely that farmers would admit that they would undertake measures regardless of whether compensation was available or not, if to do so would lead to the removal of such compensation.

to which the scheme had contributed to a reduction in nitrate leaching, it nevertheless concluded that, given that the scheme had encouraged changes in practices which were highly correlated with nitrate leaching and that these changes would not have occurred without the scheme, the scheme had indeed contributed significantly towards meeting the objectives of reducing nitrate concentrations in sources of public drinking water.

4.7 Conclusion

Although not the sole source of NPS pollution, this review has been set in the context of agricultural pollution because this is a well recognised and major type of NPS pollution. As a result, agriculture provides the backdrop for many of the contributions in the NPS literature. We started with the seminal paper by Segerson (1988) which was the first to apply the moral hazard in teams theory to the problem of NPS pollution. The problem of moral hazard arises because of the feature of joint production of the ambient pollution level and the non-observability of individual emissions. Through the imposition of a tax/subsidy per unit of deviation from the target ambient level, Segerson shows that the target level of pollution can be achieved. To impose such a tax/subsidy instrument, the regulator requires information on the damage function, polluters' profit functions and how the stochastic level of ambient pollution is determined.

By allowing for risk aversion Herriges *et. al.* (1994) and Xepapadeas (1995) address two concerns with the Segerson ambient tax/subsidy scheme: non-budget balancing and political unacceptability. We also explored the role of expectations in determining the optimal ambient tax/subsidy scheme. We saw that if polluters are unaware of their contribution to the ambient level of pollution or believe it to be small, the optimal ambient tax rate will be higher (Cabe and Herriges, 1992). Xepapadeas (1992) showed that, if polluters act strategically this will also affect the optimal size of the ambient tax/subsidy rate. In particular, if a polluter emits more pollution in the expectation that other polluters will reduce their emissions when they expect the ambient level to exceed its target, we saw that the optimal ambient tax/subsidy rate should be larger.

Griffin and Bromley (1982) were the first to show that under certain conditions, input taxation could be as efficient as emission taxation. To be efficient, the emission production function should be known and taxes should be applied to all inputs that generate pollution according to their marginal contributions to ambient pollution. Obviously, this approach relies on the observability of inputs, however, it was noted that in the absence of uncertainty, observability of inputs combined with knowledge of the emissions function implies inferability of emissions. So, rather than using the indirect approach of taxing inputs, why not tax emissions directly? If there is uncertainty, we argued that input taxation could play much the same role as Xepapadeas' (1995) effluent tax, i.e. to shift the burden of risk to the regulator where the regulator is risk neutral and the polluters are risk averse.

Xepapadeas (1997) and Byström and Bromley (1998) draw attention to the adverse selection nature of NPS pollution, where the polluter's type affects its level of emissions and is private information to the polluter. We present Xepapadeas' model but show that with some reinterpretation Byström and Bromley's analysis follows through using the same model. In Xepapadeas' model type relates to efficiency of input use in terms of emissions production, so that, a more efficient polluter generates less emissions for a given level of input use. Although the regulator does not know an individual polluter's type, they have a prior distribution over the possible range of polluters' types. Using the adverse selection framework, Xepapadeas' derived a non-linear input tax. How this tax is constructed is shown in Figure 4-1, and it can be seen from panel (c) of this figure that the tax payment varies with the level of input. Such a tax scheme might be implementable if there are separate contracts between the regulator and each polluter governing the purchase of the optimal input level and the appropriate payment of the tax. However, this scheme will not be implementable if the input is sold in the market because there is nothing to prevent buyers that face different taxes to trade the input between themselves, thereby, undermining the effect of the tax scheme on the ambient level of pollution.

Finally, we presented a review of actual practice. To date, ambient taxes have remained largely a theoretical exercise. Experimental studies are being used to assess likely responses should such a scheme be introduced. Tradeable permit schemes where point sources trade with NPS have also emerged as a possible approach to reduce the cost of pollution control in watersheds. Examples of schemes in operation are limited to the US. Given the significant costs of implementing efficient input taxes/standards policy-makers have opted for taxes confined to one or two inputs directly related to agricultural pollution. Nitrogen taxes have been introduced in some countries although they are not widespread. However, they have met with some success in reducing nitrate pollution. They are attractive to policy-makers because their use is closely correlated with nitrate pollution and since they are purchased, taxation of nitrogen fertiliser is relatively easy which cuts down on administrative costs. In the following chapter we examine the implications of imposing a nitrogen tax on UK farmers. There is new interest in voluntary approaches to achieving environmental objectives. They may offer a way to reduce compliance as well as enforcement costs. The NSA scheme was relatively successful in meeting its objectives however, there is issue of how such schemes are to be funded.

This review is not intended to be an exhaustive list of all the contributions in the literature on NPS pollution, but to highlight the key features of NPS pollution which makes it different to point source pollution and hence, why regulation appropriate for point source is not suitable for controlling NPS pollution. The contributions in this area have been both theoretical, showing how approaches in other areas of economics are appropriate to tackling the NPS pollution problem, and empirical. The latter have attempted to show that, by implementing second-best policies, the welfare loss is not too high and may even be negative if we include transactions costs associated with implementing first-best policies. There are many issues still to be addressed in the NPS literature. The relatively higher transactions costs of implementing a first-best policy has been alluded to but not adequately analysed in the literature. The issue of learning and how it may affect the evolution of an optimal incentive scheme has not been addressed in the literature. How might the ambient tax evolve over time if there is an opportunity to learn about individuals' contributions towards the ambient level of pollution? In this review, the treatment of uncertainty relates to the relationship between emissions and the ambient level of pollution. However, there may be uncertainty relating to emissions production. Do the same factors give rise to both types of uncertainty or are they distinct? How are different types of uncertainty related to each other and how might this affect the design of an optimal instrument? Is it easier to learn about one type of uncertainty rather than another? Finally, all the studies reviewed consider one pollutant. In reality, agriculture gives rises to many types of pollutants - what might a combined instrument look like? These issues will be the subject of future research.

Chapter 5

Land-use Change and Environmental Effectiveness of Nitrogen Taxation: Towards an Integrated Approach

5.1 Introduction

The motivation for this chapter arose from a desire to link policy governing nitrogen (N) inputs in a catchment to in-stream concentrations of nitrate (NO_3). The Integrated Nitrogen model for European Catchments (INCA) is the result of joint work by the Aquatic Environments Research Centre (AERC) at the University of Reading and its European partners under the aegis of the EU-funded project 'Integrated Nitrogen Model for European Catchments' to simulate the transport and retention of N within a catchment. Output from this model includes daily estimates of streamwater NO_3 and ammonium (NH_4) concentrations and fluxes at discrete points along a river's main channel. To establish the policy link, an economic model is designed to assess how changes in N taxation affect land-use choice and N fertiliser application rates. These effects are then incorporated in INCA to determine how nitrate concentrations change as taxation changes.[1] We use this integrated approach to assess how policy may impact on fertiliser applications and land-use decisions in the Kennet catchment in the UK which has not been the subject of such a study before.

Historically, the concern for N stemmed from its link to methaemoglobinaemia or blue baby syndrome and stomach cancer. There have been no cases of blue baby syndrome in the UK since the 1970s and evidence of the link between nitrates and stomach cancer is mixed (Croll and Hayes, 1988). Of greater concern today is the contribution of excess N to the deterioration in the natural ability of an ecosystem to sustain a variety of species. Eutrophication which occurs when there is an excessive discharge of nutrients into water bodies can disturb their ecological balance by promoting algal growth which leads to the depletion of oxygen. In 1995, 30% of the rivers in the UK had high concentrations of nitrate (greater than 30 mg per litre). However, there has been a modest improvement with this figure falling to 29% in 2002.[2] However, eutrophication in rivers is not that common because inland waterways then to be phosphorous limited and eutrophication is controlled by that nutrient which is limited in supply. Nevertheless there is a concern that the accumulation of nitrogen discharged along a river length is leading to excessive loads being deposited in marine and coastal waters, where phosphorous is not limited. Concern with the deterioration in the quality of coastal waters around countries bordering the North Sea led to the passing of the OSPAR Convention in 1992. QSR (2000), a report commissioned under the auspices of the Convention, states that rivers account for 65 - 85% of the total nitrogen input to coastal waters.

Agriculture is a significant source of N pollution (Croll and Hayes 1988, Dosi and Stellin 1989, Burt and Johnes 1997, Davies 2000, Powlson 2000). We saw in Chapter 4 that this type of pollution is diffuse and hence difficult to control. The reason put

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[1] The analysis in this chapter contributes to a larger study to develop a generic version of INCA, which can be applied to a wide variety of catchments across Europe. The objective of that study is to aid the understanding of the mechanisms involved in the transport and retention of N, which will help identify the key management issues to be addressed in controlling N.

[2] Source: http://www.environment-agency.gov.uk/yourenv/eff/water/213902/river_qual/?lang=_e

forward was unobservability of individual emissions which ruled out the more traditional Pigouvian emissions tax. Chapter 4 reviewed the alternative measures which aim to control non-point source pollution. In practice, input standards and to a lesser degree input taxation have been utilised to control the excessive application of fertilisers. In Chapter 4, we outlined the conditions required for efficiency in input taxation. In particular, assuming the regulator has sufficient knowledge to implement input taxes, there should be as many different taxes as there are inputs and polluters. However, due to administrative costs and inability to maintain separate markets to prevent arbitrage, uniform taxation provides a second-best policy. We also saw in Chapter 4 that many studies found that, given the substantial transactions costs associated with implementing a first best policy, the use of a second best policy instead may not result in too high a welfare loss. In this chapter, we provide an empirical analysis of input taxation, specifically N taxation. The empirical analysis is new in the sense that an integrated catchment management approach has not been carried out before for the study catchment. While we use a well-recognised approach to analyse agri-environmental policies, i.e. linear programming we opt for a relatively new modelling technique called Positive Mathematical Programming (PMP) to calibrate the model for the reasons given below. In addition, in contrast to many studies we do not confine ourselves to addressing arable crop production alone.[3] By introducing the link between manure, grassland production and stocking capacity the model is more representative of many farm types and the relationship between nitrogen taxation and the strength of the substitution effect between different sources of nitrogen can be observed.

We describe the economic modelling approach in Section 5.2. The model is presented in Section 5.3. The description of the case-study and empirical analysis are contained in Section 5.4. In this section we also present the results and compare our findings to the results of other similar studies. Finally, Section 5.5 concludes.

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[3] Eurotools Final Report (2000) is an exception

5.2 Comparison to other studies

The literature suggests that the effect of the tax should be small and land areas allocated to crops receiving a lot of nitrogen should decrease in favour of crops receiving less nitrogen. Additionally, livestock numbers, particularly swine, will rise because manure becomes relatively more competitive as a source of nitrogen. We will briefly outline some studies which have also assessed the impact of taxation on N fertiliser.

Vatn *et. al.* (1997) also adopt an interdisciplinary approach to assess the impact of policy on N leaching rates. Their approach differs to ours in that it covers only agricultural land but spans a 20 year period from 1973 - 1992. Within their model, crop growth is a function of N and other agronomic factors. The choice variables in the economic sub-model are technology, crops and inputs, of which fertiliser is one such input. They examine three policies: 100% N tax; 50% catch crop/grass requirement and a subsidy to spring tillage. We will focus on the first policy. They state that the N tax produces a relatively modest impact on the N leaching rate. This concurs with our results, although the magnitude of their effect is considerably higher than ours - a 15% decrease in the leaching rate. A possible explanation for their much larger effect is the considerably longer time period of their study, which as we noted above, is required to capture the full effect of reducing N inputs on nitrate concentrations in the stream-water. They also note that increasing the tax rate results in fairly linear response in N leaching and that a 200% tax results in a doubling of the reduction in N leaching. As expected, the change in the relative price ratio of inorganic and organic nitrogen brought about by the tax encourages the substitution of chemical fertiliser with manure. However, those farms that already had a substantial manure capacity, did not show a significant response to the tax, probably because they were using much less chemical fertilisers to begin with.

A regional study carried out by Umstätter (1999) investigated the impact of an N tax. Similar to this study, he uses a static deterministic model. However, the environmental link is incorporated into the economic model through the inclusion of two equations governing soil erosion and nitrate concentration. The tax envisaged implies a 300%

increase in the price of nitrogen. This substantial rise in the price of nitrogen would be expected to lead to significant adjustments in terms of land-use and fertiliser applications. Umstätter found a shift from wheat and corn, crops in receipt of large applications of N, to barley which receives less. Both types of livestock - housed and grazing - increase in his model, whereas we found only housed livestock increased in response to the tax, although dairy cattle fell only very slightly. The difference in livestock results between the two studies appears to be due to the different ways in which grassland is modelled. In Umstätter, grassland yield is not a function of nitrogen applied and instead the yield is assumed to be constant. Therefore, grazing livestock in his model are also net producers of organic manure and so like housed livestock, their numbers increase in response to an increase in N taxation.

Brady (2002) sets out to examine the cost-effectiveness of an N tax already in place. In Sweden, as part of a drive to reduce the total N load to the Baltic Sea by 50% of its 1987 level, they have introduced a tax on nitrogen together with subsidies on cover crops and regulations concerning set-aside. The tax imposed comprises of approximately 30% of the price of nitrogen. To assess the impact of the tax, Brady links agricultural practices with coastal N loads through a pollution function. Unlike the economic analysis in this chapter, his model is spatially distributed. However, it includes arable land only and therefore considers only chemical fertiliser. Of the policies examined, he found the N tax to perform best and he argues that actual abatement could be improved by increasing the tax rate and eliminating the other policies. Like us, he finds that the area of set-aside increases substantially (in the absence of crop rotation requirements) in response to increased N taxation.

5.3 Economic modelling approach

Traditionally, linear programming has been used to assess policy impacts within agriculture (Walker and Swanson 1974, Horner 1975, Hartley 1986, Hanley and Lingard 1987, Fearne, Lingard, Tiffin and Barnes 1994, Moxey *et. al.* 1995). Given the link between agricultural pollution and water quality, this approach has also been used to analyse water quality issues (Braden *et. al.* 1989, Johnson *et. al.* 1991, Wossink *et. al.* 1992, Lee and Howitt 1996, Fleming and Adams 1997, Vatn *et. al.* 1997, Hanley *et. al.* 1999, Oglethorpe & Sanderson (1999), Umstatter 1999, Schou *et. al.* 2000, Falconer and Hodge 2001 and Brady 2002, 2003, Aftab *et. al.* 2003). In pursuing the profit-maximising objective, farmers carry out many activities subject to resource and institutional constraints. Policies such as taxation and regulations introduced to limit the use of polluting inputs or outputs can be easily incorporated into the model to analyse the response of farmers and ultimately how these responses relate to changes in environmental quality. Furthermore, linear programming is preferred over an econometric approach when there is a problem of insufficient data.

Although a natural starting point from which to address farm management issues, problems associated with linear programming models have led to the development of extensions to the traditional model. These problems relate to situations where (i) the solutions are infeasible or (ii) if feasible, the number of activities produced by the model fall short of the actual number of activities observed (Hazell and Norton 1986, Schniederjans 1995). Two approaches have been developed to address these shortcomings - Goal Programming addresses (i) and Positive Mathematical Programming (PMP) has been developed to overcome (ii). Goal programming derives its name from viewing constraints as goals to be attained. In this approach, the traditional linear programming model is modified by introducing new variables called positive and negative deviation variables which reflect the differences between the left hand side and right hand side of the inequality constraints. The problem is then reformulated as one of minimising the sum of the deviations. In this way a feasible solution is obtained.[4] A related approach is the minimisation of Total Absolute Deviation (MOTAD) where the objective is to minimise the variance of income subject to obtaining a given expected level of income. As such,

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[4] The interested reader is referred to Schniederjans (1995).

this approach applies to situations of risk and uncertainty. In our case we have chosen PMP as our methodology because (i) the model is deterministic and (ii) in initial runs of the model we found feasible but an insufficient number of solutions. In earlier runs of the model the solution involved the farmer allocating all the available land to the cultivation of wheat. This is an extreme case of the problem of too few solutions. Intuitively the problem is very easy to understand. In the absence of other constraints apart from land, the maximisation of profits involves the allocation of the entire land area to that activity producing the highest return. In reality, farmers pursue a number of activities reflecting the heterogenous quality of their land. In addition, farmers diversify to minimise exposure to risk. By relying too heavily on a single activity, the farmers expose themselves to increased risk of disease and increased vulnerability to unfavourable movements in prices. This tendency for over-specialisation in the solution is obviously a major drawback and a couple of options are available. The first is to tie down the variables by setting constraints to ensure that the solution values for the activities equal the observed values. This is not very satisfactory however, as it forces the model into a tight framework so that it becomes very limited in its response once different policy scenarios are introduced (Howitt 1995a, Umstätter 1999). An alternative is to introduce non-linearities into the objective function either on the cost or on the revenue side. This will improve model performance, however, we can improve the model still further by specifying the coefficients of the non-linear terms appropriately. How this is done is described later. Using the PMP approach ensures exact calibration to the chosen base year, i.e. model results match observed values. PMP was originally developed by Howitt and later described in Howitt (1995a).

5.4 The model

The model assumes a single decision-maker/farmer choosing the land allocation between various activities, numbers of livestock and nitrogen application rates to maximise profit.[5] It is assumed that all the land in this representative farm is suitable for any activity. The farmer's activities consist of the production of crops $c = 1, ..., C$, grazing livestock $k = 1, ..., K$ and housed livestock $h = 1, ..., H$. Because legumes do not receive nitrogen unlike other crops, we will distinguish between legumes and other crops by letting $c = 1$ denote legumes. Yields of crops and grassland are denoted by y_c and y_g respectively (how these are determined is described in greater detail below). Activity levels are denoted by: X_c (crops), X_g (grassland), Z_k (grazing livestock), and Z_h (housed livestock).[6] [7] Chemical/inorganic N is applied to crops at a rate of n_c kg per hectare and to grassland at a rate of n_g kg per hectare.

All prices are assumed to be exogenously given - the farmer is too small relative to the rest of the market to influence either output or input prices through purchasing decisions. Prices and variable costs are given by p and vc respectively. In the case of crops, variable costs refer to seeds, phosphate fertiliser and sprays but exclude the cost of N fertiliser. Grazing livestock variable costs refer to miscellaneous costs such as veterinary fees and bedding - concentrate costs are not included, as it is assumed that grazing livestock obtain all their feeding requirements from grass. In the case of housed livestock, variable costs refer to both concentrate and miscellaneous costs. Inorganic N is purchased at a price of Pn per kg. Since 1992, under the reform of the CAP, farmer support has gradually switched from a price oriented to an income based approach. Income support includes

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[5] The absence of farm-level data required this approach. Such an approach is not uncommon (see Moxey *et. al.* 1995). However, there are criticisms with this approach, which question the validity of such aggregation. In addition, the results obtained from such a model must be viewed in the light that such an approach overestimates the mobility of the factors of production.

[6] Commercial forestry is omitted from the analysis, as the time between planting and harvesting spans many years, whereas both the economic model and INCA cover a period of one year.

[7] Since the soil type in the study catchment is predominantly loamy (Jarvis *et. al.*, 1984), land is not distinguished by soil type.

arable area payments to crops ap_c and headage payments for livestock $hage_k$. The farmer can choose to voluntarily set-aside land X_{vs}, for which they receive a set-aside payment sp. Non-linearity is introduced into the objective function through the inclusion of the following terms: $\gamma_c X_c^2$ (for crops), $\gamma_k Z_k^2$ (for grazing livestock) and $\gamma_h Z_h^2$ (for housed livestock). These terms enter the objective function as costs and represent the hidden costs associated with each activity which are observable to the farmer but not to the modeller. How γ is defined will be shown later.

The problem to be solved by our single representative farmer is given by

$$\begin{aligned}
Max \underset{X_c, X_{vs}, Z_h, Z_k, N_c, N_g}{\Pi} &= \sum_{c=1}^{C} \left(p_c y_c + ap_c - vc_c - n_c Pn - \gamma_c X_c\right) X_c \\
&+ \sum_{h=1}^{H} \left(p_h - vc_h - \gamma_h Z_h\right) Z_h + \sum_{k=1}^{K} \left(p_k + hage_k - vc_k - \gamma_k Z_k\right) Z_k \\
&- n_g X_g Pn + sp X_{vs}
\end{aligned} \tag{5.1}$$

subject to:

$$y_c = \theta_c \left(a_c + \delta_c b_c N_c - c_c N_c^2\right), \quad \text{where } N_c = n_c + m \tag{5.2}$$

$$y_g = \theta_g \left(a_g + \delta_g b_g N_g - c_g N_g^2\right), \quad \text{where } N_g = n_g + m \tag{5.3}$$

$$\sum_{c=1}^{C} (1 + \beta) X_c + X_g + X_{vs} \leq TL \tag{5.4}$$

$$m \left(X_g + \sum_{c=2}^{C} X_c\right) \leq \sum_{h=1}^{H} Z_h n_h + \sum_{k=1}^{K} Z_k n_k \tag{5.5}$$

$$X_g = \sum_{k=1}^{K} \frac{Z_k \omega_k}{\phi y_g} \tag{5.6}$$

$$sr = \sum_{k=1}^{K} \frac{Z_k lu_k}{\phi X_g} \leq \overline{sr} \tag{5.7}$$

The first three terms in the expression for total profits in (5.1) are the net returns from crops, housed livestock and grazed livestock respectively. The last two terms in (5.1) are the total cost of nitrogen applied to grassland and the return to set-aside respectively. Other fertiliser costs for grassland such as phosphate and potash are relatively small and so are omitted from the analysis. Total profits are maximised subject to a set of constraints to which we now turn.[8]

Expressions (5.2) and (5.3) represent the yield functions for crops and grass respectively. The yields are functions of the total nitrogen applied N_c (crops) and N_g (grassland), where N_c is the sum of chemical nitrogen n_c and organic nitrogen/manure m, and N_g is the sum of chemical nitrogen n_g and organic nitrogen/manure m.[9] Chemical and organic N are assumed to be perfect substitutes for each other. We assume that manure m is applied at a uniform rate to crops (with the exception of legumes which synthesise their own nitrogen and so do not receive chemical nitrogen either) and grassland.[10] The parameter values of the yield functions are adjusted to reflect conditions prevailing in the study catchment.[11] The parameter θ shifts the yield function up or down to reflect variations in soil productivity and δ adjusts the curvature to reflect differences in nitrogen productivity.

Constraint (5.4) shows that the allocation of land to various activities is limited by the total land available TL. To obtain arable area payments referred to above, the farmer must set-aside a specified fraction of land covered by crops for which subsidies are claimed. This fraction, β may vary from year to year. Set-aside land must be managed in accordance with CAP rules. This generally means the prohibition of fertiliser applications, although manure applications are allowed to establish a green cover if the manure is generated on the farm. For the purposes of this study we assume that no fertiliser is applied to the set-aside land.

Constraint (5.5) shows that manure application to land cannot exceed manure pro-

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[8] Our measure of profits is gross margin. Gross margin is the difference between the value of output and its variable cost, i.e. it excludes fixed costs. Gross margin is widely used as a measure of profitability of enterprise (see FBD, 1997-2000 or Nix and Hill, 1994-1998).

[9] Manure is not traded and so does not have a market price.

[10] This is in line with much of the literature - Schnitkey and Miranda 1993, Roka and Hoag 1996, Fleming *et. al.* 1998 and Innes 2000. Brady (2003) states that perfect substitutability implies that land will be spread with either manure or chemical nitrogen but not both. Once all the available manure has been used up, chemical nitrogen will be purchased to fulfill any remaining requirements. However, he also states that there is evidence to suggest that farmers actually apply both chemical nitrogen and manure to each crop and that the application rate of manure tends to be uniform and a function of the land area.

[11] This approach is also used by Fleming and Adams (1997) and Brady (2002).

duction, i.e. manure is not imported into or out of the catchment. Manure production per head of livestock is given by n_k and n_h for grazing and housed livestock respectively.

According to constraint (5.6), the area of grassland must be sufficient to support grazing livestock. Constraint (5.6) is derived from equating two alternative expressions for the stocking rate per hectare: $\frac{y_g}{\omega_k} = \frac{\text{total DM/ha}}{\text{DM/head}}$, where dry matter (DM) required per head of livestock is denoted by ω_k; and $\frac{Z_k}{\phi X_k} = \frac{\text{no. of livestock}}{\text{area of grassland}}$, where X_k is the grassland allocated to livestock k. The term $\phi < 1$ reflects the assumption that not all grassland is available in any given year. At any one time, the area of grassland available for grazing will be less than the total area of grassland since a portion of it will be in rotation. We assume that all permanent grassland is in rotation, whereas temporary grass is cultivated like an annual crop and harvested each year.

Similarly to the crop support regime, there are certain restrictions governing the receipt of headage payments. To obtain livestock support, constraint (5.7) requires the stocking density be maintained below a certain level $\overline{sr}$. In 1995 this value was 2.5 livestock units per hectare, which subsequently fell to 2 from 1996 onwards (Nix and Hill, 1995). Aggregation across livestock types is possible when each livestock type is converted to its livestock unit. These conversion factors are given in Table B.6 in the Appendix.

Substituting for X_{vs} and writing down the Lagrangian we have:

$$\begin{aligned} L \;=\; & \sum_{c=1}^{C}\left(p_c y_c + ap_c - vc_c - n_c Pn - \gamma_c X_c\right) X_c + \\ & \sum_{h=1}^{H}\left(p_h - vc_h - \gamma_h Z_h\right) Z_h + \sum_{k=1}^{K}\left(p_k + hage_k - vc_k - \gamma_k Z_k\right) Z_k \\ & -n_g Pn X_g + sp\left(TL - (1+\beta)\sum_{c=1}^{C} X_c - X_g\right) \\ & +\chi\left(\sum_{h=1}^{H} Z_h n_h + \sum_{k=1}^{K} Z_k n_k - m\left(X_g + \sum_{c=2}^{C} X_c\right)\right) + \rho\left(\phi y_g X_g - \sum_{k=1}^{K} Z_k \omega_k\right) \\ & +\eta\left(\phi X_g \overline{sr} - \sum_{k=1}^{K} Z_k lu_k\right) \end{aligned}$$

where χ, ρ and η are the Lagrange multipliers on constraints (5.5), (5.6) and (5.7) respectively. Before solving the model for the empirical application, we will first solve the model analytically.

5.4.1 First-order conditions for the solution of the model

Inorganic and organic nitrogen

$$\frac{\partial L}{\partial n_c} \;:\; p_c \frac{\partial y_c}{\partial N_c} = Pn \qquad \text{for } \; c = 2, ..., C \tag{5.8}$$

$$\frac{\partial L}{\partial n_g} \;:\; \rho\phi \frac{\partial y_g}{\partial N_g} = Pn \tag{5.9}$$

$$\frac{\partial L}{\partial m} \;:\; \frac{\sum_{c=2}^{C} p_c \frac{\partial y_c}{\partial N_c} X_c + \rho\phi\left(\frac{\partial y_g}{\partial N_g}\right) X_g}{\left(X_g + \sum_{c=2}^{C} X_c\right)} = \chi \tag{5.10}$$

According to (5.8) and (5.9), inorganic N is applied up to the point at which its marginal value product is equal to its marginal cost. ρ reflects the value of increased N application in the form of increased grass yield which in turn can support a greater number of livestock, thereby, increasing the farmer's gross margin. Equation (5.10) says that the optimal amount of manure per hectare is where the marginal value of another kg of manure applied to crops and grass is equal to its marginal cost χ.

Optimal mix of land-use

$$\frac{\partial L}{\partial X_c} : p_c y_c + a p_c - v c_c - n_c P n - 2\gamma_c X_c - \chi m - sp(1+\beta) = 0; \ \forall\ c \geq 2 \quad (5.11)$$

$$\frac{\partial L}{\partial X_1} : p_1 y_1 + a p_1 - v c_1 - 2\gamma_1 X_1 - sp(1+\beta) = 0 \quad (5.12)$$

$$\frac{\partial L}{\partial X_g} : -n_g P n - sp - \chi m + \rho \phi y_g = 0 \quad (5.13)$$

Equation (5.11) relates to crops receiving N applications. The first-order conditions for legumes and grassland are given by (5.12) and (5.13) respectively. For each land-use, the optimal area is where the marginal net benefit of an extra unit of land devoted to that particular land-use is zero.

Optimal number of livestock

$$\frac{\partial L}{\partial Z_k} : p_k + hage_k - v c_k - 2\gamma_k Z_k + \chi n_k - \rho \omega_k = 0 \qquad \forall k \quad (5.14)$$

$$\frac{\partial L}{\partial Z_h} : p_h - v c_h - 2\gamma_h Z_h + \chi n_h = 0 \qquad \forall h \quad (5.15)$$

Similar to land-use, equations (5.14) and (5.15) show that for livestock the optimality conditions require marginal net benefit of the last unit to be zero. Both types of livestock produce nitrogen which is a source of value expressed as χn_k and χn_h, whereas grazing livestock also assimilate the nitrogen applied to grassland, the cost of which is reflected in the term $\rho \omega_k$.

The derivatives w.r.t. the Lagrange multipliers are:

$$\frac{\partial L}{\partial \chi} \quad : \quad \sum_{h=1}^{H} Z_h n_h + \sum_{k=1}^{K} Z_k n_k - m\left(X_g + \sum_{c=1}^{C} X_c\right) \geq 0; \qquad \chi \geq 0 \tag{5.16}$$

$$\frac{\partial L}{\partial \rho} \quad : \quad \phi y_g X_g - \sum_{k=1}^{K} Z_k \omega_k \geq 0; \qquad \rho \geq 0 \tag{5.17}$$

$$\frac{\partial L}{\partial \eta} \quad : \quad \phi X_g \overline{sr} - \sum_{k=1}^{K} Z_k l u_k \geq 0; \qquad \eta \geq 0 \tag{5.18}$$

From (5.2) and (5.3) we also have

$$\frac{\partial y_c}{\partial N_c} = \theta_c \left(\delta_c b_c - 2 c_c N_c\right) \tag{5.19}$$

$$\frac{\partial y_g}{\partial N_g} = \theta_g \left(\delta_g b_g - 2 c_g N_g\right) \tag{5.20}$$

Calibration of empirical yield functions

Because not all the parameter values of the model are known, we need to solve/calibrate them and this section will analyse how this is done. To do the calibration, we require base year data which we denote by the superscript ^{o}. In this section we wish to determine the values of θ_c, δ_c, θ_g and δ_g. Using (5.2), (5.8) and (5.19), the values of δ_c and θ_c can be determined. We obtain

$$\delta_c^o = \frac{2 y_c^o c_c N_c^o p_c^o + a_c P n^o - c_c P n^o N_c^{o2}}{b_c \left(y_c^o p_c^o - P n^o N_c^o\right)} \tag{5.21}$$

$$\theta_c^o = \frac{y_c^o}{a_c + \delta_c b_c N_c^o - c_c N_c^{o2}} \tag{5.22}$$

Using equations (5.3), (5.9), (5.13) and (5.20), we can obtain expressions for δ_g and θ_g:

$$\delta_g^o = \frac{2c_g N_g^o \left(n_g^o Pn^o + sp^o + \chi m^o\right) + Pn^o \left(a_g - c_g N_g^{o2}\right)}{b_g sp^o + m^o \left(\chi - Pn^o\right)} \tag{5.23}$$

$$\theta_g^o = \frac{y_g^o}{a_g + \delta_g b_g N_g^o - c_g N_g^{o2}} \tag{5.24}$$

The parameter values of a_c, a_g, b_c, b_g, c_c and c_g are known and fixed across years. Thus, θ_c and δ_c are fully determined, whereas δ_g and θ_g are not because χ is still unknown. To solve for the value of χ in the base year, we use first-order conditions (5.8), (5.9) and (5.10) to show that the shadow value of manure is equal to the nitrogen price, i.e. $\chi^o = Pn^o$. This is as we would expect, because by assumption they are perfect substitutes for each other. If the shadow value of manure was less than the nitrogen price, the farmer would continue to use manure until at the margin the two prices are equal. Note that we do not calibrate the yield function for legumes because, as stated already, they do not receive N applications. Instead we observe the base year yield a_c and set $\theta_c = 1$ and $\delta_c = 0$ for legumes.

Calibration of activity levels

Using equations (5.11), (5.14) and (5.15), we can solve for each γ :

$$\gamma_1^o = \frac{p_1^o y_1^o + ap_1^o - vc_1^o - sp^o}{2X_1^o} \tag{5.25}$$

$$\gamma_c^o = \frac{p_c^o y_c^o + ap_c^o - vc_c^o - n_c^o Pn^o - sp^o - \chi^o m^o}{2X_c^o} \qquad \forall \ c \geq 2 \tag{5.26}$$

$$\gamma_h^o = \frac{p_h^o - vc_h^o + \chi^o n_h}{2Z_h^o} \qquad \forall \ h \tag{5.27}$$

$$\gamma_k^o = \frac{p_k^o + hage_k^o - vc_k^o + \chi^o n_k - \rho^o \omega_k^o}{2Z_k^o} \qquad \forall \ k \tag{5.28}$$

The absence of superscripts on n_k and n_h indicate that these parameters are assumed to be fixed across years. Thus, as in the case of the crop adjustment parameters, the γ terms are also fully determined.

5.5 Empirical study

5.5.1 Study catchment

The study catchment is the Kennet River and its watershed (Figure 5-1). The Kennet is a chalk groundwater fed tributary of the mid part of the River Thames in the south east of England. In terms of the management issues it presents, the Kennet catchment is typical of many lowland permeable catchments within the UK (Wade *et. al.* 2002). It is a rural catchment with arable farming being the major land-use. The catchment extends over an area of 113,800 ha of which almost 60% is devoted to agricultural production. Within this, more than 2/3 is allocated to arable farming (DEFRA, 2001). There are three types of grassland in the Kennet catchment - permanent, temporary and rough. The area of rough grassland is negligible relative to the catchment size so we omit it. In the empirical model, we use a weighted average of the N applied to grassland, where the weights are the percentage areas (75:25) covered by permanent and temporary grassland. The upper River Kennet is designated a Site of Special Scientific Interest due to its outstanding chalk river plant and animal communities (Wade *et. al.* 2002). In addition, there is a Nitrate Sensitive Area located within the catchment at Osborne St. George.

According to Croll and Hayes (1988), nitrate concentrations tend to be highest in arable areas, which are located mainly in the south and east of the UK. Low average rainfall in the south east of the UK contribute to increased concentrations of nitrates in these areas. Analysis of the water quality data shows that arable farming is a major source of nitrates in the Kennet system and the mean streamwater NO_3 concentration is approximately 6 and 4 mg of nitrogen per litre in the upper and lower reaches of the Kennet respectively (Wade *et. al.* 2002). Although this is well below the limit set down

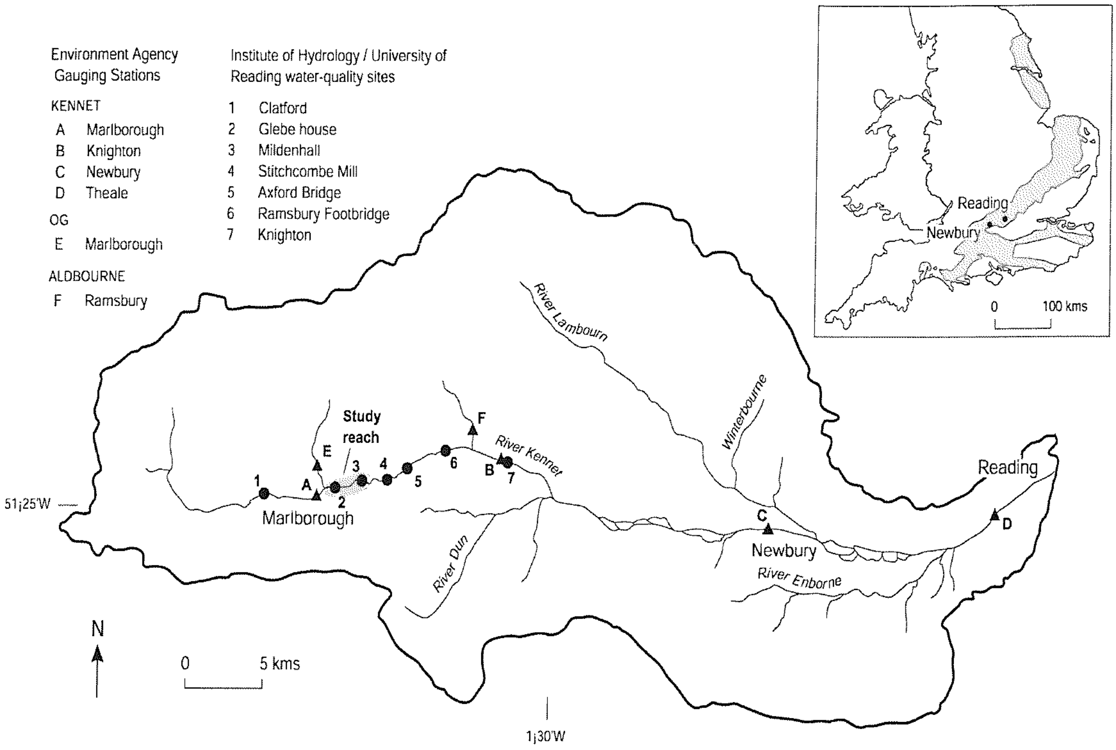

Figure 5-1: The Kennet Catchment

in the Nitrate Directive of 11 mg of nitrogen per litre (CEC, 1991), nevertheless, there are concerns regarding the ecological status of the River Kennet. Over the last 10 years, concerns have been voiced about its apparent ecological deterioration. In particular, the poor growth of *Ranunculus* together with the unsightly growth of epiphytes downstream of Marlborough, one of the four main towns lying along the Kennet, have raised concerns (Wright 2002, cited in Wade *et. al.* 2002). Poor growth of *Ranunculus* is a possible indicator of nitrate pollution. The adverse impact of eutrophication on *Ranunculus* is reported in DEFRA (2002). Combined with this disturbance in the ecological balance of the river system, more numerous drought events (1991-2 and 1996-7) caused by increased variations in climate can exacerbate the impact of elevated NO_3 concentrations by reducing the capacity for dilution (Wade *et. al.* 2002). These factors impinge on water abstraction issues, where the desire is to avail of the water resource without upsetting the environmental integrity of the catchment.

5.5.2 The data

In the absence of survey data, all data are obtained from secondary sources and are not Kennet specific. This is a drawback of the model, however, the Kennet is a fairly typical lowland catchment as stated above and, given the relatively hi-tech nature of modern farming together with the wide dissemination of agricultural advice, it is expected that national average N inputs per crop type are representative of fertilisation practice in the Kennet. Prices used are for the UK as a whole, however, this should not matter because, as stated above, the farmer is a price-taker and national prices are assumed to be fairly representative of regional prices.

Five years' data were collected and cover the period 1995-1999. All financial data were taken from the Farm Management Pocketbook (Nix and Hill, 1994-1998), which forecasts one year ahead all data pertaining to agricultural production and relates to the UK as a whole. Yield data for crops were obtained from the Farm Business Data (FBD, 1997-2000) and apply to the Reading Province, which includes the Kennet catchment.

An approximation of grass yield and N inputs characteristic of the area were obtained from Stiller (2003). Numbers of livestock and areas of crops grown within the catchment were provided by the Department of the Environment, Food and Rural Affairs (DEFRA, 2001). This data is derived from the Agricultural Census which is carried out every June. Data on the application of inorganic N were obtained from the British Survey of Fertiliser Practice (BSFP, 1996-2000). This relates to average inorganic N applications for England and Wales. As there are no crop specific data for average applications of organic N because this is closely related to the availability of organic N, an average figure was estimated using observed livestock, nitrogen production per head coefficients and land area receiving N. Figures for N production per head were obtained from MAFF (2000). The dry matter requirement per head of livestock is determined by combining livestock units and dry matter requirement for dairy which was obtained from CAB (1980). The data are contained in Appendix B.

5.5.3 Empirical procedure

In Section 5.3.1 we outlined the analytical solution to the model. There we also showed how the terms involved in the calibration of the model are determined. To solve the problem numerically, we adopt the PMP approach discussed in Section 5.2.[12] This approach, as outlined by Howitt (1995a,b), is a three step procedure. Stage one involves the maximisation of the objective function (5.1) excluding the non-linear terms subject to resource and institutional constraints (5.2) -(5.7) and calibration constraints. Calibration constraints limit each activity to its observed value, i.e. for the general case of activity q, the calibration constraint is specified as $q \leq q^o + \varepsilon$, where ε ensures that the calibration constraint does not bind simultaneously with one of the other constraints at the observed activity level. The shadow value of the calibration constraint, denoted by λ, is the additional marginal 'hidden' costs required to ensure that at the margin, the returns to all land-uses are equal. Hence, stage one of the procedure yields the value of

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[12] The economic model is numerically solved in GAMS using the MINOS5 solver.

λ for each of the activities to be calibrated. Stage two of the process defines γ. The hidden costs associated with activity q are parameterised by γq^2. The marginal hidden cost λ is therefore equal to $2\gamma q$. Rearranging, we find that $\gamma = \frac{\lambda}{2q}$. Comparison of this expression with the analytical expressions for γ derived from the first-order conditions (5.25) - (5.28) shows that the numerator in each of these expressions is equivalent to λ. Hence, at the solution the marginal hidden cost of each activity is equal to its marginal net benefit. Stage three involves modifying the problem as characterised by (5.1) - (5.7) (i.e. omitting the calibration constraints) to incorporate a given policy scenario and obtaining its solution.

Following this process, the model is calibrated to a base year and the values of θ_c^o, δ_c^o, θ_g^o, δ_g^o, γ_c^o, γ_k^o and γ_h^o are used with data from other years to see how well the model predicts land-use and livestock decisions for those years. To capture how well the model works, we estimate a summary statistic - the weighted average of the absolute percentage differences between the observed and the simulated values for these years. For example, the entry for 1995 in Table 5.1 refers to the weighted average of the absolute deviations for the years 1996 to 1999 inclusive. To eliminate the adverse effect of significant variations in prices between years on the performance of the calibrated model compared to observed data, the calibration procedure was also carried out using the averages of years as a 'base year'. The years chosen for this purpose are shown in Table 5.1. In both cases, the averaged data include 1996 and 1999 data because these years were on average characterised by the highest and lowest returns to activities respectively. These summary statistics are presented in Table 5.1.

The figures in the 'Overall' column relate to the annual average prediction error across years. For example, in the case of the 1995 calibration, a weighted sum of absolute deviations for crops, livestock and nitrogen is obtained for each of the four years, 1996 - 1999. These weighted sums are then averaged to obtain an annual average prediction error.[13] In the 'Nitrogen only' column, the annual average prediction error is estimated

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[13] The weights are worked out as follows: crop weight = crop area/total land area; livestock weight =

Table 5.1: Calibration Results

Calibration Year	Overall	Nitrogen only
1995	33	4
1996	56	8
1997	106	38
1998	82	19
1999	129	16
average of 1996 & 1999	70	26
average of 1996, 1997 & 1999	35	4

using absolute deviations for nitrogen applications only. It is clear from the table that the calibrations based on 1995 and the three year average performed the best, while the calibration based on 1999 was the worst overall, with the 1997 calibration the worst for nitrogen only. On the basis of this, calibration based on 1995 was chosen to perform the policy scenarios as it marginally beat the three year average overall. We can assess how well the 1995 calibration model performs by estimating the percentage absolute deviation and comparing these figures to reported values. Percentage absolute deviation (PAD) is defined as the average absolute deviation between the simulated and observed value divided by the average observed value.[14] Norton and Schiefer (1980) suggest that PAD values of 13% are promising. Moxey *et. al.* (1995) report values between 10 and 14%. We found values for nitrogen application under 10% apart from 1999 when the value was 38%. PAD values for arable and livestock were in the range of 7% to 38% for the years 1996, 1997 and 1998. Similarly to the case for nitrogen the PAD figures for 1999 were quite high. This trend is also noted in Moxey *et. al.* (1995) who state that the comparison between calibrated and observed data worsens as the distance from the base year increases. Thus, we can conclude that the 1995 calibration model performs very well for nitrogen applications but less well for arable and livestock. The calibrated parameter

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total livestock units for each livestock type/total livestock units; nitrogen weight = (nitrogen application x crop area)/total nitrogen application for all crops. Note that the livestock weights do not include housed livestock because livestock unit equivalents for pigs and sows are not available.

[14] In constrast to the goodness of fit measures presented in Table 5.1 which provide an overall summary of the goodness of fit of the calibration model across the period, PAD measures goodness of fit for each year of a given period.

values for 1995 are contained in Table 5.2.

Table 5.2: Calibrated Parameters for 1995

Activity	γ	θ	δ
wheat	0.005	1.510	0.661
w-barley	0.011	1.166	0.801
s-barley	0.04	0.83	1.274
oilseed	0.047	1.261	2.695
linseed	0.076	0.703	1.666
legumes	0.048		
grassland		0.78	2.429
dairy	0.048		
beef	0.017		
18 mth old beef	0.013		
ewes	5.9×10^{-5}		
goats	0.425		
pigs	1.4×10^{-4}		
sows	0.02		

5.5.4 Taxation Scenarios

In the model, we propose a tax on the N content of fertiliser rather than on fertiliser in general. This approach is supported by theory, which says that the instrument should be directed as closely as possible to the target of policy. Placing a tax on fertiliser in general rather than on the N content in Finland led to the increased use of fertiliser with a higher nutrient content (Rougour *et. al.* 2001). In this study, we investigate the impact of an N tax varying between 25% and 200% of the price of N fertiliser which spans the range used by the majority of other studies. The Lagrangian function of the model is modified to reflect the introduction of a tax t on the N content of fertiliser.

$$\begin{aligned}
L \; = \; & \sum_{c=1}^{C} \left(p_c y_c + ap_c - vc_c - n_c(Pn + t) - \gamma_c X_c\right) X_c + \\
& \sum_{h=1}^{H} \left(p_h - vc_h - \gamma_h Z_h\right) Z_h + \sum_{k=1}^{K} \left(p_k + hage_k - vc_k - \gamma_k Z_k\right) Z_k \\
& - n_g \left(Pn + t\right) X_g + sp \left(TL - (1+\beta) \sum_{c=1}^{C} X_c - X_g \right) \\
& + \chi \left(\sum_{h=1}^{H} Z_h n_h + \sum_{k=1}^{K} Z_k n_k - m \left(X_g + \sum_{c=2}^{C} X_c \right) \right) + \rho \left(\phi y_g X_g - \sum_{k=1}^{K} Z_k \omega_k \right) \\
& + \eta \left(\phi X_g \overline{sr} - \sum_{k=1}^{K} Z_k lu_k \right)
\end{aligned}$$

Results

The model used to analyse N taxation scenarios employs 1995 calibration parameters as stated above and 1998 data.[15] In Table 5.3 the percentage changes in the broad categories of land-use and grazing livestock for each tax rate are presented. In Tables 5.4 and 5.5 a more detailed breakdown of the changes within land-uses and livestock are presented.

Table 5.3: Impact of Taxation on Broad Categories of Activities

Land-use	25%	50%	75%	100%	200%
Crops receiving N	-9	-17	-25	-33	-59
Land-uses not receiving N	17	33	48	63	97
Grazing livestock	-10	-19	-29	-37	-44
Grassland	-9	-18	-27	-36	-40

It is evident from Table 5.3 that the area of land under crops that receive N decreases linearly up to the highest tax rate. The percentage reduction in grazing livestock is greater than the reduction in grassland area indicating a fall in the stocking rate. Hence,

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[15] The reason for choosing 1998 data is that, when we link the economic model with INCA, the data for both models should relate to one year and 1998 is the only year for which hydrological data for the Kennet was available.

in response to the increase in the price of N fertiliser, grassland is less intensively used than before.

Table 5.4: Impact of Taxation on Crops

Crops	Land Area Reduction					N Reduction				
	25%	50%	75%	100%	200%	25%	50%	75%	100%	200%
wheat	12	23	33	43	79	7	13	20	28	59
w-barley	9	18	26	34	60	8	16	25	35	74
s-barley	6	11	17	21	37	10	22	34	48	100
oilseed	3	6	9	12	23	6	12	18	25	54
linseed	3	5	7	9	22	30	62	96	100	100

Table 5.4 shows that with the exception of oilseeds, the area reduction for each crop is inversely related to the reduction in N fertiliser applied to it. For example, linseed experiences the smallest reduction in area while suffering the largest drop in fertiliser application. This suggests that as we would expect, land and fertiliser are substitutes for each other. It appears that, as the tax on N increases the farmer compensates falling yields as a result of reduced N applications by preserving the area of land allocated to crops. In contrast, the farmer is reluctant to reduce fertiliser applications and the area of land allocated to oilseeds in response to the tax. A possible reason why oilseeds do not fit in with the general pattern is because they are highly profitable. In contrast to what we may expect the percentage reduction in nitrogen does not correspond with intensity of nitrogen use, i.e. the percentage reduction is higher for crops which receive lower applications of nitrogen (see Tables B.1 - B.5 in Appendix B). However, the expected pattern does emerge when we consider total nitrogen applied, i.e. the greater the total application of nitrogen to a crop type the greater the reduction in nitrogen applied.

All the figures in Table 5.5 represent a percentage reduction in grazing livestock. Ewes suffer the largest reduction reflecting the fact that they offer the lowest return to the farmer and the effect of the tax is to make them even less profitable, so that, at the highest tax rate the farmer would choose not to have any ewes. Beef is the next least profitable enterprise and shows a large reduction at the 50% tax rate. The impact of the

Table 5.5: Percentage Reduction in Livestock in response to Tax

Grazing Livestock	25%	50%	75%	100%	200%
dairy	1	1	2	3	5
beef	10	19	28	37	67
18 mth old beef	3	5	8	10	19
ewes	25	49	72	94	100
goats	1	2	2	3	5

tax on other livestock types is small even at the highest rate of 200%.

In contrast to the impact of the N tax on grazing livestock, a rise in the price of nitrogen encourages an increase in the numbers of pigs and sows. The reason for this is that, housed livestock are net producers of manure, which becomes a relatively cheaper source of nitrogen as the tax on chemical nitrogen increases. The percentage rise in pigs ranges from 7% for a 25% rise in the price of nitrogen to a 51% increase for the 200% tax on nitrogen. The substantial rise in pig numbers points to a potential cause for concern. As housed livestock increases, issues relating to the storage of manure arise. Accidental seepages from slurry pits are more likely as storage capacity rises. Such pollution incidents tend to be much more serious due to their toxicity and potentially greater discharge volume at any one time than pollution from N leaching or surface run-off. Thus, regulations governing maximum storage capacity or a manure tax may be appropriate to cap the rise in pig numbers.

The impact of a joint tax on both sources of N was also modelled. Equal rates of taxation on both sources of N capped pig numbers at the level observed in the absence of any taxation on N. An increase in the price of organic N makes inorganic N more attractive as they are substitutes. Differential taxation with a relatively higher tax on inorganic N restricts the rise in pig numbers, while encouraging a more efficient use of organic N. Although a manure tax may usefully contribute to a comprehensive policy to curtail N use, it would be difficult to impose for the reasons discussed in the previous chapter. The application of manure to land is unobservable.[16] Estimates of manure

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[16] So is the application of inorganic N for every farmer and the use of an inorganic N tax implicitly

application may be obtained from livestock numbers and data on manure production per head. However, although it has been assumed for the purpose of this model that all manure produced is applied to the land, in reality some farmers may import/export their manure supply from/to other farms. Thus, in practice a manure tax would be difficult to implement.

In terms of land-uses not receiving N, the area of set-aside land increases commensurately with the decrease in crop and grassland area. The area of legumes shows no change regardless of the level of taxation. This is unexpected because legumes become more competitive as the price of nitrogen increases as it does not receive any nitrogen. The explanation for this appears to be that the model is insufficiently non-linear (the yield function is linear for legumes), so the choice of which land-use to switch into in response to N taxation is between two levels of returns and whichever is the highest is chosen. At all levels of taxation, the return to set-aside land is higher than the return to legumes. This problem of linearity, is similar to the problem we had at the outset which provided the rationale for using the PMP approach. To mitigate this problem, an econometric approach using non-linear estimation to estimate the values of γ, θ and δ for each activity could be used. Although this approach would not yield exact calibration, the model if estimated in this way might be more flexible in response to policy scenarios. However, the use of non-linear estimation is not possible due to the short time period which the data available cover, which was why we opted for the PMP approach in the first place. From the point of view of this study, the lack of response of legumes to N taxation is not a problem because land-use types in the economic model are aggregated into broad categories for the purpose of running INCA. How this is done is discussed below.

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assumes that the purchase of N fertiliser and N application coincide. This may not necessarily be the case, which makes the control of N pollution via such a tax more difficult and less efficient.

5.5.5 Integration with INCA

The economic analysis has enabled us to assess the changes in N inputs within agriculture arising as a result of rising N taxation. INCA provides a tool to assess the contribution of N inputs from a range of sources including agriculture to catchment N pools and river nitrate concentrations (Whitehead *et. al.* 1998a). To assess how these changes in tax rates affect stream-water nitrate concentrations, the two models are linked through land-use distribution and fertiliser applications - the two factors which influence the magnitude of N inputs. Before we present the results from INCA, it will be helpful to briefly describe the INCA model.[17]

INCA simulates the key factors and processes affecting the dynamics of N in both the land and in-stream components of river catchments (Whitehead *et. al.*, 1998a,b). Sources of N are atmospheric deposition, fertiliser additions, mineralisation, nitrification and nitrogen fixation. N sinks consist of plant uptake, immobilisation and denitrification. A schematic of the sources and sinks involved is shown in Figure 5.2. Excess N is available for leaching to groundwater. These sources and sinks are differentiated by land-use type and varied according to environmental conditions such as soil moisture and temperature. The model provides for historical patterns of N additions and subtractions by including a stock of N in the soil, groundwater and stream reaches. The model simulates the flow of water through different land-use types to deliver the N load to the river system. The N load is modified by abstractions and discharges, as well as by in-stream processes of nitrification and de-nitrification.

Land class in INCA is categorised according to the Institute of Terrestrial Ecology (ITE) land-use classification scheme. The ITE land-use classification scheme consists of arable, urban, forest, short-vegetation (ungrazed), short-vegetation (grazed and not fertilised) and short-vegetation (grazed and fertilised). For the purpose of the INCA model, the Kennet River is divided into sections called reaches and associated with each

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[17] Readers interested in a more in-depth explanation of INCA are referred to Whitehead *et. al.* (1998a,b) and Wade *et. al.* (2002).

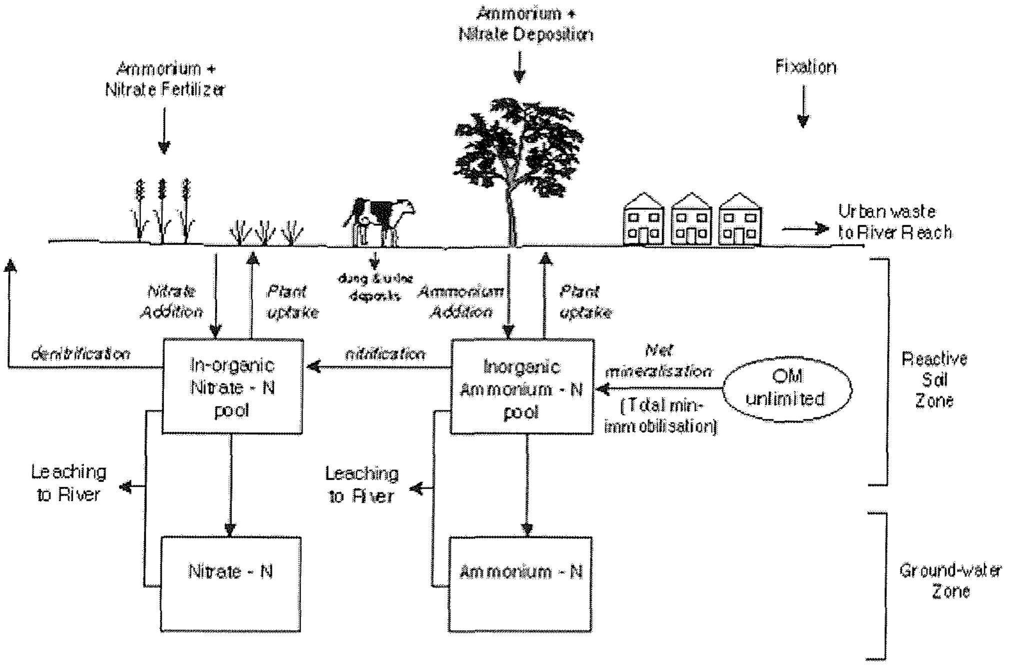

Figure 5-2: Nitrogen inputs, processes and outputs in the soil and groundwater system (taken from Whitehead *et. al.* 1998a)

reach is a subcatchment. The area of each land-use within each subcatchment is estimated using Geographical Information Systems (GIS). Factors relating to each land-use type include fertiliser application, N transformation process rates, initial values of nitrate concentrations in soil and groundwater, etc.

Several N models have been developed in recent years. Models such as MAGIC-WAND (Cosby *et. al.* 1985, Jenkins *et. al.* 1996), MERLIN (Cosby *et. al.* 1997) and PNET-CN (Postek *et. al.* 1995) focus on upland systems, forests or particular processes. There are models that are based on lowland agricultural systems (e.g. Addiscott and Whitmore 1987, Cooper *et. al.* 1993). QUASAR (Whitehead *et. al.* 1997, Whitehead and Williams 1984) address N dynamics in rivers specifically. However, despite all these developments there are still very few models that integrate both river and catchment processes. An exception is a model by Lunn (1995) but it is driven by a complex hydrological model, SHE (Abbot *et. al.*, 1986). Thus, the main advantages of INCA are that it encompasses both catchment and river processes and it is driven by a fairly simple hydrological model which cuts down on the number of parameters to be calibrated before the model can be used for scenario analysis.[18]

Since INCA was developed using a set of land-use classifications reflecting all land-use types in the catchment, not just agricultural, the first step in linking the two models is to reclassify the land-uses in the economic model. The re-classification of agricultural land-uses for INCA is shown in Table 5.6.

Table 5.6: Mapping of Land-use Types

Economic Model	INCA
wheat w-barley s-barley oilseed linseed	arable
pulses set-aside	forest
grassland	short vegetation, grazed and fertilised

All crops receiving N are grouped under arable, whereas legumes and set-aside are grouped under the heading of forest because these land-use types do not receive fertiliser applications. In the economic model it was assumed that all grassland is grazed and fertilised. To obtain the baseline scenario, the areas of land-use types obtained from the economic model when there is no tax on nitrogen were aggregated accordingly. The results are given in Table 5.7.

The area of urban land is obtained from Wade *et. al.* (2002). Since the total area of the catchment is 113,800 ha, the remaining land area is allocated under the heading

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[18] It is very difficult to compare the relative predictive accuracy of these models because of the uncertainty in deriving the optimum parameter set for each model (Bevan, 1993).

Table 5.7: Baseline Land-use Areas

Land-use Type	Area
arable	27355
forest	25328
short veg. grazed & fertilised	18714
short veg. ungrazed & unfertilised	0
short veg. grazed & unfertilised	37266
urban	5137

of short vegetation (grazed and unfertilised).[19] Using the information in Table 5.7 and the percentage distribution of land classes within each of the subcatchments contained in Wade *et. al.* (2002), we estimate the areas of each land-use (based on the aggregation of agricultural land-uses) within each subcatchment for the baseline scenario.

The baseline scenario also requires fertiliser inputs for each land-use type. In INCA only two land-use types receive N fertiliser applications - arable and fertilised grassland. In the case of arable, a weighted average of the application of inorganic and organic fertiliser to the five crops receiving N fertiliser is estimated. In the case of grassland, the total N fertiliser input is simply the sum of organic and inorganic N applications (see Table 5.8).

Results from INCA

The INCA model is run for the baseline scenario as well as for the five taxation scenarios. The percentage breakdown of land-uses within subcatchments and fertiliser inputs corresponding to each tax rate are calculated in the same way as described above for the baseline scenario. The results are shown in Table 5.8 and relate to the subcatchment associated with reach 11 of the Kennet River.

Table 5.8 shows that there is an imperceptible change in the leaching rate as the

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[19] The preferred allocation of residual land would have been to ungrazed and unfertilised, however, according to Wade *et. al.* (2002) there is no such grassland in the Kennet catchment. Although the residual land category is grazed unfertilised grassland (which includes moor, heathland and bracken), we make the simplifying assumption that this area of land is not available for grazing by livestock owned by our representative farmer.

Table 5.8: N Input and Leaching Rates in response to changes in N Taxation

	Total N Fertiliser Applied (kg/ha/yr)		NO_3 Leaching (kg/ha/yr)	
	Arable	Grass	Arable	Grass
Base	186	148	30.7	16.7
25%	178	142	30.7	16.6
50%	171	137	30.6	16.6
75%	162	132	30.6	16.6
100%	155	127	30.6	16.6
200%	127	108	30.6	16.6

application of fertiliser changes and this change is well within the natural variability of the leaching rate. Despite the absence of any effect on the leaching rate, Table 5.9 shows that varying the price of nitrogen does have some effect on the mean concentration of nitrates in the river.

Table 5.9: Mean Concentration of Nitrates (mg/l)

	Reach		
	1	11	25
Base	6.32	6.08	4.36
25%	6.21	5.96	4.22
50%	6.02	5.84	4.08
75%	5.87	5.72	3.97
100%	5.64	5.6	3.83
200%	4.94	5.05	3.45

This apparent contradiction, i.e. no effect on leaching rates but an effect on nitrate concentrations, is due to the importance of groundwater in the Kennet catchment. Approximately 80% of the Kennet catchment is underlain by chalk and as such the system is dominated by groundwater inputs. To achieve a good simulation of the observed streamwater nitrate concentrations, the groundwater concentration of arable land is set at a relatively high level of 10mg per litre (Wade, 2003). This is significantly higher than for other land-uses, namely, grassland and forest, which were set at between 4 and 6 mg per litre. The latter concentration is the same as that obtained from a borehole located in the middle of the catchment. It is uncertain whether the value of 10 mg per litre is accurate due to lack of borehole data. As a consequence, the model simulations suggest the predominance of groundwater inputs in controlling stream-water nitrate concentrations, implying that changes in fertiliser inputs may have little effect. Furthermore, in contrast to the more usual notion of leaching, which is the movement of solute down through the soil zone into the groundwater table, leaching in INCA is defined as the export of nitrogen from both the soil and groundwater zones into the river. Thus, the predominance of groundwater and the assumption of relatively high initial concentration of nitrates in it appears to explain the negligible impact of changes in N inputs on the leaching rate.

The reduction in nitrate concentrations, albeit small, occurs as a result of the switch to land receiving lower fertiliser applications which implies an increase in the proportion of land-uses with lower initial groundwater nitrogen concentrations. For example, as the percentage of set-aside increases, the input of groundwater with a concentration of nitrate in the range of 4 to 6 mg per litre increases and the input of groundwater with a concentration of 10 mg per litre decreases.

In general, the response of stream-water nitrate concentration to changes in nitrogen inputs would be expected to be delayed. Note that the INCA model produces a daily time series of nitrate concentrations over the period of a year. However, as stated in the previous chapter, the lag time between discharge of emissions at source and the impact of those emissions in the receptor can be considerable, often much longer than a year. As noted above, the response is further dampened by the magnitude of groundwater inputs. This suggests that INCA should cover a much longer time period and that economic instruments should take account of the size of the groundwater zone in a catchment.

5.6 Conclusion

This study has examined the potential reduction in nitrate concentrations due to various taxes. Before we could proceed to analyse the impact of N taxation on decisions relating to fertiliser usage and land-use distribution, it was necessary to calibrate the model to a base year. The purpose of calibration is to generate a model which produces base year results relatively accurately, otherwise, the results of policy simulations will have little relevance. As stated in the introduction few studies that use the PMP approach include livestock and hence ignore the linkages between manure, grassland production and stocking capacity. Yield functions for crops and grass as well as activity levels were calibrated. Before empirically calibrating the model using Howitt's (1995b) approach, we presented the analytical solution of the calibration variables and highlighted the link between this and Howitt's method. We tested the performance of calibrations based on each of the years of the study as well as on averages of years and found the 1995 calibration performed best.

Having calibrated the model we considered tax rates ranging from 25% to 200% of the price of nitrogen. The economic model showed a substantial redistribution of land-use towards set-aside, especially for higher tax rates. Also, farmers switched towards manure as a relatively cheaper source of nitrogen. Grazing livestock are both consumers and producers of nitrogen and the net effect of the tax on nitrogen was to reduce their numbers. However, housed livestock which are producers only of nitrogen increase in numbers. In the absence of regulations on storage capacity, it was noted that this increase may give cause for concern as the potential for N leakage increases. Although a tax on manure would cap the rise in pig numbers, such a tax would be difficult to implement.

The output from the economic model - land-use distribution and fertiliser applications, provided data to run INCA, the hydrological model which enabled us to assess how changes in N inputs in the catchment result in changes in nitrate concentrations in the River Kennet. Even the highest tax produced a modest impact on nitrate concentrations with a negligible impact on leaching rates. The dominance of the groundwater zone in the Kennet as well as the short time period which the model covers were the reasons put forward for the modest changes in nitrate concentrations resulting from taxation.

The findings in this analysis mirror some of the results of previous studies - decrease in crops receiving a lot of nitrogen, increase in the use of manure and increase in certain types of livestock. However, there were differences - grazing livestock fell and the entire reduction in crop land area was put into set-aside.

There are some limitations of this study which should be flagged. One such limitation is the lack of catchment specific data. However, given the relative uniformity of modern agriculture in the UK, it is not expected that there would be a large variation in agricultural practices and so the use of national level data in place of catchment specific data may not be too problematic. Where it probably matters a lot is in the parameter specification of yield functions as this will have a large influence on how taxation affects the decision to reduce N applications. A more important issue in relation to yield functions is perhaps their functional form. As yet, there is no consensus on the correct functional form to use (Brady 2003).[20] Yet another factor to be taken into account is whether modelling yield as a function of nitrogen alone is accurate. A weakness of the PMP approach as specified above is that the costs implied in the non-linear component cannot be directly related to specific production factors (Bauer and Kasnakoglu, 1990). Futhermore, the inclusion of these costs means that the total profit in the calibrated model falls short of the actual gross margin (Umstätter, 1999). This makes it difficult to assess the impact of the nitrogen tax on farmers' welfare. The static nature of the economic model and the limited time period covered by INCA mean that we fail to capture the relationship between behavioural responses to the N tax across years and the long-term response of the stream-water nitrate concentration to N tax policy. Although not taken into account in this study, the inclusion of management practices which differ in their nitrogen intensity may expand the range of possible responses to a nitrogen tax.

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[20] Eriksen (2001) and Brady (2002) use a quadratic form, whereas England (1986) and Sylvester-Bradley *et. al.* (1987) use a linear plus exponential form.

Chapter 6

Conclusion

As stated in the Introduction, this thesis has explored how the introduction of appropriate incentives can modify behaviour in the realm of the environment. The two main areas of the environment focused upon were GM and non-point source pollution. Within these areas, policies relating to biodiversity, R&D and the taxation of non-point source pollution both generally and specifically within agriculture, have been examined. The development of policy prescriptions within the environmental context require a good understanding of natural phenomena. This is what makes the study of environmental economics such a demanding and interesting discipline. In all of the analyses carried out in this thesis, we have attempted to carefully address the issues relevant to the objective of our study.

Chapter 2 considered a very simple model of the relationship between species diversity and their food supplies. The model assumed that species variety is directly related to the number of crops for which a critical level of the non-GM variety of the crop is grown. Without this assumption, it is conceptually possible for all but one crop to be grown as GM and any level of biodiversity to be sustained as long as a sufficient amount of the non-GM crop is grown. Thus, if insects are non-discriminatory in their feeding habits, intervention is confined to subsidising the growth of non-GM crops. If on the otherhand, insects are specialised feeders, depending on the current level of GM-only crops grown, intervention in the form of a subsidy to farmers to grow non-GM crops may be required along with a tax on R&D firms to internalise the externality of species loss. Thus, intervention in the R&D market is directly a result of how we modelled the link between species diversity and the supply of non-GM crops. By modelling it in this way, the proportion of crops for which GM technology is made available becomes an important variable and its optimal level is determined by the equality between the return to R&D and, depending on the amount of GM-only crops grown, the marginal cost of species loss or the level of the subsidy required to sustain a critical level of non-GM crops. Thus, this chapter showed the importance of modelling biological phenomena in determining policy prescriptions and how adopting different models can lead to very different results.

In Chapter 3 we intensified our focus on the R&D market and examined the strategic interaction between firms when they take account of the likelihood that pests will develop resistance to their technologies. We saw that experience of pathogen resistance to antiobiotics and pest resistance to chemical pesticides gave us every reason to believe that pests would also develop resistance to pest protected GM crops. In fact there is some laboratory and field evidence that this is already occurring.

The analysis in Chapter 3 introduced the problem of pest resistance into the standard game-theoretic model of R&D. Biotechnology firms can choose to incorporate one, two or more toxin producing genes into a single cultivar, a technology known as pyramiding, to reduce the development of resistance in pests to the technology. The model we considered involved a single innovation with firms possessing two R&D investment strategies. These strategies are required because firms face two types of threats. The market threat is from a potential rival who is racing against them to win the patent. The biological threat is from pests which are continually eroding their profit stream by undermining the effectivess of their technology. To combat this threat, we introduced the possibility of investing to reduce the biological threat into the standard model.

Many of the models in the literature assume drastic or non-drastic innovation and we know from Beath *et. al.* (1989a,b) that, which type of innovation is assumed is crucial for the results. So we carried out our analysis for both types. In addition to employing the Nash equilibrium solution concept, we also utilised the concepts of profit incentives and competitive threats, as identified by Beath *et. al.*, to determine whether the incumbent firm had a higher or lower incentive to invest in innovation than the entrant. Their assertion that, under the assumption of drastic innovation, the role of competitive threats in determining the outcome is effectively eliminated holds apart from the case where the pest effect is endogenous, i.e. where we allow the firms to invest in reducing the development of pest resistance. This is because in the drastic case, competitive threats are equal and the relative sizes of the incentives to invest rely on the asymmetry in the profit incentives. When we introduced the possibility for firms to modify their technology, competitive threats were no longer equal even in the drastic case and the determination of whether the incumbent invests more or less than the entrant was much more complex.

In the case of non-drastic innovation, both firms could earn profits in the post-innovation market and these profits would depend on the technology for which they hold a patent. Thus, both firms faced different competitive threats and it was much more difficult to ascertain the relative sizes of the incentives because the profit incentives and competitive threats could work both ways.

The analysis showed that in the cases of drastic innovation, where the ability to modify the technology to slow down resistance in pests is absent, the incumbent invested less than the entrant. The results were ambiguous in the case of non-drastic innovation and we found parameter values where either result could hold, i.e. the incumbent could invest more or less than the entrant. When firms possess the ability to modify their technology in a way that makes it more effective against pests, it was not possible to separate out analytically the relative incentives from each other. However, we did find that the direction of relative magnitude tended to work in the same direction, i.e. if the incumbent's incentive to invest in winning the race was greater than the entrant's, then its incentive to invest in promoting the success of its technology against pests was also greater. In this way, the two types of R&D expenditures act as complements for each other. This appears to make sense if we believe that both incentives are drawn from the same underlying profit incentive and competitive threat.

To further elucidate our results we ran some simulations. Our analytical results in the case of drastic innovation and endogenous risk of pests suggested complementarity between the incentive to win the patent race on the one hand, and the incentive to combat the pest effect on the other. Our numerical simulations enabled us to rule out only one case, i.e. where both the incentive to win the patent race and modify the technology are larger than the corresponding incentives for the entrant. In the case of non-drastic innovation and retaining the assumption of endogenous pest effect, we found that we could rule out the case where the incumbent's incentive to win the patent race is smaller while its incentive to resist pests is greater than the entrant's. We might surmise from this that, if the incentive to win the patent race is not strong enough, it is unlikely that the firm will have a larger incentive to combat the pest effect than the entrant. However, we could not rule out the reverse, namely, the firm might have a stronger incentive to win the race but a lower incentive to modify its technology. This may be because the incumbent perceives the market threat to be higher than the biological threat, especially in the case of drastic innovation where it faces the possibility of being replaced in the market by its rival. Further findings from the simulations indicated that the possibility of pests developing resistance tends to favour the incumbent, i.e. it can raise the incumbent's incentive to win the patent above that of the entrant's if initially lower, whereas, it is unlikely to fall below the entrant's incentive if initially higher. Finally, we found that, by expanding firms' investment strategies to include the ability to reduce the threat posed by pests, both firms' incentives to win the patent race were increased.

There is no doubt that this is an extremely simple model and yet the analysis quickly becomes very involved, reducing the possibility of obtaining analytical results. Nevertheless, even this simple model has produced some interesting results and points to the necessity of adapting the standard model to consider the environment in which firms operate.

The purpose of this chapter and the related R&D literature is to assess the relative incentives of firms to carry out R&D and to determine the potential market structure, whether it be persistent dominance or action/reaction. To model the evolution of market structure, it would be better to model a sequence of innovations rather than just a single one. When faced with future opportunities to innovate, firms will have different incentives than in the case where there is no such opportunity because actions today can affect returns in the future. So one possible extension to the present model is to introduce a sequence of innovations.

Since we noted the potential for spillover effects between innovations in Chapter 2, another possible extension to the model would be to incorporate the possibility of learning. Learning could take place both in relation to the patent race and in relation to the fight against pests. Certain firms may possess a comparative advantage in one or other of these areas, which may affect their relative incentives in developing these strategies.

Another factor which has been shown in the literature to affect the incentive to carry out R&D, is the way in which costs are modelled. We assumed a once and for all investment in both the patent race and the defence against pests, which remains fixed regardless of whether the patent race is won or not and regardless of the nature of the pest resistance effect. This is largely due to our static approach. However, in the context of a multi-stage race or a sequence of innovations, it would be interesting to explore how different specifications of the cost structure might affect the relative incentives to do R&D.

In Chapters 4 and 5, we left the issue of GM and R&D behind and addressed the problem of non-point source pollution. Chapter 4 served as a literature review of the design and performance of instruments in controlling this category of pollution. A large part of the review dealt with the moral hazard aspect of this type of pollution. Within this literature, some choose to place their analysis in the context of abatement and others in the context of emissions. We chose the latter and showed how the various contributions in this field were linked to each other. The seminal article in this literature is by Segerson (1988), where she sets the problem of non-point source pollution in the context of the problem of moral hazard in teams. Moral hazard arises because individual emissions are unobservable and polluters' emissions contribute to the ambient level of pollution. She derives an optimal tax/subsidy scheme which overcomes the problem of moral hazard. Later contributions deal with certain aspects of the Segerson tax/subsidy scheme which make implementation difficult. The issues explored are risk neutrality, substantial information requirements, political acceptability and expectations.

We also reviewed the literature on tradeable permits, input taxes and standards. In the latter two cases we saw that optimality requires that all inputs involved in the generation of pollution be controlled according to their contribution to damages. However, pursuing such a first-best policy involves substantial transactions costs so a second-best policy, where control is limited to a subset of inputs, might be more practical. Some empirical studies have found that the net welfare loss in employing such a second-best policy may not be high and may even be negative. In the review of actual practice we saw that there are some tradeable permit schemes in place in the US where trades are generally based on emission reducing actions on the part of non-point sources in return for a permitted emissions increase by point sources. Voluntary approaches have also been used to reduce NPS pollution and the EU NSA scheme is one such example.

Finally, Chapter 5 offered an empirical analysis of one of the instruments discussed in the previous chapter - an input tax. The aim of the study was to develop an economic model which could be used in conjunction with INCA to assess how changes in policy might affect stream-water concentrations of nitrates. Having successfully calibrated the model, we assessed various scenarios which involved increasing the tax rate on nitrogen fertiliser. As a result of nitrogen taxation, land was reallocated towards set-aside. In response to the nitrogen tax, manure became relatively competitive and so manure producing livestock increased in numbers. A note of caution was voiced concerning this potential consequence of a nitrogen fertiliser tax. Increased storage of manure could lead to leakages, where the environmental impact could be far larger than the chronic and relatively low-level escape of nitrogen from fields. A comprehensive policy to reduce nitrate concentrations would be to tax both sources of nitrogen. However, it was recognised that it would be very difficult to implement a tax on manure given that manure is not traded in the market and so does not present a point at which the tax can be collected as in the case of chemical nitrogen. Even if manure is traded, many livestock farms would not need to enter the market as all their manure requirements could be satisfied on-site.

We incorporated the land and fertiliser response of our catchment farmer into INCA to determine the impact of nitrogen taxation on nitrate concentrations in the River Kennet. Unfortunately, we found a negligible effect on the leaching rate, although we observed some reduction in the stream-water nitrate concentration. This suggested an incapability of INCA to pick up the effect of large changes in land-use on nitrogen loadings. This may be specific to the Kennet catchment as it is characterised by a substantial groundwater component with a high initial concentration of nitrates. This tended to dampen any response in the streamwater nitrate concentrations to changes in nitrogen loadings.

Some areas for possible improvements in the economic model were indicated in the conclusion to Chapter 5. As is usually the case in empirical studies, the main drawback is lack of data and this case is no exception. We noted the importance of correct specification and parameterisation of crop and grass yield functions. In the absence of suitable data, we resorted to adjusting yield functions to reflect conditions prevailing in the Kennet catchment. Future work would be to extend the scope for model response by including more activities. As stated in the chapter, the economic model is not spatially differentiated, although this short-coming is mitigated in INCA. Limiting activities to suitable soil types would restrict the response of land to nitrogen taxation but would reflect agronomic practice which underpins cultivation decisions. Finally, the impact of groundwater on stream-water responses suggested that any policy designed to affect the latter should take the former into account. Excluding the impact of groundwater will result in the apparent failure of nitrate policy. To pick up on-going changes in nitrate concentrations, a dynamic framework for the economic analysis would be appropriate and the period covered by the INCA model should extend beyond a single year.

Appendix A

Proofs for Chapter 3

Case 5: Equating the expressions in (3.25) and (3.26) given in the main text, we obtain

$$(1+y)\phi = (1+x)\psi + \delta; \qquad \delta \geq 0 \tag{A.1}$$

and equating expressions in (3.23) and (3.24) from the text, we have

$$\frac{\omega x}{y} = \frac{(1+u)^2}{(1+v)^2}; \qquad \omega = 1 - \alpha(1-\theta_1) \leq 1 \tag{A.2}$$

Note that

$$\phi - \psi = \frac{\omega\theta_2 (u-v)}{(1+u)(1+v)} \tag{A.3}$$

$\Rightarrow$

$$sign\,(\phi - \psi) = sign\,(u - v) \tag{A.4}$$

Recalling that (x_2, y_2) are the equilibrium investment levels in competing for the patent, we have the following:

Result (i)

$u = v \ \Rightarrow$

$$y_2 = x_2 + \frac{\delta}{\phi} \quad \Rightarrow y_2 > x_2 \tag{A.5}$$

and

$$y_2 = \omega x_2 \quad \Rightarrow x_2 > y_2 \tag{A.6}$$

both of which cannot be true.

$x_2 = y_2 \Rightarrow$

$$\phi = \psi + \frac{\delta}{1+y} \quad \Rightarrow \phi > \psi \Rightarrow u > v \tag{A.7}$$

and from (A.2)

$$(1+u)^2 = \omega(1+v)^2 \Rightarrow u < v$$

which is impossible. So we can only have $x = y$, $u = v$ if $\delta = 0$, $\omega = 1$, which implies $\theta_1 = 1$.

Result (ii)

$u > v \Rightarrow$

$$\omega x_2 > y_2 \quad \Rightarrow x_2 > y_2 \tag{A.8}$$

and

$$(1+y_2)\,\phi = (1+x_2)\,\psi + \delta \Rightarrow y_2 \gtreqless x_2 \tag{A.9}$$

so $u > v \Rightarrow x_2 > y_2$. If $x_2 > y_2$, we have from (A.1) that

$$\phi = \frac{1+x_2}{1+y_2}\psi + \frac{\delta}{1+y_2} \Rightarrow \phi > \psi \Rightarrow u > v$$

and from (A.2)

$$(1+u)^2 = \frac{\omega x_2}{y_2}(1+v)^2 \Rightarrow u \gtreqless v$$

Thus, $u > v \Leftrightarrow x_2 > y_2$.

Result (iii)

$u < v \Rightarrow \psi > \phi$ and by (A.1)

$$1 + y_2 = (1+x_2)\frac{\psi}{\phi} + \frac{\delta}{\phi} \Rightarrow y_2 > x_2 \tag{A.10}$$

From equation (A.2), we have

$$\omega x_2 < y_2 \Rightarrow y_2 \gtrless x_2$$

$\therefore u < v \Rightarrow x_2 < y_2$.

$x_2 < y_2 \Rightarrow$

$$1 + u < 1 + v \Rightarrow u < v \tag{A.11}$$

and from (A.1)

$$\phi = \left(\frac{1 + x_2}{1 + y_2}\right)\psi + \frac{\delta}{1 + y_2} \Rightarrow \phi \gtrless \psi, \text{ but with } x_2 < y_2 \Rightarrow u < v \ \Rightarrow \phi < \psi.$$

Appendix B

Data for Chapter 5

Table B.1: Land-use data 1995

Land-use	Area (ha)	Price/tonne (£/tonne)	Subsidy (£)	Variable costs (£)	Nitrogen (+ manure 20 kg/ha)	Yield (tonnes)
wheat	23935	92.80	250	162.60	192	6.1
w-barley	7825	88.70	250	152.18	141	5.6
s-barley	2487	91.74	250	116	100	5.1
oilseed	5268	150	405	139.23	187	4.4
linseed	919	120	480	156.80	56	1.7
legumes	1658	91.10	360	172.50		3.7
set-aside	8434		315			
grassland	23692				127	

Table B.2: Land-use data 1996 (1995 prices)

Land-use	Area (ha)	Price/tonne (£/tonne)	Subsidy (£)	Variable costs (£)	Nitrogen (+ manure 20 kg/ha)	Yield (tonnes)
wheat	24180	100.74	264	174.04	185	6.1
w-barley	8876	107.88	264	159.25	138	5.6
s-barley	2766	99.73	264	126.09	95	5
oilseed	3803	166.27	416	147.81	190	4.4
linseed	1134	141.82	509	152.37	53	1.7
legumes	1615	97.81	382.35	200.5		3.7
set-aside	6811		334.31			
grassland	23952				123	

Table B.3: Land-use data 1997 (1995 prices)

Land-use	Area (ha)	Price/tonne (£/tonne)	Subsidy (£)	Variable costs (£)	Nitrogen (+ manure 20 kg/ha)	Yield (tonnes)
wheat	25795	99.31	251	168.45	191	6.1
w-barley	9956	94.89	251	146.15	141	5.6
s-barley	2558	99.64	251	124.08	91	5
oilseed	5628	166.06	403	139.06	214	4.4
linseed	1524	142.34	489	135.78	69	1.9
legumes	2040	108.8	300	194.53		3.6
set-aside	4124		321.9			
grassland	23075				122	

Table B.4: Land-use data 1998 (1995 prices)

Land-use	Area (ha)	Price/tonne (£/tonne)	Subsidy (£)	Variable costs (£)	Nitrogen (+ manure 19 kg/ha)	Yield (tonnes)
wheat	25002	75.64	234	182.96	171	6
w-barley	8511	73.17	234	152.20	118	5.5
s-barley	2411	76.61	234	126.28	88	5
oilseed	6420	137.61	390	145.89	203	4.4
linseed	1848	119.27	454	130.09	56	1.7
legumes	2323	96.33	339	167.89		3.6
set-aside	4125		299.08			
grassland	22235				113	

Table B.5: Land-use data 1999 (1995 prices)

Land-use	Area (ha)	Price/tonne (£/tonne)	Subsidy (£)	Variable costs (£)	Nitrogen (+ manure 22 kg/ha)	Yield (tonnes)
wheat	22390	62.78	216	171.41	184	6.2
w-barley	5385	62.22	216	141.48	139	5.6
s-barley	4298	65.12	216	112.61	101	5.1
oilseed	4713	133.80	245	158.78	200	4.4
linseed	4861	115.96	419	148.04	54	1.7
legumes	2305	72.32	313	149.86		3.7
set-aside	7577		273.21			
grassland	21924				116	

Table B.6: Livestock data 1995

Livestock	Number	Output value (£)	Subsidy (£)	Variable costs (£)	Dry Matter requirement (kg/head)	livestock unit	Nitrogen production (kg/head)
dairy	11303	1477.75		100	5110	1	48
beef	3662	296	111	40	4088	0.8	15
18 mth old beef	10192	415	111	49	3577	0.7	15
ewes	41710	41.30	17.5	7.20	767	0.15	
goats	219	271		38	767	0.15	
pigs	38142	27.75		21.25			13
sows	3355	555		425			19.5

Table B.7: Livestock data 1996 (1995 prices)

Livestock	Number	Output value (£)	Subsidy (£)	Variable costs (£)
dairy	11074	1515.84		97.81
beef	4040	284.83	111.5	41.08
18 mth old beef	10188	417.64	111.5	49.88
ewes	38991	44.31	17.12	7.53
goats	163	275.82		39.12
pigs	35374	26.90		21.03
sows	4731	537.94		361.89

Table B.8: Livestock data 1997 (1995 prices)

Livestock	Number	Output value (£)	Subsidy (£)	Variable costs (£)
dairy	10305	1326.95		113.87
beef	3952	254.03	117.67	41.75
18 mth old beef	9509	378.63	117.67	50.29
ewes	40471	46.59	18.03	7.78
goats	143	290.37		34.16
pigs	38182	31.79		20.40
sows	5224	635.79		446

Table B.9: Livestock data 1998 (1995 prices)

Livestock	Number	Output value (£)	Subsidy (£)	Variable costs (£)
dairy	10141	1145.97		114.71
beef	3879	230.53	107.37	42.21
18 mth old beef	8564	343.22	107.37	54.14
ewes	38571	45.15	12.85	8.26
goats	161	280.81		33.04
pigs	37618	31.02		20.10
sows	5282	651.56		422.14

Table B.10: Livestock data 1999 (1995 prices)

Livestock	Number	Output value (£)	Subsidy (£)	Variable costs (£)
dairy	10332	1109.43		114.18
beef	3994	191.16	99.90	45.49
18 mth old beef	8885	322.90	99.90	61.55
ewes	38242	39.87	12.49	8.03
goats	118	253.33		39.25
pigs	42955	27.70		16.77
sows	5513	579.80		352.34

Table B.11: Parameter Values

Year	Total Agricultural Land Area (ha)	Nitrogen Price (£)	Set-aside requirement (%)
1995	74218	0.33	0.15
1996	73137	0.35	0.13
1997	74695	0.37	0.05
1998	72875	0.3	0.05
1999	73453	0.23	0.1

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