Searching for Solutions:

Renewable Resources, IPR and Problems Resistant to Resolution

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Abstract

The paper argues that environmental policy making may be viewed as a dynamic contest, in which opportunistic rent seekers pursue strategies for the appropriation of resource rents and policy makers present strategies to prevent this. The evolutionary nature of this process is described as a "Red Queen Game", using the example of the management of antibiotic resistance. It is demonstrated that management strategies that fail to consider the predictable strategic response emanating from the managed population can only have short-term effect. It is also demonstrated that the private benefits from generating such short-term solutions are potentially greater than the private benefits generated from resolving the problem with finality. For this reason there are incentives for the environmental policy making process to continue as a profitable process of "searching for solutions" rather than as a final resolution of the underlying problems.

Keywords: Environmental Policy, Evolutionary Processes, Resistance Management

[1] I need to thank my co-author on the chemical accumulation research (Robin Mason) without implicating him in any of the remaining errors.

Introduction: Problems Resistant to Resolution

Analysts of environmental policy are prone to feelings of déjà vu as they see the same sorts of policy problems cycle and re-cycle. For example, a recent study of the problem of pesticide accumulation in groundwater found that new pesticides (replacing previously-banned products) had nearly identical chemical characteristics. This implies that these new chemicals could be expected to accumulate in groundwater at the same rate as the old ones, despite the fact that there is an absolute prohibition against pesticide contamination of drinking water contained within the Drinking Water Directive. (Swanson and Vighi 1998). Despite having strict prohibitions against accumulative chemicals on the books, it appears that no progress is being made towards less-contaminated drinking water. The problem of pesticide accumulation continues unabated (and will rear its head again in section 7 below).

The general point raised by this one example is that recurring problems are replete in the area of renewable resources. On the one hand this may be just one more example of the general lack of progress toward utopian societies. On the other it raises the question of whether there is some more specific explanation for the absence of final and definite resolution of social problems within this particular context. Where does this resistance to resolution arise from in environmental policy making? Does this have something to do with the nature of the resources involved, the problems targeted or the policies employed?

We argue here that environmental policy problems are resistant to resolution for all three of the above reasons. First, the resources involved are themselves likely to be dynamic rather than static in nature, and hence prone to cycling solutions. Second the problems are usually sourced in opportunism, and opportunists are likely to have a sequence of strategies to employ rather than a single one; opportunism is also more a dynamic, than a static, phenomenon. Thirdly, these two dynamic phenomena imply that policies must be created to take into consideration the dynamic nature of the resources and the strategists; if not, they are unlikely to generate anything other than an impermanent sort of solution.

In short, the solution concept required by society in addressing environmental problems will necessarily be a dynamic and long-term one. Solution concepts that are devised otherwise necessarily have only short-term impact, and the problem will re-emerge. The first point of this paper is to demonstrate how static approaches to dynamic problems predictably meet with resistance.

This paper will make this argument in three steps. First, the paper will present an explicit model of resistance management, within the context of the current problem of antibiotic resistance. It will demonstrate how opportunistic invaders break down solutions, and how there are benefits to certain actors within society to having impermanence built into the management system. Secondly, we will then demonstrate that these same points apply in situations where the opportunists are polluters rather than pathogens – environmental problems can be the result of the appropriable benefits derived from resistance to management. Finally, we will discuss the problem of resistance to management generally – to highlight how environmental policy problems continue because of the benefits from their continuance.

What is the lesson to be learned for environmental policy making? At best this examination of the incentive mechanisms used for problem solving indicates that policy making processes must take into consideration a longer view regarding dynamic problems than is their custom. If the strategic opportunities presented by policies introduced within these contexts are not taken into consideration, then the best that can be hoped-for is the maintenance of the status quo. Real societal progress cannot be achieved through the application of static solution concepts within highly responsive populations. At worst this discussion indicates that some

environmental policy making may be popular more for reasons of profitability than of public-spiritedness: searching for solutions is privately profitable while imposing resolution is not.

The paper proceeds as follows. In section 1 we introduce an evolutionary analogue to the problem of opportunistic response to static management strategies: the problem of antibiotic resistance. This example provides the basic dynamics for considering how solutions generate strategic responses. Section 2 provides the evolutionary mechanics, the basic model, and implications for socially optimal management of evolved resistance. Section 3 sets out the optimal approach to R&D for the solution of this problem. Section 4 then demonstrates the failings of an IPR-generated solution to the problem. Section 5 discusses why patent mechanisms might be used in this situation, even though they are demonstrably inadequate to the task. Section 6 trans-locates the entire discussion to the arena of environmental policy making regarding chemical accumulation in groundwater, and demonstrates that many of the same problems exist. Section 7 then discusses generally how resistance to management must be taken into consideration when devising environmental policies. Section 8 concludes.

1. Introduction to the Problem of Antibiotic Resistance

The management of antibiotic resistance is now perceived to be a problem that requires some form of social intervention.[2] After several decades of application, it is now apparent that the effectiveness of antibiotics is dependent on their aggregate rates of application, both across space and across time. The first encounter with the problem occurred in the context of penicillin-resistant staphylococci, soon after the discovery of penicillin, in the early 1940s. Multi-drug resistance was first noted in the late 1950s.[3] Many important treatments have now exhibited declining effectiveness in the face of rising pathogen resistance, including the primary treatments for TB, meningitis, malaria, dysentery and typhoid. There is widespread agreement that the continuing rise in antimicrobial resistance is an important global public health problem and governments are beginning to develop action plans to address the problem.[4]

The problem with developing such a plan is that little is understood about the nature of the problem itself, or the nature of a possible solution concept. Many of the commentators addressing this issue consider it as one of the management of an exhaustible resource, and the management issues then concern the optimal rotation between existing treatments. That is, the policy analysts focus on the optimal approach to cycling between a limited number of antibiotics. (Laxminarayan and Brown 1998; Brown and Rowthorn 2000). This is a static sort of solution concept, resting on the assumption that there are a given number of antibiotics available for dealing with the underlying pathogen population, and determining how best to apply this given set of treatments.

We take a very different and more dynamic approach to the nature of the problem of antibiotic resistance. We note that the resource of resistance is much more similar to a renewable resource, in that it has the capacity to regenerate itself if use is discontinued early

[2] We will follow the convention of referring to *resistance* as the characteristic that antibiotics have when they are able to reduce the fitness of pathogens effectively. Then the corresponding characteristic of the pathogen population is referred to as *virulence, i.e.* the capacity to continue to reproduce in the face of antibiotic applications. Then the social management of antibiotic resistance refers to the management of the antibiotic's capacity to reduce pathogen fitness (or ability to reproduce itself).

[3] House of Lords Committee on Science and Technology. Session 1997-98, 7th Report: Resistance to Antibiotics and other Antimicrobial Agents. London:The Stationary Office.

[4] UK Antimicrobial Resistance Strategy and Action Plan. Department of Health, June 2000, available at www.doh.gov.uk/arbstrat.htm

enough. We base our model in the biological literature analysing the evolution of pathogen populations (Stenseth and Maynard Smith 1984, Comins 1977, Anderson and May 1991). From this we derive the basic equations of motion describing how pathogen populations and treatment effectiveness co-evolve across time.[5] The essence of this relationship is that if a specific antibiotic is extensively applied, it will drive the existing population of pathogens toward ever-greater virulence. This is because the antibiotic will result in the demise of only that proportion of the pathogen population that is susceptible, leaving only those possessing the non-susceptible trait to reproduce. Continued application results in an increasingly problematic pathogen population, and the need for new strategies on the part of the manager.[6]

However, so long as there is a more general population of pathogens from which to draw, the reduction of the antibiotic application will afford the capacity for the pathogen population to evolve in a less directed fashion (Anderson and Dobson 1986). This dilution effect then provides for the loss of virulence amongst the pathogen population, or (equivalently) the recharge of the stock of resistance. In this way, the resistance stock of a particular treatment may be considered as a renewable rather than an exhaustible resource.

The optimal management of a renewable resource is a very different matter from that of one of an exhaustible resource. In Goeschl and Swanson (2001), we show that the optimal management plan is one that makes use of every available antibiotic simultaneously, rather than rotating between them. The larger the number of antibiotics applied, the lower the level of aggregate virulence of the pathogens and the greater the optimal percentage of treated cases. This is because the recharge rate of the stock of resistance is available for every distinct treatment, and so it is essentially a nonexclusive resource from the social perspective. In fact, given an adequate number of treatments being applied simultaneously, it is even possible to treat all cases of infection without influencing the evolution of the pathogen population. For these reasons, the pursuit of additional treatments for the same pathogen population is a social good, with rising marginal benefits.

In this paper we demonstrate from this model of managing resistance as a renewable resource that the socially first-best outcome would obtain when a large number of distinct treatments are used simultaneously at very reduced rates. This concept of optimal management contrasts sharply with the real world, where single antibiotics are applied universally until their effectiveness is lost. We explain this by reference to the peculiar incentive structure created by intellectual property right (IPR) mechanisms, when applied to this form of renewable resource. In essence, IPR incentives do not create incentives to generate multiple solutions to the same problem; they are instead focused on finding the next solution to new problems. Even more serious of a problem is that the optimal solution to antibiotic resistance problems would generate a steady state solution: it would cause a pathogen population to cease generating new problems for society to solve. IPR systems, on the other hand, have an in-built cycle within them. There is no incentive to use the old solution to solve the problem beyond the time horizon of the patent that was granted. Therefore, the solution concepts that IPR systems generate are necessarily time-delimited ones (ones matching the period of the patent); there are no incentives under an IPR system to look for steady state solutions. The pursuit of impermanent problem-solving under IPR systems rather than socially optimal steady state solutions is the reason that recurring problems are in-built within this context.

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[5] The precise model underlying this paper is developed and analysed in Goeschl and Swanson, "Lost Horizons: The Interaction between Dynamic Problems and Dynamic Policies", paper presented to AEA meeting, New Orleans, 2001.

[6] Hence the evolutionary nature of the contest requires an increasing rate of application of management strategies in order to maintain parity in the contest. This is what is termed a "Red Queen Contest" in evolutionary biology, after the Red Queen in Alice in Wonderland who states that "around here, we must run faster and faster just to stand still…"

2. A Model of Resistance Management

The optimal management strategy for resistance depends entirely on how its motion is conceptualised. How does virulence increase with antibiotic use? How long does it continue to remain ineffective after removal of the treatment? How and why would resistance be restored after removal? These are the fundamental workings of resistance, and a precise understanding of the nature of the resource is necessary before its management may be considered.

We give very specific answers to the above questions and then address the issue of optimal management on the basis of the resource we have described. These are the premises on which we proceed. First, antibiotic use on a given population of pathogens generates greater virulence at the population level by disproportionately eliminating those pathogens in the pathogen that are not virulent. Second, there is a not insignificant fitness cost to carrying a trait that is not currently being selected for - hence the removal of a particular treatment creates the prospect for removal of the trait for virulence.[7] Third, the removal of a trait for virulence from an individual pathogen, and hence the decline of virulence at the population level, requires the interaction of the pathogen with pathogens from a more general population (i.e. a population not subject to the same treatment strategy). Then the rate at which virulence declines (after the removal of treatment) depends on the proportion of the treated pathogen population that is virulent, and the level of interaction between this population and other (untreated) populations. This rate will also be related to the level of treatment that may occur within the system without effecting a positive increase in virulence. This we term this the level of *absorption* within the system: the capacity of the system to absorb treatment without affecting the evolution of the system. Essentially it represents the capacity of interaction of the treated pathogen population with a broader population of pathogens to dilute the effects of treatment at an individual site. Finally, this points to our definition of an individual *treatment site*, which describes a break between a population of pathogens in close and frequent interaction and other more remote but still interacting populations.

A common feature of all models of pathogen evolution is that the direction of movement of the managed pathogen population depends on the virulence of the residual population remaining after treatment (see e.g. Munro 1997, Mangel 1985). Since by definition the residual population unaffected by treatment will be precisely those that are more virulent, the continued application of treatment drives the population toward total virulence. Our particular approach is based on the *lag-load* concept of evolution that offers an easy method of formalizing these dynamics (Stenseth and Maynard Smith 1984, Rosenzweig 1996).[8] This concept is combined with the idea of absorption in evolutionary ecology, where the impacts of treatment are diluted by in-migration (May and Dobson 1986, Comins 1977). The impact of treatment on the evolution of virulence is taken to be the difference between these two effects: treatments net of absorption driving virulence of the pathogen population upwards at the treatment site.

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[7] This fitness cost to carrying the trait must lie somewhere between insignificantly small (in which case the trait once obtained will be retained forever) and substantially large (in which case the trait will be discarded once not selected for, and irrespective of the rate of interaction with untreated populations). An alternative way of allowing for selection against virulence is to consider that genes conferring virulence may be recessive (Comins 1977).

[8] Most other models of evolution of virulence adopt some formulation of the Hardy-Weinberg Law based on a one-locus, two-allele model (cf. Mangel and Plant 1983, Plant et al. 1985, Munro 1997). This restriction is not necessary: The lag load concept captures a wider class of combinatorial effects and time scales and makes it easier to integrate migration (Stenseth and Maynard Smith 1984). Also, more complex genetics-based models do not yield qualitatively different outcomes as Mangel and Plant (1983) point out.

Now we proceed to outline the basic model. Think of the aggregate population of pathogens as being distributed across a number of distinct treatment sites - e.g. a number of hospitals.[9] The patients at each treatment site are much more likely to interact with one another (microbially speaking), than they are to interact with those from other sites. Now assume that treatment commences at only one of these sites. Then, depending on the level of application of the treatment, the population of virulent pathogens begins to rise. If the treatment is withdrawn before the pathogen population is wholly virulent, then the level of virulence will again decline towards zero (at an increasing rate). This is attributable in part to frequent interaction with the remaining nonvirulent pathogens at the treatment site, and also to the much less frequent interaction with the population of untreated pathogens arriving from other sites.[10]

These assumptions place resistance management squarely within the realm of resource economics - as a special form of renewable resource. The nature of the recharge function in this case is what makes it a special form of renewable resource. If all treatment halts, then the recharge function will regenerate resistance with sufficient time. If there is treatment, then it must be below the level of absorption within the system, determined by the level of interaction between the treatment site and other, independent sites; otherwise, any level of treatment always drives virulence higher.[11] Basically, recharge in this model comes from dilution of the treated population at one hospital with pathogens arriving from untreated populations at other hospitals. It is in-migration (from untreated sites) that is the source of the recharge within the treated system.[12]

Social Optimum - Single Treatment Site, Single Antibiotic

To further illustrate the model, consider first the unrealistic case of the optimal level of treatment at a single site, given this background rate of recharge. The social optimum would involve balancing the marginal benefits from the marginal extension of the treatment (to one more infected individual) against the marginal social costs of that treatment. The marginal social costs consist of the explicit costs of the application (i.e. the cost of one further application) plus the implicit cost of any subtraction from the stock of resistance. An equilibrium will obtain across time with reduced levels of applications, as extended applications result in: a) increasing virulence, b) reduced benefits from treatments, and c) increasing social costs as the stock of resistance declines.

The equilibrium concept of interest is that known as the *steady state:* the optimal treatment level that is able to continue indefinitely in the case of a renewable resource. With regard to

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[9] The incorporation of hospitals as major loci in the communication system is relevant. Although it is estimated that only about 20% of antibiotic prescriptions occur in hospitals, it is far more common that antibiotic-resistant organisms will be found in those environments. It is estimated that hospital-acquired antibiotic-resistant pathogens claim 5000 lives and incur costs of GBP one billion each year. (Plowman,R., Graves,N. Griffin,M. et. al. 1999)

[10] One implication of the distinct rate of interaction is that, if the level of virulence within the treated population reaches some critical mass (e.g. total virulence), then the high frequency of interaction with this population is able to maintain that equilibrium even in the face of low frequency interaction with an untreated population.

[11] Although we will refer to other sites as those without treatment, it is in fact only necessary that the evolutionary impacts of treatments at these sites be independent of those at the site under consideration. We will return to the implications of this point later.

[12] Of course, there are other social problems implicated in the maintenance of some flow of pathogens from other treatment sites, e.g. the infection of previously uninfected patients. Our model will demonstrate at least the possibility of a solution that includes the treatment of all infected, and so the solution of the evolutionary problem may imply the solution of these other epidemiologial problems as well. In the remainder of this paper, we focus narrowly on the single pathogen population/ single host population problem.

resistance management, there is the possibility of a period of transition (when virulence is evolving toward its long term optimum) but the steady state equilibrium describes the optimal level that will obtain forever thereafter. In the steady state equilibrium, the marginal treatment must balance the benefits of an additional treatment (at the steady state level of virulence) against the costs of one further treatment, inclusive of the social cost of operating at a lower level of resistance forever (i.e. at a higher rate of virulence forever). This implicit social cost is known as the *steady state shadow value of resistance*: it is the value of a stream of treatment benefits flowing in perpetuity at the rate of recharge, discounted by the resource's "own rate of discount".[13]

This illustration gives concrete meaning to the concept of the social management of resistance. Extensive use of a treatment now comes at the expense of the future, because each unit of resistance affords the possibility of a flow of effective treatments in perpetuity at the rate of recharge. The optimal level of treatment will take this cost to the future into account when contemplating expansion of treatment for a current gain. It is a trade-off (as always with renewable resources) between reduced costs today versus placement on a path of higher costliness forever.[14] The precise magnitude of those higher costs is equal to the rate of recharge available from a unit of resistance.

In this single antibiotic example, the optimal policy for a single treatment site would be to delimit treatment with the antibiotic in the present in order to manage its resistance for future users. In fact, after an initial period of more extensive use (in which the steady state level of virulence was developed), the use of the antibiotic in the future would be held at a constant level determined by the rate of recharge at the treatment site. At this level of use, the treatment would retain its steady state level of resistance forever, but a significant proportion of the infected individuals would have to go without treatment in order to preserve this effectiveness. *This is the first, and most fundamental, rule of antibiotic resistance management: extensive levels of treatment with an antibiotic at a given point in time come at the expense of its future effectiveness.* (Munro 1997; Cornes et al. 1995)

More Complicated Solutions: Multiple Antibiotics

There is no reason for there to be a single form of treatment that operates successfully on a given pathogen population. There is a virtually limitless number of methods for interfering in the basic processes of pathogen regeneration, and distinct treatments might be addressed to intervening at any of these points. The prevailing number of antibiotics in use against a given pathogen population is a function of the resources expended on research and development (R&D), and the incentives guiding these resources toward realisation.[15] So, a far more realistic management problem must be concerned with the optimal method for applying multiple forms of antibiotics. What is the optimal level and pattern of treatment with multiple antibiotics?

We will assume that each antibiotic is distinguished by the cost of an individual treatment and its prevailing stock of resistance. This assumes only that virulence is specific to a particular

[13] The own rate of discount refers to the social discount rate net of the impact of a change of resistance on the rate of flow of resistance. (Dasgupta and Heal 1979)

[14] It is important to distinguish between notions of cost irreversibility and resource irreversibility. Of course it is possible (unless the point of critical mass has been passed) to regain a particular stock of resistance once it has been lost, but only at the expense of further foregone treatments in the future. In this sense the current treatments irreversibly secures a path of future higher costs. The point of resource irreversibility, however, is not passed until the point of critical mass in virulence is reached. For these reasons expectations concerning technical advance in this area are critical to the determination of the optimal level of current treatment.

[15] This point is the subject of the following two sections. In this section we confine our analysis to the issue of optimal application of multiple treatments.

treatment or, equivalently, that two treatments with impacts on the same stock of resistance are the same for management purposes.

Would the optimal management plan involve cycling between treatments with different costs (where costs are evolving with use, and inclusive of the costs of virulence)? Looking to the steady state as the solution concept rules this out. Instead, after a period of disproportionately more extensive use of the lower cost treatments, in the steady state the use of each antibiotic will equal the rate of recharge within the system. This implies that the virulence levels will be higher for the lower cost treatments, but that the number of treated individuals will be the same for each. Nevertheless, all treatments that exist will be used simultaneously, so long as the benefits from a treatment exceed the (explicit) cost of one treatment.

In general, the optimal aggregate rate of use of antibiotics would not allow for the treatment of every infected individual. As in the case of the single antibiotic above, there are costs to the future from more extensive use of any given treatment. Given the small number of antibiotics available at any point in time and the rate of recharge, it is likely that the optimal level of aggregate treatments would be less than total population of infected individuals in the steady-state.

There is the possibility however of a "golden age steady state": this would occur where the number of antibiotics times the rate of recharge equates with the flow of infected individuals.[16] This is the hypothetical first-best resolution to the resistance management problem. It provides for the effective treatment of all infected individuals for all time. It does this by allowing treatment without affecting evolution, and it provides for the continuation of this situation in perpetuity.

It is important to note that the existence of this golden age steady state is dependent upon both an adequate number of antibiotics and the continuing recharge of the treatment site. This of course depends on the nature of treatments being afforded at other interacting sites. It is sufficient if the pool of interacting pathogens comes from sites receiving independent forms of treatments (rather than no treatments at all). This independence requirement again multiplies the number of required antibiotics by a factor required to maintain this recharge.

This points to the second fundamental principle of resistance management: *the first-best objective is the development of an optimal portfolio of treatment strategies in space.* This optimal portfolio of treatments balances the costs of each application, with the loss of its resistance and the interaction between treatments (within the portfolio). If the choice of the number of distinct antibiotics is unconstrained, then movement to the first-best management portfolio is attainable and immediate. The first-best portfolio is the golden age steady state, where the number of antibiotics in use at each site times the recharge flow between sites (that is itself dependent on the aggregate number of antibiotics in use) equates with the number of treatable individuals. This first-best strategy allows for the effective treatment of all infected individuals without any impact on resistance.

3. Solving Resistance Problems: Socially Optimal R&D

What is the socially optimal approach to resistance management? That is, how many antibiotics should society create when these are indeed costly? The marginally beneficial antibiotic is that one for which the benefits from the marginally increased portfolio just equate

[16] One qualification of this statement is that there may be some degree of cross-resistance, implying that there is rivalry between the use of two antibiotics thus connected. Cross-resistance does not appear to be of significant magnitude in the area of antibiotics, however.

with the costs of the R&D necessary to produce it. These benefits consist of the following two components:

Private and Social benefits of an additional antibiotic

1) Private benefits of additional antibiotic
- Potential increase in the number of individuals effectively treated
- Potential increase in the B-C ratio per treatment application

2) Social benefits of additional antibiotic
- (steady state value) - accretion to present value of benefits by increasing the flow used in steady state
- (portfolio value) - contribution to the value of the entire portfolio by maintaining or increasing the recharge rate

First, consider the private benefits generated by the addition of a substitute antibiotic. The first point listed under 1) above refers to the possibility that the additional antibiotic might afford a solution to an individual for whom other antibiotics are no longer effective (due to virulence). The second point refers to the potential difference in the private benefits and costs, i.e. the possibility that the new treatment has a lower cost of application than does the earlier existing set of treatments.

The more substantial benefits from the development of a marginal antibiotic lie in the social arena (listed under heading 2) above). These are values that are unlikely to motivate a private firm under existing institutions, but are available under a different set of institutions.

One social value of a marginal antibiotic lies in its contribution to the overall flow of treatments available for use in the *steady state*.[17] The new antibiotic is able to use the rate of recharge *nonexclusively*, without impacting on the rate of recharge of the other antibiotics. This implies that the aggregate level of treatments may be expanded, while the individual levels of steady state virulence for each of the earlier used antibiotics will be unaffected. Therefore, at a very minimum, there are *constant returns* to the generation of further antibiotics, up to the number required to enter the golden age steady state (n^*).[18]

It is also possible that the addition of a marginal antibiotic generated increased returns in the steady state (e.g. due to the attainment of greater expected benefits at the same level of virulence). This would be the case if it were possible to rank the treatable individuals with regard to the anticipated benefits they are expected to receive from a given treatment. If this were the case, then the returns from further treatments with a single antibiotic would be diminishing. Then the addition of a new antibiotic would allow the substitution of the new for the old at the margin, allowing a reduction of the average level of virulence within the system (or the acquisition of greater expected benefits at the same level of virulence).[19]

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[17] This value would be available to private firms, if management were introduced to cause them to consider the pursuit of the steady state use of antibiotics. Under existing institutions, this value would be pursued in the form of the categories listed under 1) above.

[18] The appendix describes the case of constant returns to additional antibiotics in the steady state. That is, the case of steady state increasing returns requires only that there are diminishing rather than constant benefits from the application of any single antibiotic to a pool of individuals. With any sort of prior information, this would seem to be the more general case (see footnote 13 and the associated text for further discussion).

[19] This would be the case if, for example, the damages from the infection were heterogeneous across the population of infected individuals, e.g. because the individuals infected were different ages and there was a threat of mortality. Then it would be possible to rank the individuals in terms of anticipated benefits from treatment. The addition of a new antibiotic would enable the treatment of a larger number of the "high benefit patients" with a much greater expectation that the treatment would

The more important reason to anticipate that there is increasing value to increasing numbers of antibiotics is the endogeneity of the recharge function itself. This function is the source of the steady state value of each antibiotic, but it itself is dependent on a large number of independent treatments for its existence. As greater numbers of antibiotics are generated, the independence of treatments at a given site, and the independence between sites, is maintained, extended and ensured. It is even possible to think of the rate of recharge as itself being an increasing function of the number of antibiotics in existence. This is the *portfolio value* of a marginal antibiotic, and it provides a return through increasing the effectiveness of every other previously existing treatment.

This means that there is not only a significant divergence between the private and social valuation of the marginal antibiotic, but this gap may also be widening. Given that we are only considering the steady state equilibria, each new antibiotic may be viewed as expanding the flow of treatable individuals by an equal amount (equal to the rate of recharge). Given that the recharge rate may itself be extended with each additional antibiotic, the combined effect is one of potentially *increasing returns*. The marginal antibiotic produces at least constant returns in the number of individuals treatable, but also the possibility of an additional return in the effectiveness of all treatments taken together (the portfolio effect).

This may be demonstrated in a simple example. Assume that the treatment site has a recharge rate of .20, i.e. a dilution from untreated sites of 20% of the pathogen gene pool per period. With the application of a single antibiotic, the benefits from application require an initial period of extensive use prior to attaining the optimal level of virulence - thereafter the steady state level of application obtains. With the addition of a second antibiotic a lower level of steady state virulence may be able to obtain for both the previous antibiotic and the new one (if it were used alone), and twice as many individuals are treatable in the steady-state. The third antibiotic reduces the level of virulence for all three, and adds another flow of treatable individuals. This process of increasing returns continues through to the fifth antibiotic, the development of which enables the immediate attainment of the golden steady state - the perpetual treatment of all infections in the absence of virulence. After the attainment of the "golden age", the addition of further treatments only serves to reduce the cost of treatments, not to increase the number treated, in the steady state.

This indicates that the development of further antibiotics has many of the characteristics of a public good - its total benefit equates with the sum of the benefits it renders both at the margin and within the margin (through increasing the effectiveness of previously discovered treatments). Again, and fundamentally, this is because the rate of recharge can be used nonexclusively - the addition of a further antibiotic makes use of this rate of recharge without subtracting from its availability to other treatments. In fact, the greater the number of antibiotics available the more diluting this rate of recharge will be (as more treatment strategies are available for other sites), and the system-wide benefits from further antibiotics are reaffirmed. *In general these various elements all confirm the third rule of resistance management*: *there are likely to be increasing returns to adding to the portfolio of treatments available for treating any given pathogen.*

Of course the optimal number of treatments will depend on the slope of the marginal cost function for producing additional treatments, as well as the slope of the marginal benefit function. The marginal cost of producing a larger set of treatments at a given point in time will certainly be an increasing function as well. Crucial to the slope of this function will be

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be successful (i.e. with reduced virulence to the aggregate treatments available). Adding additional antibiotics would then substitute greater expected success with the "high benefit" individuals for the more extensive level of treatment of "low benefit" individuals, by allowing the pursuit of lower virulence rates of use for both treatments.

expectations about the rate of “exogenous technical change”: anticipated change that reduces the cost of postponing discoveries into the future.

Hence, constant or increasing returns on the benefit side alone do not necessarily justify a movement directly to the golden age steady state. However, the existence of these returns on the social benefits side of the equation certainly does provide a strong argument in favour of any investments that might either produce a diversity of cost-effective treatments, or reduce the cost of producing a diversity of such treatments. The social benefits of resistance management in general justify serious consideration of the strategy of investing in the creation of a diverse portfolio of treatment strategies.

4. IPR-generated Incentives: Patents and Sequential Searches for Solutions

The first-best socially optimal management resistance management strategy involves: a) a large number of distinct antibiotics; b) applied relatively nonextensively; c) with different sites employing entirely distinct portfolios; and d) no loss of resistance. This description of course does not match very well to the currently prevailing situation regarding antibiotic management. In fact, many of the questions regarding optimal management (cycling, labelling) do not match very well with this description of the first-best social optimum.

It is our argument that this mismatch is caused by the fact that the current system is driven by an incentive system, and an industrial structure, that is disaggregated across both time and space. The incentive system that is used to address this social problem is an R&D sector generating antibiotics in pursuit of time-delimited intellectual property rights. The industrial structure utilised is a decentralised medical sector employing antibiotics on a case-by-case basis, choosing the prescribed antibiotic primarily under a simple cost effectiveness criterion. The combination of these sectors provides a perspective that is delimited in both time and space: the lost horizons of the title of this paper.

This is apparent from a brief consideration of the perspective of each sector on the social problem. First, the medical sector is focused on minimising the costs of disease to the individual patient. This results in the employment of the currently recognised "least cost treatment" for the pathogen problem on a nearly universal basis. The sector merely responds to the price-cost ratio uniformly, and employs the same antibiotic universally. This sector has no incentives to consider spatial externalities in use, and no capacity to take into consideration temporal externalities. Any distinctions between treatment strategies in use at different sites is merely incidental. There are no incentives to restrict the use of any antibiotic at any given site, in order to maintain resistance into the future, as other sites will simply use up any residual resistance. To the extent that any information or incentives exist to restrict use, these incentives are negated by the rules of liability that require uniform methods and standards of treatment. In short, the users of antibiotics have no incentives other than to pursue the application of a single treatment, and to apply it extensively and universally.

The more important sector for addressing problems of resistance management is the R&D sector. This sector is the one that society relies on to provide solutions to the problems raised by pathogens. The R&D sector is provided with incentives to pursue these solutions via *IPR regimes*: systems of term-delimited property rights that allow exclusive marketing rights to products that embody new solutions to significant problems. The rents from these systems are intended to provide the incentives for firms to resolve these problems. The pharmaceutical industry is motivated by the pursuit of these time-delimited property rights to create products that provide solutions to existing problems of infectious disease.

What is the extent of the system of incentives provided by such property rights? We have already demonstrated that the benefits from an additional antibiotic are made up of the private values (from reduced costs of application) and the social ones (from accretions to the aggregate stock of resistance available to treat the pathogen problem). Most often, the patent-based incentives are viewed as the pursuit of the former - the provision of a substitute treatment at a lower effective cost. The pursuit of further antibiotics under such a motivation depends on the existence of one or two possible conditions: 1) if the first set of antibiotics did not pursue the most obvious and least cost modes of intervention; and/or 2) if the technology

for producing substitute antibiotics is advancing independently of expenditures within the industry and affording rapid gains in cost effectiveness.[20]

If neither of these conditions exists, then the profit-based motivation for pursuing additional antibiotics is likely to be small during the life of the existing treatments. As discussed previously, it is more likely that the marginal antibiotic generates far greater social benefits than it does private ones. This is because it both adds another layer of potential treatment, and (potentially) reduces the level of virulence and increases the effectiveness of all of the other treatments in use. Of course none of these social benefits are available to the private investor under an IPR system, because the earlier treatments will already be over-prescribed (removing the need for a further layer of treatment) and in any event the developer has no interest in adding to the life or effectiveness of its competitors. Most of the benefits from developing additional antibiotics flow to society at large, in the form of increased and lasting effectiveness in the existing range of treatments. There is virtually no benefit to the private investor from creating a second antibiotic, once a cost effective one is already in use.

5. Why Recurring Problems Don't Attract Permanent Solutions. Or, the Private Benefits from Searching for Solutions

This indicates a general problem with an IPR system's approach to the resolution of resistance problems; they simply derive from conflicting paradigms concerning the nature of technical progress. IPR systems are built on a linear and monotonic view of progress, consisting of two fundamental tenets. First, each solution once achieved is permanent. Second, each solution once achieved renders previous solutions redundant. Thus, IPR systems are built on a conception that is something akin to a ladder-like view on progress: each step up the ladder renders previous steps irrelevant and affords a permanently higher platform from which to proceed. Biological problems on the other hand operate more in the manner of a treadmill than a ladder, as befits the world of Red Queen contests. The object in Red Queen contests is to match the opponent's strategy with your own that *both* maintains your relative position in the game *and* manages the pace and direction of the contest. There is no reason to gain a step on the opponent if the new rules of engagement render future gains unlikely. Thus, biological problems are necessarily cyclical in nature, and call for calculated responses (considering long-term impacts) rather than attempts at large technological leaps.

This fundamental incompatibility between IPR systems and biological solution concepts is the primary reason that a portfolio-based solution is not being sought in the realm of antibiotic resistance. Society currently has no mechanism in place or in process that would provide incentives for the generation of a portfolio of simultaneous solution concepts for a given biological problem. Such an incentive mechanism would have the characteristics of a prize system rather than a patent system, rewarding the discovery of each successful treatment irrespective of its capacity to replace immediately other existing treatments. This incentive mechanism would also have to provide the means for overcoming the clear liability implications deriving from the simultaneous treatment of a uniformly-afflicted population of patients with a heterogeneous set of antibiotics. Clearly, very little thought is being given to

[20] Assumptions regarding technological change are crucial to our arguments in this paper. We assume that there is no unanticipated exogenous technical change relevant to the pursuit of further antibiotics, (i.e. nothing other than that captured in the upward sloping MC curve). This implies that all potential antibiotics may be discovered at any given point in time, so long as sufficient resources are expended to do so. To the extent that the R&D sector has resistance itself to the absorption of additional resources at a given moment of time, or to the extent that advances in other sectors will cross over into the R&D sector with time, this assumption is limiting.

the derivative problems of providing a workable, long-term and portfolio-based solution to the fundamental problem of antibiotic resistance.

If patent systems are the wrong sort of incentive system to supply for resistance problems, then why is it the case that they continue in operation in this area? That is, if IPR systems do not solve the underlying problem, then why are there not incentives to replace them with incentive mechanisms that do?

The reason for this probably lies in the distinction between the social benefits from resolution and the private benefits from cycling. Consider once again the problem of antibiotic resistance. There are two very different approaches to its resolution: one broad and permanent, the other narrow and perpetual. The broad-based approach would involve the creation of a large set of simultaneous treatments sufficient to eliminate the need for further R&D on that problem. Once society has paid for the R&D necessary to acquire this set, no further rents would accrue to innovators in this sector. The narrower approach pursues a sequence of stop-gap measures that maintains the fundamental need for R&D, and hence provides a sector from which rents may flow perpetually.[21]

Thus, IPR systems may be seen to create perverse incentives regarding recurring problems, not only for the pursuit of additional useful antibiotics, but also for the depreciation of the effectiveness of the existing ones. If the existing patent holder has a reasonable expectation of receiving rents from future innovations in the antibiotic market, then there is no incentive to maintain the effectiveness of existing treatments beyond their patent lives. Previously-patented solutions become generic competitors once their patent life has expired, and so the decline in the pre-existing treatment's effectiveness is a necessary condition for the support of the successor's monopoly rents.

The IPR incentive mechanism generates the situation in which it is privately optimal to generate an ongoing sequence of distinct patented antibiotics, running down the effectiveness of each over the life of the patent. Then there is no incentive within this system to consider the potentially socially beneficial implications of the discovery and use of greater numbers of antibiotics across space and across time and, more importantly, there is no private incentive to remove the existing incentive system. The rents from cycling solutions are very likely much greater than the rents to be achieved from permanent resolution.

6. Translocating the Problem into the Environmental Arena: Accumulating Chemicals

The problem of antibiotic resistance is an excellent starting point for considering problems resistant to resolution, as it is a real-world example of evolutionary forces in action. However, the point of this paper is that resistance problems occur wherever opportunistic invaders seek opportunities (i.e. nearly everywhere) and wherever resistance to opportunism is erodable via subsequent opportunism. To illustrate this point, we will now turn to the problem of chemical accumulation in groundwater and see the similarities between the resistance to resolution here as was the case for antibiotic resistance. (see Swanson and Vighi 1999 for a general discussion).

Chemical contamination has been a regulatory challenge for several decades now. Increasingly, environmental problems regarding chemical contamination arise not so much from the toxicity of the chemicals involved as their ability to accumulate in natural resources. This point is highlighted by the troubles caused by DDT and other chlorinated hydrocarbon

[21] In theory it is possible that the permanent solution to the recurring problem could generate the same amount of rents as the impermanent one, if society recognised the innovators' contribution to the permanence of the solution; in practice, it is probably easier for an innovator to periodically resolve the same problem than to persuade society to pay for the permanence of a solution.

pesticides developed in the 1960s. It was considered at the time that the relative stability of these chemicals was a desirable characteristic – the compounds could be applied at relatively low rates of toxicity, with fewer applications required per year. Problems soon arose, however, as the pesticides accumulated at increasing rates while moving up the biological chain. The ultimate waste sink for these persistent chemicals turned out to be man himself. By the 1970s, human milk in many countries contained levels of DDT concentrations exceeding the World Health Organisation's guidelines for DDT in cow's milk (see Conway and Pretty (1991) for further details). The same is true for most of the problematic chemicals of today. Many pesticides currently present in high concentrations in drinking water are comparable to aspirin in terms of their toxicity. The real social problem regarding these chemicals relates to their rate of accumulation and not their innate toxic characteristics.[22]

The majority of consumers in Europe receive their drinking water from untreated groundwater. (Soderqvist 1998). When agricultural chemical use occurs in the proximity of aquifers, there is the potential prospect of groundwater, and hence drinking water, contamination. This depends on the particular characteristics of the chemical involved: its biodegradability and its affinity for water. In July 1980, the European Commission responded to the problem of chemical accumulation in drinking water by issuing a directive (Number 80/778/EEC), setting a *maximum admissible concentration (MAC)* for individual chemicals and micro-organisms in human drinking water of 0.1 microgrammes/litre, and a `cocktail' standard of 0.5 microgrammes/litre for the total concentration of all chemicals. (The cocktail standard was subsequently removed in 1996.) This limit was determined by measurement technology, 0.1 microgrammes/litre being the lowest detection level of scientific instruments available at that time (see Faure (1994).) States failing to meet the conditions of the Directive risk condemnation by the European Court of Justice, and imposition of penalty payments. Moreover, since the Directive is also implemented in national legislation, any company that supplies water that does not meet the requirements of the Directive risks being found civilly or even criminally liable; see Faure (1994).

European countries have responded to the Directive in a variety of ways; the most common is to institute a *product-specific ban (PSB*) on the offending chemical. The merits of this form of regulation -- the removal from use the particular chemical already present at high concentrations; and the signalling of society's disapproval of excessive accumulation -- explain the popularity of the approach: by 1993, 78 countries had instituted this type of ban (see Rolike (1996)). For example, the Federal Republic of Germany has banned on an individual basis three hundred of the (approximately) one thousand pesticides registered for use. Italy banned in 1990 the sale and use of atrazine on maize and alachlor on soya in response to increasing concentrations of these chemicals in groundwater. (See Zanin et al. (1991), Bergman and Pugh (1996), for further discussion of this case.) In this manner the EU takes an uncompromising stance with regard to chemicals with characteristics that cause them to accumulate in groundwater.

How are these chemical products produced? The agricultural chemical manufacturing industry had an annual global turnover of approximately US$25 billion in 1992 (see Nadai (1995)). At that time twelve firms accounted for around 80% of these sales i.e. the market is very concentrated. The industry is science-driven, with firms sustaining product differentiation through large investments in research and development. (Some estimates of the R&D costs of bringing a new product to market in 1994 were as high as US$147 million.) Only the twelve large firms are involved in R&D to any significant degree. Innovation is protected by long patent lengths; protection extends for twenty years in the European Union. Once the patent expires, however, regulation mandates the release of the full dossier of data for any out-of-patent chemical to any firm that can manufacture a similar product. There were approximately ninety agrochemical firms engaged in the manufacture of previously-patented

[22] See Lloyd and Swanson (1996) for discussion.

products in the European Union in 1994. Hence competition from generics after patent expiration is, to a reasonable approximation, perfect.

In summary, a concentrated chemical industry designs chemical characteristics that are used in pest-control products in agriculture. When successfully marketed, agricultural chemical sales by chemical firms occur in two phases: first under monopoly, while the innovating firm enjoys patent protection; then under perfect competition, as imitating firms are allowed to enter the market. Once a problem of water contamination occurs, chemical accumulation in drinking water is regulated in the EU by a combination of a MAC plus PSBs.

Does this regulatory system impose a permanent solution for chemical accumulation problems, or does it different incentives regarding these problems? A recent paper demonstrates that in this context once again the incentives here are for cycled solutions rather than real progress. (see Mason and Swanson, 2001).

It is the MAC/PSB form of regulation of the natural resource that raises the possibility of strategic behaviour by the incumbent in order to retain a flow of rents in perpetuity. In the absence of this combination of regulation, other firms will enter the market at the end of the patent life and remain there in perpetuity. Environmental regulation ensures that these firms must eventually cease production, since sales of the first chemical are banned once the product's accumulation reaches the MAC. The incumbent can exploit this fact to restrict generic competition, by ensuring that its patented products have accumulative characteristics. This means that it is then able to enter onto the market a sequence of patented solution concepts for the same underlying problem, extracting rents for each. The interaction of environmental regulation and IPR system enables the innovator to maintain a permanent stream of rents, without ever pursuing a final solution concept.

This phenomenon of patent-based cycling may be seen in the case of the EU chemical accumulation problem. Concentrations of atrazine, a herbicide used in maize cultivation, in Italy reached the MAC specified in the European Directive in 1984; in 1989, eleven wells in the Veneto region recorded atrazine levels of over 1 microgr/l. Local restrictions in 1986 against contaminated drinking water supplies had little effect, and a nationwide ban on the sale and use of atrazine was imposed in 1990. In addition, the sale and use of alachlor on soya was also prohibited; and the maximum permissible doses of several chemicals were reduced significantly. See Zanin et al. (1991).

What evidence is there that chemical manufacturers in Italy have responded to the MAC-PSB regulation in the way predicted by the model in this section? Figure 2 (taken from Vighi and Zanin (1994)) shows information on the likely accumulation rates (GUS indices) for 14 herbicides now in use in Italy.[23]

Chemicals labelled with numbers are herbicides used in Italy before the banning of atrazine (labelled `1' in the figure). Immediately striking is the clustering of all but three of these chemicals at moderate solubilities and half-lives, and hence with transitional to leaching

[23] The *GUS index* indicates the ability of an agricultural chemical to accumulate in groundwater, and has two components. The *water solubility* of a chemical is measured by its partition coefficient KOC. KOC measures the tendency of a substance to bind to soil solids, and is obtained conventionally by a calculation based on the KOW, which is the partition coefficient for non-ionic molecules in an organic medium (octanol) versus water. The higher the coefficient, the less soluble is the chemical in water. Degradability of the chemical is measured by the (logarithm of the) half-life in soil (t1/2). The GUS index is then defined by GUS = log t{1/2} (4 - log KOC); herbicides are classified as *water leachers* (if GUS > 2.8), *non-leachers* (if GUS < 1.8), or *transitional* (1.8 < GUS < 2.8).

values of the GUS index. The chemicals labelled with letters are three herbicides that have been registered for use in Italy after the imposition of the ban on atrazine. The GUS indices of two of these products are greater than those of the previous substitutes for atrazine (linuron and terbutylazine, labelled `7' and `11' respectively); the GUS index of the third is comparable to previous levels. *Figure 3 shows, therefore, that the result of the atrazine ban has been an increase (at best, no decrease) in the accumulation ability of the chemical herbicides in use there.*

The hoped-for effect of MAC-PSB regulation is to decrease in chemicals' accumulation abilities. Why has the result been the opposite? One explanation is demand-driven -- chemicals must have a certain minimum level of persistence (GUS index) in order to be useful. But there is little empirical evidence that this is the case -- all current studies suggest that there is no (hedonic) demand for the accumulative nature of these chemicals (based once again on the respective GUS index). (Soderqvist 1998). An alternative, supply-side explanation is provided by the discussion above. Manufacturers may have strong incentives to increase the accumulative characteristic of patented chemicals for strategic reasons. This is obviously not a conclusive test of the model. The evidence does suggest, however, that firms are not reacting in a simple fashion to the regulation introduced in Italy.

This case study demonstrates the opportunities for strategic behaviour by opportunistic firms that can be created by environmental regulation. Product bans, by sending out a clear message as to which products and technologies are socially acceptable and which are not, seem a sensible way for regulators to attack the problem of over-exploitation of natural resources. This ignores, however, the opportunities that may be created for strategic behaviour by the opportunists that are being managed. The imposition of a regulatory limit on chemical accumulation defines a threshold that manufacturers can use strategically; the anticipation of a future patent gives the incentives to do so.

Chemical accumulation problems are another example of a situation in which opportunists are supplying a sequence of solutions rather than a final solution – in order to maximise the rents that may be received from undertaking problem solving in this area. A single carefully calibrated chemical solution would balance the costs of pest control and water accumulation and provide a permanent resolution to this trade-off. However, such an approach does not provide the opportunity for an unending stream of rents, as does the cyclical approach to chemical accumulation. Keeping problems alive is one way in which problem-solvers generate rents.

7. Environmental Policy Making when Resistance is Endogenous

What are the implications of this discussion for environmental policy making? The general argument is that the underlying problem regarding environmental pollution flows from the existence of a population of opportunists ready and willing to attempt the appropriation of unprotected resources. Just as with a population of pathogens, the attempt to manage the population with a “static” strategy is doomed to failure. It merely directs the evolution of the problem, and does not address the fundamental nature of the problem.

What is the distinction between static and dynamic approaches to environmental management? The difference lies in the incorporation of the reaction to the planned policy. Just as with the pathogen population, the environmental opportunists have a wide range of strategies to use in order to attempt to appropriate resource rents. When an environmental policy maker implements a policy that removes a single strategy from the opportunist’s arsenal, this does little other than to divert the opportunist toward other strategies. The fundamental problem cannot be resolved without taking into consideration this feedback

effect. Resistance to management is endogenous to the situation, and so a static sort of solution concept cannot be effective.

Why is this concept of resistance management more suitable to environmental problems than might be to other social problems? This is attributable to the fact that the most difficult resources to protect from such opportunists – air, water – are those which we wish to make available for all for reasonable uses (breathing, bathing) but which then provide a myriad of opportunities for opportunists. The concept of resistance management requires a certain level of "community" for its existence, because there must be opportunities for opportunism to flourish. The evolutionary paradigm indicates that the attempt to maintain some segments of the natural environment and natural resources within the public domain will therefore require increasing levels of public investment to maintain the same level of public goods. This is the implication of the Red Queen contest; more and more complicated strategies are necessary just to maintain parity.

It might be for this reason that we see increasingly complicated institutions required to address the same fundamental environmental problem. In the nineteenth century nuisance law was adequate to the task. In the twentieth century nuisance law combined initially with planning law, and then entirely new environmental agencies were developed. One argument for this progression has been demand-based, i.e. the accumulating institutions represent increasing demands for environmental quality (the environmental Kuznets curve debate). Another argument would be supply-based, i.e. evolving strategies are required to maintain parity in the contest with opportunists (the resistance management hypothesis). It is very likely a combination of the two effects that has produced the increased complexity of management strategies that has resulted over the past hundred years. (Swanson 1992)

What is the nature of a *dynamic approach* to environmental policy? Both the antibiotic management and the pesticide management case studies are instructive. In both cases the imposed policy failed to consider the response of the managed population. The use of a single antibiotic pervasively and persistently simply directed the pathogen population toward its strategies successful in that environment. The use of product-specific bans on accumulative pesticides pointed the chemical manufacturer in the direction of those strategies that were privately-profitable in that context. Both case studies indicate the importance of incentivising environmental policy in a fundamental manner. The object of environmental policy must not be the prohibition of specific strategies so much as the inculcation of the social object regarding the resource. Prohibitions simply direct the evolution of the contest, while resolution might require recognition that the resource must be allocated in some fashion in regard to the activity.

For example, in the case of antibiotic management, the optimal policy probably is to recognise that resistance management requires the restricted use of the available antibiotics. This manages resistance by moving to the only solution concept that is sustainable.[24] In the case of pesticide management, the optimal policy probably involves the recognition that a level of pesticide contamination will occur and to tax accumulation at the level that will generate the optimal level of accumulation. The alternative is to halt the production of all chemicals that have an affinity for bonding with water, rather than simply those products that appear in groundwater. (Swanson 1999) In either case the basic point is to recognise the fundamental contest that is occurring for the allocation of the resource, and to anticipate its continuance within the solution concept. This will not provide for "win-win" solutions to environmental problems, but instead will resolve the problems with finality by recognising the zero-sum game nature of resource allocation decisions.

[24] Of course maximum sustainable yield is not always socially optimal management, but in the case of a health-related good it is arguable that there is no social interest in substituting other capital goods for health.

Most importantly, why is it that environmental policy making continues to cycle solutions rather than resolve conflicts in resource allocation? This points to the fundamental paradox of resistance management: it guarantees an infinite stream of rents to those searching for solutions. There is always a value to be appropriated from the generation of a solution to a problem. When the problem then re-emerges (unexpectedly!), this renews the value that society will pay for its solution. For example, a pharmaceutical firm does not get paid less for the second antibiotic treatment it develops after the first develops pathogen resistance. The second generation of accumulative pesticides did not cost less. Agents may operate this rent-stream treadmill forever without society ever making one step of forward progress.

The resolution of the underlying problem truncates this stream of rents, and hence it is in no private agent's interest to do this. If society could make differential payments to problems that were resolved rather than solved, then such an incentive might exist. However the prevailing IPR system provides the same time horizon of rents irrespective of the duration of the solution; any additional benefits accruing to society are lost horizons to the agents.[25]

For these reasons there is little reason to expect environmental policy making to move toward the final resolution of the fundamental resource allocation problems concerned. Even if the public agencies involved made the attempt to incentivise the final resolution of environmental problems, it is very difficult to see how this can ever be made to benefit private agents. So long as the public sector is reliant on the private sector for the supply of solution concepts, the search for solutions is likely to go on.

8. Conclusion

Opportunists are the same whatever the context, and whether they are pathogens or polluters. They are relatively straightforward agents that apply opportunistic strategies to the appropriation of relatively unprotected resources. The managers of opportunism must recognise that thwarting one strategy does not represent success, since the basic program of the opportunist is to maximise resource appropriation not the simple-minded application of a specific strategy. This is what I have termed the endogenous resistance to environmental problem solving.

Given resistance to management, there must be resistance management incorporated into effective policy making. At its simplest this only implies the consideration of the potential responses to a specific policy, i.e. there must be some consideration of the dynamics inherent in the situation. Otherwise policy making only determines the possible pathways down which opportunism evolves; it does not halt it.

Even more fundamentally, resistance management requires that the fundamental problem of resource allocation be identified and resolved in order for progress to occur. For example, chemical contamination of groundwater is inherent in the nature of most herbicide products. In order for all chemical contamination by herbicides to be prevented, it would probably be necessary to disallow the production of all chemicals with an affinity to water. This is unlikely to be a socially acceptable outcome, and so it is more likely that the problem requires that society make a determination of the level of affinity that chemicals might have for water. This is the fundamental resource allocation decision inherent within the issue of groundwater contamination, and policies that address other issues are avoiding the resolution of the problem.

[25] This points to one obvious solution concept, i.e. IPR systems of indefinite duration. This would remove the incentive to create time-delimited solutions (such as the accumulating chemical), but it would not increase the incentives to resolve the problem. So long as the agent has some expectation of winning a future patent for a solution, it has an incentive not to solve the problem with finality.

Why is the resolution of the fundamental resource allocation problem so often avoided, in favour of partial and impermanent approaches? One reason is that the solution of a problem for a few years probably achieves the same private return for the innovator as would its permanent resolution, and also leaves the problem to re-emerge to generate a new stream of rents in the future. Resistance is the guarantor of a permanent stream of rents for a given industry.[26]

Nevertheless, societal progress should be aligned with the resolution of problems, not running in place. This means that environmental policy should be motivated to the resolution of the fundamental problem, even if industry generates greater private benefits from a string of short-term solutions. This is difficult to accomplish, both because the public sector is usually reliant on the private sector for solution concepts and because it is driven in part by private sector demands.

[26] In the context of antibiotic resistance, it is a problem of myopia that the private agent is internalising; if the public could perceive the permanent stream of benefits from *non-emerging problems*, then the agent would have incentives for resolving problems. Since the generation of such a counter-factual is not possible, private benefits are maximised by short-term solutions applied to problems that will then re-emerge.

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Figure 1: The Socially Optimal Number of Antibiotics

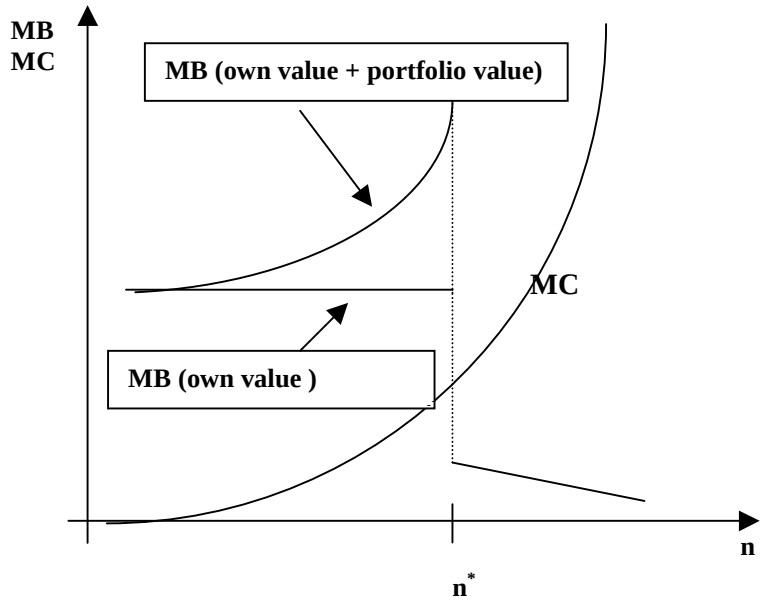

Figure 2: Accumulativeness of Replacement Chemical Pesticides (Zanin and Vighi 1994)