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The Management of Genetic Resources for Agriculture: Ecology and Information, Externalities and Policies

EVOLUTION, INFORMATION, EXTERNALITIES AND POLICIES

This paper surveys the work in several fields relating to the economics of managing genetic resources for agriculture. Most fundamentally, this is a problem relating to inherent ecological dynamics in agriculture. Ever since agriculture was first developed, there has been a race implicit within it, with pests and pathogens eroding the resistance of the crop varieties currently in use and new varieties being devised to replace them. This contest can never be won with finality by agriculturalists, and the correct formulation of the question concerning agricultural sustainability must be whether it is possible to remain a player in the race indefinitely. As inputs into agriculture, genetic resources play a prominent role in the continuation of the contest, and their optimal conservation – in order to ensure an optimal supply of resistance into the indefinite future – is at present a necessary condition for the continuance of agriculture. This paper examines what is meant by the optimal management of genetic resources, as important inputs into both the improvement of productivity and the maintenance of agricultural sustainability. The four facets of the problem cover ecology, information, externalities and public policy.

The ecological facet concerns the definition of the dynamic processes inherent within the agricultural system. This requires the identification of the forces within the natural world which produce the changes in the pathogens and pests that result in the erosion of crop resistance. To counterbalance these forces, agriculture has devised a system for introducing particular traits and characteristics into crop species that resist evolutionary forces. The contest is to maintain a steady state of relative balance between the two. The first task is to describe the contest and derive the ecological constraint within which agriculture must exist.

The informational facet of the problem concerns the nature of the industry which works on the solution to the underlying ecological constraint. This is a classic research and development (R&D) problem, namely the need to generate solution concepts in anticipation of predictable, but non-deterministic,

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problems. Crop genetic resources act as information in this process, both as stocks (in the form of accumulated traits of known usefulness) and as generators of current flows. The plant breeding sector works to generate, use and appropriate the value of this information.

The externalities in the management problem concern the values of genetic resources which will not be taken into consideration when decisions are made concerning the conservation of genetic resources. Plant breeders will clearly wish to invest in the provision of supplies of crop genetic resources for purposes of their R&D work, but there are also resource values falling outside their decision-making framework. These involve the longer-term, and somewhat diffusive, insurance and informational values of crop genetic resources. Private plant breeders have the incentive to invest optimally in the supply and use of genetically based information, but only to the extent that values are appropriable on a timescale relevant to them. The gaps within this objective identify the public good nature of genetic resources and define the reason for which the public sector must be involved in supplying the socially optimal amount of genetic resources for agriculture. These externalities are defined later.

The existence of externalities implies that there is a clear public interest in the provision of optimal supplies of genetic resources for agriculture which are not being met by private-sector efforts alone. Once this is accepted, there are two fundamentally different approaches to the solution of the problem, namely *ex situ* and *in situ* conservation. These are fundamentally different both in their impacts on land use and in their implications for genetic resource conservation. One is focused on the conservation of existing stocks of useful crop genetic resources, while the other is focused on the appropriation of incoming flows of useful information. Both forms of conservation are essential for the distinctive role each plays, but it is important to analyse both in terms of the informational outputs which they generate. The optimal policy for resource conservation will be discussed.

The optimal management of genetic resources for agriculture is an important public function, because it has long-lasting implications for the sustainability of farming and because it is clear that there are impacts which are unmanaged otherwise. Any discussion of sustainability in agriculture must include an analysis of the optimal methods of management relating to the resources required to maintain an equilibrium within it. Currently, there is no substitute for the informational stocks and flows inherent within genetic resources for the solution of the continuing problem of instability (that is, erosion of resistance) in agriculture. Therefore the optimal management of genetic resources must be carefully considered in order to identify the precise nature of the tasks that must be undertaken to sustain global agriculture. This paper attempts to make a contribution to this area by outlining the fundamentally ecological and informational nature of the problem that must be resolved.

THE ECOLOGICAL PROBLEM: EVOLUTION AND AGRICULTURE

What does agroecology have to say about the stability of the modern system of agriculture? Biologists would ask how it is possible that pathogens and their hosts could coexist for hundreds of thousands of years without temporary advantages in one of the species leading to the natural extinction of the other. Increasingly, the answer given has been that pathogen and hosts coevolve by changing their genetic structure, and thereby their phenotypical traits, and that, while we observe fairly stable *ecological* relationships, there are races of 'genetic innovation' going on underneath this apparent equilibrium (Hofbauer and Sigmund, 1989). It is the underlying race to innovate that sustains the balance between predator and prey, and maintains the stability of the system.

In ecological terms, the stable dynamics witnessed in agriculture are known as a 'Red Queen' race (from *Alice in Wonderland*). It is necessary to continue to make moves in order to stand still. In coevolutionary settings of predator–prey models, it is possible to show that the populations of hosts and pathogens will reach an ecological steady rate where virulence, or its mirror image, susceptibility, do not change. In other words, the system converges to a long-run equilibrium of host off-take and stable population levels. This does not imply that the underlying dynamics have stopped, in fact, both pathogen and host populations continuously update their strategies in order to cope with the constant increase in the opponents' ability to improve its growth parameters.

How has the development of agriculture affected these evolutionary contests within the biosphere? The choices formerly made by evolution have been supplanted by human choice in certain spheres of activity, but the general nature of the contest remains. Humans have selected the crops and crop varieties most easily appropriated by themselves (and hence denied to competing pathogens), but this simple act of selection introduces genetic drift within the competing population pathogens that renders them increasingly competitive. This harvest's appropriation generates the next harvest's competition, and the race is on. Ever since human societies interjected themselves into the role as selector, the innovation contest between them and the pathogens affecting their crops has been going on.

The process is apparent in the studies of declining resistance in agriculture. There has been steady erosion of the productivity of the best performing and most widely used crop varieties owing to evolutionary pressures from pathogens. This has been addressed by means of the periodic interjection of new varieties into agriculture, and their consequent decline. A cycle of introduction and subsequent decline is documented for a range of crops and crop varieties (Evans, 1993; Smale, 1996; Rejesus *et al.*, 1996). A recent empirical analysis has even estimated the impact of 'age' of a variety (that is, years in agricultural use) on its productivity, and found that it is significantly negative (Hartell *et al.*, 1997). Though human choice has constantly altered the setting for the evolutionary contest, the basic nature of the problem remains unchanged. In the management of crops and crop varieties, we continue in a contest of appropriation and innovation with natural predators and pathogens.

The essence of the contest can be captured within a simple model of coevolution by adopting some formal techniques from evolutionary biology.

Let us denote by r the relative fitness of a particular pathogen of a particular crop. For the purpose at hand, 'fitness' is defined as the pathogen's ability to consume host tissue, measured against some fixed point in time. To say that 'r has increased' therefore means that the pathogen would be able to consume more host material per unit of time than before.

In terms of intertemporal methods of decision making, r may be regarded as a stock variable of a 'bad', which could be called 'virulence', or a 'good' which could be called 'resistance' (Hueth and Regev, 1974; Cornes *et al.*, 1995). The dynamic processes which govern the behaviour of r over time are attributable to changes in various characteristics in both the host and the pathogen, changes which alter the biotic potential of either organism, with r indicating the relative standing of each in this contest. Each may be seen as being engaged in an intricate exchange of moves to counter the change in strategies of the other, and this can lead over time to the development of the ecological interrelationships as well as the genetic structures of host and pathogen populations (Allard, 1990).

For simplicity, we will assume a one-to-one relationship between parasite and host (that is, a parasite only feeds on one variety of host plants and this host plant variety only has one parasite).[1] The expected increase of relative fitness of pathogen i equals the product of the natural mutation rate μ, a discrete change in fitness of size Δ occasioned by a 'beneficial' mutation in the genetic structure, and the probability (k) that a mutation of this size will become established in the pathogen population.

Basically, the *pathogen specific factors* determining changes in virulence/resistance can be expressed as:

$$E(\dot{r}_i) = \mu \cdot \Delta \cdot k_i.$$

In considering the impact of human agriculture on the dynamics of pathogen evolution, the first characteristic in the equation (that is, the rate of mutation) is relatively exogenous, but the others are not. As summarized in Table 1, the impact of agriculture on pathogen dynamics has operated by determining the relative rates of availability of particular hosts and by generating greater discrete changes in pathogen fitness. In essence, the impact of agriculture has been to reward those pathogens which are adapted to the now widely cultivated modern varieties, while encouraging large gains in fitness (severe selection pressure) on those which are not.

To analyse the dynamics of host evolution within this hostile environment, it is important to note, first, that responsive evolutionary forces must exist in nature, in order to counterbalance the dynamics inherent within the pathogen populations. Otherwise, aggregate production by host populations will always be in a state of decline, as pathogens seek out and exploit these opportunities. The previously noted long-term stability within the overall system indicates that hosts possess the scope for evolutionary development in order to counter pathogen evolution and restore equilibrium (Allard, 1990).

The *host specific factors* determining changes in resistance/virulence are given as:

$$E(\dot{r}_i) = \pi \cdot \Gamma_i \cdot v.$$

This formulation of host dynamics is analogous to the representation of the pathogen dynamics set out previously. We will define π as the natural mutation rate of the host (which is presumably lower than that of pathogens) and Γ as the discrete change in the host's ability to produce in the face of pathogen infestation. Finally, we have the likelihood that this random change will become dominant within the host population, which we denote by v (Burdon *et al.*, 1990, p. 238).

TABLE 1 *Impact of agriculture on pathogen dynamics*

Ecological part affected	Symbol	Nature of impact
Pathogen	μ: mutation rate	no impact, exogenously given
	Δ: size of relative change in fitness	more competitive environment (lower general level of fitness) generates greater relative changes in fitness by successful mutants
	k: probability of successful mutation => host availability	enhanced likelihood of success for pathogens adapted to 'intensely cultivated' crops

Even in the absence of human intervention, host species have the inbuilt capacity for change that is necessary for survival within a dynamic environment. Natural selection within crops would select a *flow* of traits and characteristics capable of surviving in the then prevailing pathogen environment. In effect, the inherent stability evidenced by evolutionary processes represents a flow of responses to the problematic strategies thrown out by pathogens.

What, then, is the role of the agriculturalist in this context between hosts and pathogens? That is, how has agricultural selection performed a role in this contest of strategic response and reaction? The agriculturalist has contributed by means of observation of the results of the natural contest (observing which traits carry 'winning' strategies) allied with discriminatory transport and resource allocation of the varieties carrying those traits (accelerating the rate of their dispersal to lands made available for their introduction). In essence, the agriculturalist has aided the successful trait signalled by natural selection, through non-natural forms of diffusion and land allocation. Table 2 summarizes these impacts on agriculture.

The net effect of agriculture on these ecological contests within nature has not affected the stability of the system, but the nature of the contest has been altered. Agriculture has marked a shift from a natural form of competition to a

TABLE 2 *Impact of agriculture on dynamics of host evolution*

Ecological part affected	Symbol	Nature of impact
Host	π: mutation rate	no impact: exogenously given
	Γ: change in host resistance (potential for response to pest virulence)	greater changes in fitness through human observation of natural selection and human selection of the most successful from that set
	ν: likelihood of successful mutation	enhanced likelihood of success by means of human transport and resource (land) allocation

human-made contest of innovation. Once human societies began taking production decisions regarding which species and varieties would grow where and at which intensity, important parameters of the ecological relationship between plants and pathogens started to become societal choice variables rather than purely natural processes. This is confirmed by a glance at Tables 1 and 2.

Not only did agriculture introduce a new form of contest between human society and nature, but it has been a steadily accelerating competition since that time. The rate of evolutionary change of pathogens of cultivated crops can be expected to be higher under agriculture than the average which prevailed prior to agriculture, since the previous pests faced a less competitive environment. As humans continue to appropriate an ever-higher share of photosynthetic product, they generate an ever more selective environment and, as a consequence, a more rapidly paced contest. Our previous conquests generate ever-greater challenges.[2]

How has the agriculturalist managed to keep pace in this environment? It is apparent that farming systems have been characterized by relative ecological sustainability, both under traditional agriculture and under modern intensive methods. The compensation for the increased speed of pest evolution must, therefore, originate from the ingenious use of the instruments available to the agriculturalist to 'manage' host evolution. Sometimes this has involved the selection of varieties with a high intrinsic propensity to develop resistance, but it has more commonly been associated with the observation and rapid dissemination of traits revealed as being successful in current pathogen environments (Evans, 1993). Hence the agriculturalist has contributed to the maintenance of stability in this contest by means of observation (of natural selection), own selection and biased resource allocation.

It is possible to view the maintenance of ecological stability as a sort of constraint that should be imposed when maximizing static productivity in agriculture. That is, if the short-term objective of maximum agricultural productivity is being pursued, this ecological constraint should also be observed in order to ensure that an unsustainable agricultural production path is not chosen.[3] Keeping up in this contest of innovation should be seen as a primary and fundamental goal of agriculture; otherwise, short-term gains may be pursued at the risk of long-term instability. Hence the following stability condition (1) might be viewed as the fundamental condition for maintaining agricultural sustainability (in the context of otherwise unconstrained agricultural production).[4] The *stability condition* in the dynamics of virulence/resistance is:

$$E(\dot{r}_i) = \mu \cdot \Delta \cdot k_i - \pi \cdot \Gamma_i \cdot v = 0. \quad (1)$$

The core of the issue that we are concerned with in the management of genetic resources for agriculture is whether it is possible to sustain this equilibrium indefinitely. Genetic resources constitute the 'strategies' that are available to human society in contesting this natural race of innovation. Genetic resources are, in effect, the *information* base on which we must rely in our continuing quest to retain agricultural stability. Of course, much of this contest is undertaken by a very successful private activity – the research and development sector of the plant-breeding industry – but the interesting issue for public economists remains. Is there an important or necessary role for the public sector in the management of the contest?

THE PUBLIC GOOD NATURE OF THE PROBLEM: EXTERNALITIES AND AGRICULTURE[5]

To what extent does the agriculture industry itself make the best use of genetic resources? The previous discussion indicates that the plant-breeding industry is addressing this fundamental problem, as well as supplying and using genetic resources in order to do so. Stability has been maintained for thousands of years of agriculture, without the need for intervention from the public sector; why would it be necessary now? This section sets out a broad framework for the conceptualization of all values of genetic resources, and then compares the private sector's management objectives with those of society generally.

There are two broad forms of values which best describe the role of genetic resources in agriculture: *insurance* and *information*. Insurance refers to the value of genetic diversity in providing a broad base of independent assets on which to build production. It was the motivation to which the individual isolated farmer responded when planting a wider range of varieties to insure against crop failure. In the past, if that happened, society also faced collapse. Investing in diversity provided the portfolio of different assets which insured against complete crop failure. Information refers to the uncertainty that exists about the future, which will only be revealed with the passage of time. In the context of agriculture, information arrives whenever the nature of the next invading pest or disease is revealed, or when the nature of the best strategy for resistance is identified. Diversity is useful in this context because it acts as a receiver, capturing information on the nature of successful resistance strategies through the process of selection. A greater diversity of plant varieties increases the prospects for the survival of at least one variety when a pest or disease passes through, thus providing the necessary information for the development of a successful strategy against the prevalent pest. It signals the traits and characteristics that are successful in the new environment. When these signals are used, or accumulated, they provide the basis for continuing stability in agriculture.

To look at the way in which the agricultural industry addresses these fundamental values in their broadest sense, and how well it manages genetic resources, requires some outline of the nature of a number of key concepts. A basic assumption is that the supply of genetic resources in agriculture corresponds directly to the objective function of agricultural producers. We can then look to the individual decisions which determine the production choices in agriculture, and attempt to identify which, if any, of the values of genetic resources are external to the process. These external values (covered below) determine the public interest in conserving biological diversity for agriculture.

Expected agricultural yield

Expected (average) yield is the fundamental criterion used in the determination of the vast majority of crop choice and land use decisions. The beneficial effect of this criterion is unquestionable. One example of the aggregate impact has been the 'green revolution', the increase in worldwide grain yields at a rate of nearly 3 per cent per annum over a period of 30 years. What has been the impact on genetic resource supplies? Empirical studies indicate that there is an opportunity cost implicit in the retention of a diversity of genetic resources in production (Heisey, 1990). Nevertheless, it is very often the case that local demands of consumer and producers lead to the retention of some amount of diversity (Altieri and Merrick, 1987). In summary, with the dissipation of the need for diversity as an individual insurance good, there has been an increasing focus of production choices and land use decisions on a small set of the highest yielding varieties across the globe.

Portfolio value

This is the static value (available in a single growing season) derived from the retention of a relatively wider range of assets within the agricultural production system. It is the value which individual farmers formerly pursued when they had few other assets to rely upon. Now that individual farmers rely upon other features for their insurance needs (access to markets, crop insurance programmes and so on), the public sector must consider the cumulative impact on yield variability deriving from individual farmers' land use decisions. As long as society is averse to risk and has, therefore, a distaste for yield variability, it will have a greater desire to invest in more diversity of production methods than would any individual farmer. Yield variability is smoothed by reason of non-conversion because this implies (1) a broader portfolio of assets (varieties) within the species, (2) a wider portfolio of assets (agricultural commodities) within the country and (3) a wider portfolio of assets (available methods of production) across the globe.

A topical example of a harmful 'portfolio effect' is the current BSE problem in the United Kingdom. Disease within the food chain is a problem in any event, but when an outbreak becomes endemic within an activity in which a country is heavily invested, the costs of the pathogen become extremely heavy. 'Mad cow disease' is a portfolio problem because it is the United Kingdom's investment strategy that has made it possible for this single pathogen to have such a substantial impact on such a large proportion of the agricultural industry. The country is so heavily invested in beef and dairy breeds that it is difficult for it alone to absorb the cost of the eradication campaign that is probably necessary to restore consumer confidence.

The most important level at which this externality operates is the global one. Any given country has the same incentives as the individual farmer to rely upon other national assets for insurance in times of crop failure. This obviously does not work on a global scale; if all countries plant common varieties, expecting to rely upon one another's harvests in the event of a national crop failure, the fallacy of their reasoning would be revealed only in the context of a global crop problem. This would occur, for example, if the four primary carbohydrate crops (rice, wheat, potatoes and maize), which now provide the majority of the world's diet were subject to severe pest invasions in the same year. The continued narrowing of the range of production methods, crops and crop varieties in use across the globe continues to enhance the cumulative probability of such an occurrence.

There is another more fundamental level at which this portfolio value operates. One of the ecological functions of diverse genetic resources is to act as 'fire breaks' in the event of pest and pathogen epidemics. As agriculture intensifies, these breaks are removed, enhancing the risks of the mutation of virulent strains of pest. The ecological portfolio value of genetic resources is positive by reason of the manner in which it reduces the contagion effect.

There is empirical evidence to demonstrate that modern intensive agriculture has had a systematic impact on correlated yields across the globe. The studies of yields have indicated that there has been a corresponding increase in variability going hand-in-hand with the increased average yield. The coefficient of variation in global grain yields has nearly doubled when the experience of the 1960s is compared with that of the 1970s (Hazell, 1984; 1989). The larger part of this enhanced variability is traceable to the reduced portfolio effect across space (international and intranational) rather than within species; that is, it is the adoption of a smaller number of crops and methods (rather than genetic uniformity itself) which is contributing most to the increase in variability. This is indicative of the externality that exists across countries when they are making their land use decisions.

Quasi-option value

This is the value of retaining a wider portfolio of assets across time, given that the environment is constantly changing and rendering known characteristics far more valuable than they are currently considered to be (Conrad, 1980; Hanneman, 1989). For example, this is the value of the retention of certain varieties of cultivated species (not known to be of any substantial expected value) but which are found to be of enhanced usefulness when a particular form of pest or disease becomes more prevalent. It is the change in the value of a known characteristic by reason of an unforeseeable change in the environment. Clearly, this is a value that is not addressed by means of expected (mean) yield forms of decision making.

There is also an ecological quasi-option value. It is the value of the retention of some manner of evolutionary process intact, in the event that some trait for resistance might be identified via natural selection. That is, it is the basis for a distinct value to *in situ* conservation. For example, the continued cultivation of a wide range of varieties of wheat within a natural environment would allow natural selection to signal which variety has the resistance to a newly invading pest. *In situ* conservation allows nature to signal this information and identify the important trait in the most direct fashion.

Although individual farmers utilizing the expected yield form of decision making do not consider these values, there are other parts of the agricultural industry which do. It was argued earlier that quasi-option values are one of the driving forces within the plant-breeding industry. Plant breeders retain genetic resources and continue to breed them into their lines of high-yielding varieties, for the express purpose of addressing the recurring problem of declining resistance. Are there any externalities at work within this process? One thing is certain: society would supply a much wider range of genetic resources than those which would be perceived as imminently profitable by a plant breeder. This is indicative of the difference in the discount rates in use in evaluating supply decisions. Clearly, a business firm will use its financial rate of return (usually in the range of 10 to 20 per cent) in order to evaluate investment options. Most economists agree that a social investment decision should be evaluated at a rate nearer to 2 to 5 per cent (Pearce and Ulph, 1995) while there is an argument to be made that the social discount rate should be even lower (or possibly zero) when the survival of future generations is at stake. This difference in discount rate will make a huge difference in the amount of genetic resources that would be supplied by the public sector, but would not be supplied by the private. It means that a business firm would be considering a time horizon of not more than five to ten years in making its decisions, while the public sector should be considering possible problems arising well beyond that length of time.

It is also important to note that private firms are less likely to focus on a range of information-generating mechanisms than would an idealized public sector. This is both on account of the need to have the information in immediately appropriable form (since appropriation after ten years would be discounted to zero) and because investments in information production must be relatively secure from the standpoint of the private investors concerned (that is, they are as concerned about the distribution of any informational gains as about production). Such considerations weigh in favour of conservative forms of investments. Information is difficult enough to generate and appropriate without making investments which are relatively insecure. A public sector less concerned with issues of distribution and appropriation would probably invest in very different methods. This is one reason (explored further below) for the investment in storage methods of supply rather than the usage-based methods of supply of information.

There is no doubt that change will occur over time (in the environment and in technology) and one of the values of genetic diversity is the flexibility it allows for response to future changes in circumstances. The agricultural industry definitely recognizes this value and provides against many eventualities, but there are clear instances in which there is a difference between what the private and the public sector would supply in terms of the quasi-option value of genetic resources. These differences identify one of the most important public interests in their conservation.

Exploration value

This is the value of retaining a wider portfolio of assets across time, given that the exploration and use of little-known assets will generate discoveries of currently unknown traits and characteristics. It is a 'Bayesian' sort of value, where information derives from the process of converging expectations. Long analysed resources will no longer divulge as much information as will those which are little analysed, even though the former might have much higher expected yields. For example, this can be conceived as the value of the retention of a given land area in an 'unused' state, because it is possible that certain wild relatives of cultivated varieties will be found which may generate new and valuable characteristics if investigated. The same idea may also be applied at the field level and the species level. Any non-modern production method or crop will be relatively unknown, compared to the heavily researched crops and crop varieties. It is important to continue to retain some of these little-known wildernesses, crops and crop varieties, if only because we must admit that these have received little exploration, while other paths have been much pursued.

Once again there are good reasons to expect that private industry will take some of this value into account in its approach to conserving genetic diversity, but there are also good reasons why the private approach will be inadequate. As with individuals, private industries (even those focusing upon informational values) will be using a criterion based on expected profitability, yet an argument could be made that the appropriate objective should be to maximize the amount of information derived per unit of expenditure (Weitzman, 1993). The public sector has a much wider range of social objectives which it may consider than the private sector, and one focused on the informational rather than the current production value of the resource would favour a much greater supply of genetic resources.

Another reason is based more on national externalities. Even if private companies should wish to invest in the conservation of particular land areas in certain countries, they might find it very difficult to obtain any return from doing so across political boundaries. The absence of universally recognized property rights in informational values renders investments across borders highly dubious. Most plant breeders mention 'insecurity of investment' as the primary reason why more investments in *in situ* conservation do not occur; it is one of the primary reasons why private firms put relatively little effort into it (Swanson, 1996b). This property right failure implies the necessity of public-sector intervention.

The public interest in genetic resource conservation for agriculture

This section has demonstrated the values of genetic resources which the private sector may, or may not, take into account systematically in making conservation and use decisions. It is then the role of the public sector to intervene to conserve genetic resources for agriculture to retain those values which are underappreciated by the private sector.

This framework helps to identify the values of genetic diversity which should be the subject of public interest and investment in order to ensure the future of modern agriculture. The nurturing and advancement of the 'green revolution' has been an important event in human history, but it is equally important that a scientific basis for conservation is developed in order to ensure the sustainability of this advance. The next section outlines an approach to analysing the optimal methods of conserving genetic resources for this purpose.

THE POLICY PROBLEM: PUBLIC MANAGEMENT OF GENETIC RESOURCES

How should the public sector intervene in order to address externalities? There are two basic technologies for managing crop genetic resources, *in situ* and *ex situ* (Orians *et al.*, 1990). The fundamental difference between them lies in the quantities of land implicit in the conservation approach; one requires large quantities of land dedicated to conservation, while the other requires virtually none at all. The technologies of conservation also represent fundamentally different approaches to problem solving. In this section we will define how these strategies differ in their approach to the conservation problem in the context of the dynamic environment outlined earlier. In essence, *in situ* conservation may be defined as an approach to decision making that is focused on the *optimal appropriation of information* arriving over time, whereas *ex situ* conservation may be defined as the *optimal utilization of a given set of germ plasm* at a given point in time. The relative values of the two approaches are dependent upon the expected value of the flow of information in the decision-making context. When a flow of information across time is important, *in situ* conservation will afford additional values to those supplied by *ex situ* methods.

It will be necessary to evaluate each of the available approaches to conservation against a given societal objective. The objective here will be taken to be the maximization of agricultural productivity subject to the pathogen/host dynamics set out earlier; this gives the following expression for *maximum sustainable social welfare*:

$$Max\int_0^\infty e^{-\rho t}Y_t dt \equiv Max\int_0^\infty e^{-\rho t}\left(f(\Omega_t)^{\bar{\alpha}-\bar{r}}\right)\bar{p}_t dt \tag{1}$$

where

$$\bar{r} = \mu \cdot \Delta \cdot k_i - \pi \cdot \Gamma_i \cdot v$$

Agricultural output Y_t is here represented as a function of the expected yield of utilized crops (where the choice of utilized crops is dependent on the information in hand, which is denoted by the matrix Ω), an aggregate productivity parameter vector $\bar{\alpha}$, an aggregate of the virulence/resistance parameter r and valued according to the price vector $\bar{p}$.

This objective function states that production across time is a function of crop variety choice, which determines both productivity and resistance within the system. In turn, crop variety choice is a function of the information which the system produces across time (on the contribution of various crops to both productivity and stability). Hence information drives the model; crop selections influence its generation and depend upon its existence. The dynamics of the system are, however, both informational and ecological: crop selection determines the resistance level of the current and future systems.[6] Despite the added complexity, this remains a highly simplified version of the societal objective function regarding global agricultural production, which places emphasis on the maximization of the stable values of global yields. This abstracts from other issues such as distribution,[7] variability[8] and desirability,[9] and focuses on the single issue of how genetic resources should be managed in order to provide for maximum *sustainable* global yields in agriculture.[10] This is the question to which we now turn.

In situ conservation as a closed-loop strategy

In situ conservation (as used here) implies the existence of a group of individuals who continue to dedicate some amount of land use to a broad set of crop genetic resources under very flexible technologies. In the past, individuals in less developed countries did precisely this as optimizing agents, using crop genetic resources as a hedge against financial risks. As markets mature, individuals have access to more efficient methods of hedging risk and replace *in situ* conservation with these other financial instruments. The object of *in situ* conservation is to have some set of farmers engage in traditional farming practices in continuing fashion. This requires the creation of a system of incentives which will induce a group of farmers to act so as to maximize their risk-adjusted income by making use of the naturally sourced information available at every point in time when carrying out their cultivation decisions.[11]

Let us assume that it is possible to institute a programme of *in situ* conservation on some set of lands. This means that there is a sub-set of farmers whose choice of crop germ plasm is made in response to the shifting environment; they are using broader portfolios of germ plasm to hedge against environmental risks, rather than other sorts of risk-hedging instruments. The germ plasm which results from this method of operation then incorporates a flow of information; that is, the crop varieties in use by this set of farmers will contain traits and characteristics that are effective under currently prevailing environmental conditions. These favoured traits and characteristics represent a flow of information from nature to the farmers in the *in situ* conservation areas. Then the modern agricultural sector is able to utilize this information to inform its choices of crop varieties throughout agriculture.

The solution of the problem of maximum sustainable production by *in situ* conservation represents a well-known approach to the use of information in making. This formulation of the decision process is generally known as a *closed-loop* or *feedback* rule under which the values of the choice variables depend upon the current performance of the system under control (Holly and Hughes Hallett, 1989).[12] The solution to a problem stated within the closed-loop format is normally a function (rather than an explicit set of values).[13] That is, the solution is a process of information acquisition and utilization rather than a specific set of choices taken by reference to the information available at one point in time. *In situ* conservation therefore accords with the idea of a closed loop method of decision making; it contemplates basing the decision in each period on the best information available *in the period in which that decision is taken.*

There is no doubt that there is information arriving in each period that is potentially valuable in decision making regarding the control of modern agriculture; the object of the earlier section on evolution and agriculture was to describe the systems that continue in motion across time and how they might contribute information to agriculture. The information from nature in each period is being provided by the existence of *in situ* conservation and the fact that relative performance of various plant varieties is directly observable by the decision maker in each period. On the other hand, the amount of information is necessarily limited by the size of the set of genetic resources in continued interaction with the environment.

The cost associated with this information-generating process is equal to the opportunity costs of the land dedicated to *in situ* conservation, since the cultivation of sub-optimally performing varieties under sub-optimal technologies will reduce the expected present values of these operations.

To illustrate the nature of closed-loop decision making, consider the following simple example. Under an *in situ* conservation programme, there will be a set of farmers who will devote a fixed proportion of the available land (c) to the cultivation of a diverse set of variables (y_d) of a single crop. The quantities c and y_d are exogenously determined by the system of incentives established under the *in situ* conservation system. Meanwhile, by focusing only on yield information, the lands in the modern agricultural sector will be invested in the currently best performing crop. Assuming that there is a relatively low level of output on the lands invested in conservation, *aggregate agricultural output with in situ conservation costs* in period t is therefore:

$$Y_t = (1-c)\cdot\left[E\left(y_{e_t}\right)^{\alpha_e - r_e}\right]\cdot\overline{p}_t$$

The decision rule in each period reduces to assigning the soil resources $(1-c)$ to the asset e which maximizes output. A closed-loop decision-making process does this in a manner that makes maximum use of the information that is expected to flow into the system. Here we will focus on the use of the information flowing from nature, as derived from the land used for conservation (c). Therefore, looking forward one period, output in $t + dt$ with closed-loop decision making will be:

$$Y_{t+dt} = (1-c)\cdot\max\left\{(\hat{y}_e)^{\alpha_e - r_e};(\hat{y}_e + \Delta)^{\alpha_e - r_e};(\hat{y}_f)^{\alpha_f - r_f};(\hat{y}_f + \Delta)^{\alpha_f - r_f}\right\} \quad (2)$$

where $\hat{y}_f = \max_t\{y_d\}$.

Equation (2) just states that output in the modern agricultural sector will be produced by using the best available option from either the previous input variety e, potentially changed by depreciation or adaptation, or the best variety f available from the set of diverse resources in period t; or a variety from that set has recently been adapted to existing environmental conditions. This means that modern agriculture is able to rely upon the genetic resources within that sector so long as they produce the best yields, but that there are other sectors available if that is not the case. More importantly, the alternative sectors are simultaneously producing the information on the important traits and characteristics for adaptation while the environment continues to change.

For example, the usual pattern of use regarding a particular plant variety indicates that pest resistance will erode to render that variety economically non-resistant within four or five years; this rate of environmentally induced depreciation is represented by the third term in equation (2) above. On account of this predictable rate of depreciation (and the unlikelihood of economically significant adaptations in a monocultural system), the alternative varieties in use in the conservation system begin to become relatively more attractive; this is represented by the fourth term in equation (2). The conservation system operates as a 'bank' of previously existing but inferior varieties. However, the single most important function performed by the conservation system is the capture of a flow of adaptations within that system; this is represented in the final term in that maximand. It states that the *in situ* system will observe and make use of any important adaptation signalled within that environment. All that is required is the land use decision providing for the dedication of some amount of land to the cultivation of a wide range of diverse varieties. Then the desirable traits and characteristics identified within the diverse *in situ* system may be cycled into the more uniform modern agricultural sector on a systematic basis.

Therefore *in situ* conservation is an approach that maintains a set of farming systems for the information that such systems will generate for the decision-making process. In each period, decisions must be made concerning the maintenance of agriculture, and each and every farm practising traditional and diversity-based agriculture acts as a receptor of information on the shifting of the natural environment. The greater the number of receptors in existence, the greater the likelihood that the information on the solution to the problems inherent in the current shifts in the environment will be available. *In situ* conservation represents an approach dedicated to the capture of this incoming information.[14]

Ex situ conservation as an open-loop strategy

Ex situ conservation may be conceptualized as a very different form of approach to the problems arising in modern agriculture. It is based on the idea that the solution to future problems is probably to be found in the set of currently existing genetic resources. Rather than base decision making on the capture and use of a flow of future information, the *ex situ* approach attempts to make optimal use of an already existing stock of information (represented by the already existing closely related varieties). In short, the two approaches are distinct approaches to the same problem, and both are necessary components of a complete solution to agricultural problems.

We will conceptualize *ex situ* conservation as a process in which the decision maker selects the set of genetic resources to be used in the maintenance of modern agriculture at a single point in time (t_0). The decision maker does this by selecting the optimal set of assets from the available genetic pool at this time and storing them, for future use, as inputs into the agricultural production process. The decision-making process is distinct from the previous one because it is based on the optimal use of the set of information already existing rather than the optimal appropriation of a flow of incoming information. The decision-making rule in the open-loop case can be stated at:

$$\bar{u}_t = g_{t,t_0}\left(\Omega_{t_0}\right)$$

This is the usual formulation of an open-loop decision rule. In it the decision maker is committed to a specific decision-making process across time based on a calculation procedure $g(\cdot)$ applied to a given set of information available at some particular point in time (t_0) (Holly and Hughes Hallett, 1989). In this context the given set of information consists of the stock of genetic resources available for banking at a particular point in time. The irreversibility of genetic erosion imposes the restriction of a non-increasing set of genetic resources in storage over time (Frankel *et al.*, 1995).

Decision making of open-loop form is used when the supply of genetic resources is restricted to the use of gene banks. From the set of already existing varieties, a set is selected for conservation within the gene bank. This information set is then 'frozen' at the time of collection.[15] The remaining unbanked stocks of genetic resources are increasingly lost through displacement by modern agriculture. The flows of future information are lost by reason of the loss of the 'receptor sites' (that previously diverse agriculture represented) as traditional agricultural land uses are replaced by modern agriculture. In short, *ex situ* conservation represents a decision-making process concerning the optimal use of the already existing stocks of information inherent in landraces and other stocks of genetic resources, and nothing more.

Optimal conservation: combined strategies

Optimal genetic resource conservation for food security in agriculture is a general problem composed of two parts: the first concerns the optimal use of existing stocks of information (primarily for immediate yield improvements) and the second deals with the optimal appropriation and use of future flows of information (primarily for the maintenance of current yield levels). For the dynamic aspects of the problems of agriculture, it is best to use a dynamic approach to decision making; this implies the use of *in situ* conservation for addressing the optimal appropriation of flows of information, while *ex situ* conservation is used to optimize the use of existing stocks of information. In essence, there are two parts to this problem and therefore two instruments (*ex situ* and *in situ*) are necessary to reach the optimal solution.[16]

CONCLUSION

This paper has attempted to demonstrate the ecological and informational nature of the plant-breeding problem and the externalities that recommend public intervention within the plant-breeding industry. This has the responsibility for maintaining stability within the modern agricultural system by continually and perpetually introducing new resistance into the prevalent commercial strains. This requires a continual flow of information on successful resistance strategies available into the indefinite future.

Where is that supply of information to come from? It arrives as both a stock (of previously used crop varieties and the resistance they retain) and as a flow (of newly found successful traits within competitive environments). Both forms of information are important in the optimal management of agricultural stability, and different forms of conservation strategies are required to yield each. *Ex situ* conservation focuses on the former, while *in situ* conservation acts as the primary supplier of the latter.

NOTES

[1]It is also possible to reformulate this discussion in terms of pathogens and 'traits' or something similar which would focus the analysis on crop varieties rather than crops, but this version is retained for simplicity and clarity.

[2]Agriculture has some of the characteristics of an arms race. Escalation generates re-escalation. This indicates that there are only two bases upon which the considered adoption of agriculture would have originally occurred: (1) unceasing technological optimism regarding the innovative capacity of the species to outperform the evolutionary capacity of the pests and pathogens; or (2) discounting the impact of agriculture on future production choices. It makes no difference which was the original basis for the initiation of the contest; now that it is started, all that matters is keeping it going.

[3]This might be viewed as a practical example of the so-called 'strong sustainability' criterion (Tisdell, 1996). This is the criterion that states that a certain level of natural capital must be maintained for production to continue (Pearce, 1993). In this context, it could be argued that, at least at present, there is no substitute for natural selection as a mechanism for providing information on the optimal strategies for continuing within this contest, and therefore a constraint on maintaining the natural capital stock (of resistance) intact is required.

[4]A later section of the paper introduces a more general version of this model which includes condition (1) as a dynamic constraint rather than a static one.

[5]This section reprises Swanson (1996a). There is relevant discussion in Swanson (1996b).

[6]In this dynamic representation, the ecological constraint translates into the state variable in this programme. This is because in a static world the best way to think of this condition is as a constraint on the otherwise unconstrained maximization of static agricultural productivity. In a dynamic world, the level of virulence/resistance in the system is one very important factor contributing to the overall productivity of the system, and the generation of information (within agriculture and for use in agriculture) relating to resistance is one of the objectives of agriculture.

[7]We plead the standard excuse given by economists: redistribution is most efficiently accomplished through the most neutral taxation mechanisms available.

[8]So long as the vast majority of yields are susceptible to storage over at least one period, the problems raised by variability around a given yield level may be addressed through insurance mechanisms based upon consumption smoothing through storage. The problem that we address here is more concerned with the difficulty of ensuring that such variability does not result in continually declining levels of production, with declining consumption levels over the long term.

[9]It is of course debatable whether maximum food production is a desirable social objective, since food production for human use implies other opportunities forgone, such as the provision of habitats for other species.

[10]The issue of how to aggregate value across time is an important one in this context. Given that the issue concerns the provision of the resources for the survival of society (no reason for pure time preference) and there is little reason to expect that the demand for food will decline in the foreseeable future (elasticity of demand with income growth is probably changing no faster than are global populations), there are good reasons to believe that the relevant discount rate in this context is very near to zero.

[11]*In situ* conservation might be provided, for example, by paying farmers to dedicate certain designated lands to the use of only those plant genetic resources acquired from the previous year's harvest. There are other issues that must be considered, however. For example, it is also important for farmers to be provided with an incentive structure that causes them to consider using plant genetic resources in order to hedge risk in their agricultural decisions, so that they will retain diversity. Also there are other issues concerning the determination of the initial set of plant genetic resources available to the 'traditional farmer' and the forms of exchange (for example, between traditional farmers) that might be available between harvests. Finally, the technology utilized by the traditional farmers must be flexible enough to allow natural selection to play an important role in farmers' choice of crop varieties. In short, the essence of *in situ* conservation must be the maintenance of a set of farmers making their own decisions based on a restricted set of germ plasm choice but utilizing much of the natural information generated by the changing environment.

[12]The special case of a stationary function is normally described as a *stationary Markov strategy* (Cornes *et al.*, 1995) which takes as its arguments the currently observed results from recent choices.

[13]In other words, the vector of weights a farmer i attaches to his set of crop varieties at time t, that is, his control variable vector $\bar{u}_t$, is the outcome of a time-invariant decision rule ϕ, applied to the full set of currently available crop performance information which is a composite matrix of the mean yield vector $\bar{y}_t$ and the variance–covariance matrix of the yields $\prod_t$:

$$\bar{u}_t = \phi_i(\bar{y}_t; \Pi_t) - \phi_i(\Omega_t)$$

[14]This conception of *in situ* conservation renders it analogous to an observation mechanism used within any context of stochastic control. It is a mechanism installed for the purpose of acquiring information on the current state of the system.

[15]'The genetic resources [of crop plants] that are preserved in genetic resources centres are maintained "frozen", which in many cases is literally true' (Frankel *et al.*, 1995, p. 5).

[16]A fuller treatment of this problem is provided in a paper by Swanson and Goeschl, titled 'Optimal conservation strategies: *In situ* and *ex situ*', which will appear in a volume to be edited by Stephen Brush.

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DISCUSSION REPORT SECTION III

Anthony Chisholm (Australia)[1], opening the discussions, said that the report on water and land resources in relation to global food supply by Rosegrant, Ringler and Gerpacio (hereafter the IFPRI study) had a succinct central message: world cereal prices will continue to decline, in real terms, and land degradation does not pose a threat to global food production. However, water scarcity could threaten projected growth in agricultural production. He noted that two important assumptions are underlying the IFPRI model. First, the global yield growth rate for all cereals will decline from 1.5 per cent per year in 1982–94 to 1.1 per cent in 1993–2020 and, second, that China's GDP grows at 6 per cent per year, a lower rate than China has achieved over the past 15 years. Other things being equal, he said that the first assumption would tend to raise world prices, the second to lower them. All exercises of this type are sensitive to assumptions and highlighting them clearly is important. The other feature of the work is that it does not appear to reflect the implications of the final Uruguay Round agreement. That is likely to raise international food prices; it may only be a modest 2–4 per cent higher in a decade's time, though it is a factor that should enter the picture. It is also worth noting that there is no real consideration of the impact of climate change, where the vulnerability could mainly be with developing countries.

On land degradation, Chisholm argued that the authors make a good point, often ignored, when they indicate that existing soil erosion estimates usually do not account for soil eroded from one site sometimes being deposited elsewhere on productive agricultural land. However, on the other side, he did feel that there are a number of reasons why existing estimates of productivity loss, based on crop yield data, may understate the impact of soil erosion. For example, few studies appropriately account for costly use of inputs to substitute for loss of soil endowment, or the conversion of land to lower-valued uses due to soil erosion. It is possible that the negative rates of growth in total factor productivity (TFP) estimated for a number of developing countries in recent studies may be partly attributable to unmeasured loss of soil endowment. The picture is further complicated since non-linearities in the underlying relationships may cause there to be considerable lags between decline of some forms of soil endowment and the realization of productivity effects. To obtain a better understanding of the role of land degradation in global food production, we clearly require more detailed research linking physical/chemical measures of land degradation with soil productivity changes.

The IFPRI study identifies potential water constraints as a more serious threat to future food production than land degradation. In Chisholm's opinion,

[1]La Trobe University.

this stems from inadequate policies and institutions rather than a lack of availability of efficient technologies and management systems. Drop irrigation, a technology that has been available since the mid-1960s, conserves water and reduces drainage, but farmers will only adopt such technologies when policies and institutions provide incentive structures for socially efficient behaviour. He hoped that the highlighting of the 'water constraint' by IFPRI would result in far more thought being given to the regulation of its use, and stressed the fundamental importance of the issue.

Prabhu Pingali[2] discussed Darwin Hall's climate change paper. He felt that the paper had many interesting and informative features relating to the adaptation that might ultimately be needed in agriculture, but in more critical vein he was extremely sceptical about using regression methods to model the possible effects of climate change variables on agriculture. It appeared to him that simulation models were methodologically better fitted to the task than regression. Even in simulation the basic parameters had to be drawn from a few experiments conducted in controlled, rather than natural, conditions and not pursued over long time periods. He was also worried about the lack of reliable climate data for large parts of the world. The uncertainties of the modelling process, and the fact that we cannot put much trust in the results, do not, however, justify taking a 'head-in-the-sand', ostrich-like view. If there are effects of the size which Hall inferred, it is important to improve modelling rather than to abandon it. The urgency may not appear extreme, though the issue is potentially serious enough for people now being born to experience food security effects towards the end of the 21st century.

P.S. Ramarkrishna (India)[3] expressed the opinion that Timothy Swanson was taking a very narrow view of the biodiversity issue. In his opinion, 'state'-level actions had sometimes increased resource scarcity and had undermined the conservation of natural resources. He was much more hopeful about successful initiatives being taken at lower levels of government, or indeed at the communal level. This, he felt, needed to be brought into the discussion since there was a danger of regarding 'the government' as the locus of all solutions.

Clem Tisdell (Australia)[4], who had organized the section, summarized briefly by linking the three papers. The IFPRI work, as reported in the section and in the paper of Pinstrup-Andersen and Pandya-Lorch, was guardedly optimistic about food supplies over the short term to 2020 (decades are important in that context). The time bombs (climate change and the continuous need to replenish germ plasm) are set for later, over our ability to maintain food supplies of an adequate level *throughout* the next century.

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