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THE TIMING OF EVALUATION OF GENEBANK ACCESSIONS AND THE EFFECTS OF BIOTECHNOLOGY

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ABSTRACT

The lack of ex-ante evaluation of germplasm in genebanks has been the single most prevalent and long-standing complaint of plant breeders about the management of genebanks. Advances in biotechnology offer the possibility of faster, cheaper, and more efficient evaluation methodologies. Will these new technologies favor ex-post evaluation, as some expect, or will it lead to more ex-ante evaluation? Will it also lead to earlier development of varieties with disease resistance traits in anticipation of actual infestations? Will the prospect of further advances in biotechnology favor delay of evaluation and development? This paper addresses these questions in the case of evaluation of germplasm for resistance to a disease.

CONTENTS

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Bonwoo Koo and Brian Wright*

1. INTRODUCTION

Plant genetic resources have provided basic building blocks for the improvement of plant varieties and recent advances in biotechnology have opened up more possibilities for the use of these resources in crop improvement. Collections of germplasm (the 'material that controls heredity', Witt 1985, p.8) for conservation purposes in ex-situ genebanks have been greatly expanded over the past decades. However, though the principal justification for such extensive germplasm conservation is for its use in crop improvement, materials in genebanks are not being used extensively by plant breeders (Wright 1997). One frequently cited obstacle to greater utilization is the lack of information useful to breeders regarding the samples of germplasm held as accession in ex-situ collections.

Evaluation data[1] are of the greatest value to plant breeders seeking particular genetic traits for crop improvement, but only a small fraction of samples in the genebank

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[1] The types of information regarding germplasm can be broadly categorized as passport data, characterization data, and evaluation data (Office of Technological Assessment 1987). Passport data include information on the origin and environmental conditions of the material. Characterization data include environment-insensitive traits such as morphological, biochemical, and molecular information, while evaluation data include environment-sensitive traits such as yield potential and disease resistance.

network have evaluation data.[2] Even among the collections with evaluation data, the information currently provided by genebanks is often perceived as inadequate. While this situation has led many plant breeders to demand more complete evaluation of genebank materials for crop improvement (Duvick 1984, Peeters, and Galwey 1988; Goodman 1990; and NRC 1993), this viewpoint is not universally shared (see for example Frankel 1989).

Existing studies on the use and management of genebank collections of genetic resources deal largely with the optimal size of ex-situ genebank collections (Brown 1989 and Chang 1989), the value of genetic resources (Evenson 1996 and Simpson et al. 1996), or the optimal search strategy for useful traits (Gollin et al. 1997). However, the neglected issue of the *timing* of evaluation and utilization of genebank materials has become an important consideration for genebank managers, especially in the current rapidly changing technological environment.

The timing of identifying and isolating useful traits has been an important factor in crop improvement. For example, when the Russian wheat aphid began to affect the United States in the late 1980s, the damage might have been mitigated if the sources of resistance had already been identified. After the disease broke out, searches among wheat varieties in the United States Department of Agriculture (USDA) collection yielded almost no useful materials, and the resistance was later found from a number of varieties from Iran and Russia (Robinson 1994). Lack of preparation might have

[2] Although this point is frequently made, we must go back to Peeters and Williams (1984) for hard data. They report that 65 percent of the samples in the genebank network have no passport data, 80 percent have no characterization data, 95 percent have no evaluation data, and only one percent has extensive evaluation data.

contributed to the estimated economic damage of $670 million by 1991 (Russian Wheat Aphid Task Force 1991). On the other hand, when barley stripe rust fungus devastated Europe and South America in the 1970s, plant breeders in the United States worked to identify sources of resistance to the disease and could effectively cope with it when the disease reached the United States in 1990 (Kurt Leonard, personal communication 1999).

In this paper, we focus on the cases similar to those just mentioned, in which a trait for resistance to a pest or disease is already known but has not yet infested the relevant crop, and address the following questions on evaluation and utilization of genebank collections. When is it optimal to evaluate genebank material for a trait: i.e., ex ante in anticipation of an infestation, or ex post after infestation of the disease in the relevant crop? When is it optimal to develop a new variety incorporating the trait? What is the effect of advances in biotechnology on the timing of evaluation and development? And how is the timing of evaluation and development changed when there is a possibility of a further technological breakthrough in either of these functions in the future?

Resistance is often achieved by transferring desirable traits, found either in genebank collections or genetic stocks, into existing varieties by conventional breeding or other means such as wide crossing or genetic transformation. Identification of resistance before the outbreak of a disease can be difficult and costly. If an outbreak of a disease occurs, the development of a new disease-resistant variety will be faster if the gene for the resistance trait has already been located. However, there is some chance that the disease never occurs or occurs in the remote future, in which case the money spent for evaluation is, in hindsight—i.e., ex post—wasted. If evaluation is started after the disease occurs, excess ex-ante evaluation is avoided. However, the social losses due to

damages from the disease will be incurred during the delay until a new variety is developed.

In a simple model of evaluation and development, we find that if a disease has sufficiently low likelihood of occurrence, it is cost effective to delay evaluation of the trait until the disease occurs. In addition, the benefit from ex-ante evaluation turns out to be the largest when the hazard rate of the disease is at an intermediate, rather than at the maximum, rate. Several recent innovations in tools and methods have made evaluation for resistance traits and development of useful cultivars incorporating these traits cheaper and faster.[3] Such a cheaper and faster response might seem to favor ex-post evaluation. But we show that in economic terms advances in biotechnology that reduce the cost or increase the speed of evaluation or development tend to favor ex-ante evaluation more than ex-post.

Current advances in biotechnology imply that further innovations are likely. Well-known result of real option theory is that uncertainty about costs tends to favor delay in an investment (Arrow and Fisher 1974; McDonald and Siegel 1986; and Dixit and Pindyck 1994). Does this imply that a further anticipated breakthrough in the technology of evaluation and development tends to favor delay, in contrast to the effect of a current breakthrough? The usual real option effect is observed in our model for the

[3] Molecular genetic techniques such as restriction fragment length polymorphism (RFLP), random amplified polymorphic DNA (RAPD), and amplified fragment length polymorphism (AFLP), are used to identify specific genotypes and agronomic traits of interest and to "fingerprint" individual accessions. These techniques, together with cell culture techniques and transformation techniques involving recombinant DNA (rDNA), are also used for the development of new plant varieties by facilitating the transfer of the desired genes and the development of new cultivars in a fast, reliable, and cost-effective way (Rao and Riley 1994).

case of innovation in *evaluation*. But we show that anticipation of the possibility of a technological breakthrough in *development* may speed up, rather than delay, the timing of evaluation and development. We conclude that both the level and rate of technological progress in development may justify advancing the timing of the evaluation of genebank accessions as well as the development of cultivars incorporating newly identified traits.

Section 2 introduces the model of the expected costs under different evaluation and development alternatives, and examines the factors that affect the timing of evaluation. Section 3 analyzes the effect of current advances in biotechnology on the timing of evaluation and development, and section 4 extends the model to analyze the implications of dynamic technological changes and compares our result with existing arguments on real option theory. Concluding remarks follow in Section 5.

2. THE MODEL OF EVALUATION AND DEVELOPMENT

ASSUMPTIONS

We propose a highly stylized model that abstracts from many biological details. We consider the search for a single qualitative trait[4] (say, a resistance to a certain disease) for a specific environment in a given ex-situ collection of germplasm, either ex ante or ex post.[5] For simplicity, we assume resistance is conferred by a single gene, and (contrary to common experience) that single-gene resistance retains its effectiveness forever. The evaluation process ceases as soon as a variety with the targeted gene is identified.[6]

We postulate a two-stage process for the development of a new disease resistant variety: the *search* (or *evaluation*) *process* in which a genebank conducts a search in its collection for a disease resistant trait, and the *development process* in which a genebank develops a new variety, expressing the evaluated gene, for release to farmers.[7] We assume that the search process must be completed prior to the initiation of the development process.

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[4] Frankel (1989) categorizes two kinds of traits of concern to plant breeders; *qualitative* traits and *quantitative* traits. Disease-resistance traits are typically qualitative, and are among the most sought-after traits in germplasm collections.

[5] Ex-post evaluation is often performed by plant breeders, but for simplicity of exposition we assume the genebank manager conducts the search.

[6] Our search process is close to the process of screening, assumed by Simpson et al. (1996). In practice, some sources of a trait may be more desirable as breeding materials than others, so evaluation may continue after the first positive result of the search (Evenson and Kislev 1976 and Gollin et al. 1997). We ignore this consideration here.

[7] Gollin et al. (1997) explicitly consider the prebreeding process by which resistance genes found in the search process are transferred into a breeding program before the development process. Our model assumes that the prebreeding process is a part of the development process.

A disease breaks out at a random future period *t*, according to a Poisson disease hazard rate λ. By spending a constant flow search cost *c*, the genebank finds the targeted gene at time *s* after the initiation of evaluation, according to a Poisson discovery rate ϕ. Once a disease occurs, society suffers losses from the disease until the development of a new disease resistant variety.[8] It takes *l* periods with a constant development cost *m* per period to develop a new variety,[9] and the disease cost due to the delayed introduction of a new variety is *d* per period of infestation. Diffusion of the disease and of the new variety after development are, for simplicity, assumed immediate. The genebank is assumed to be risk neutral and the discount rate is *r*.

Figure 1 shows the decision tree of a genebank manager on the timing of evaluation and development.[10] For simplicity, we ignore the option of "no action" by assuming that the cost from a disease is high enough to justify the development of a new variety once a disease occurs.

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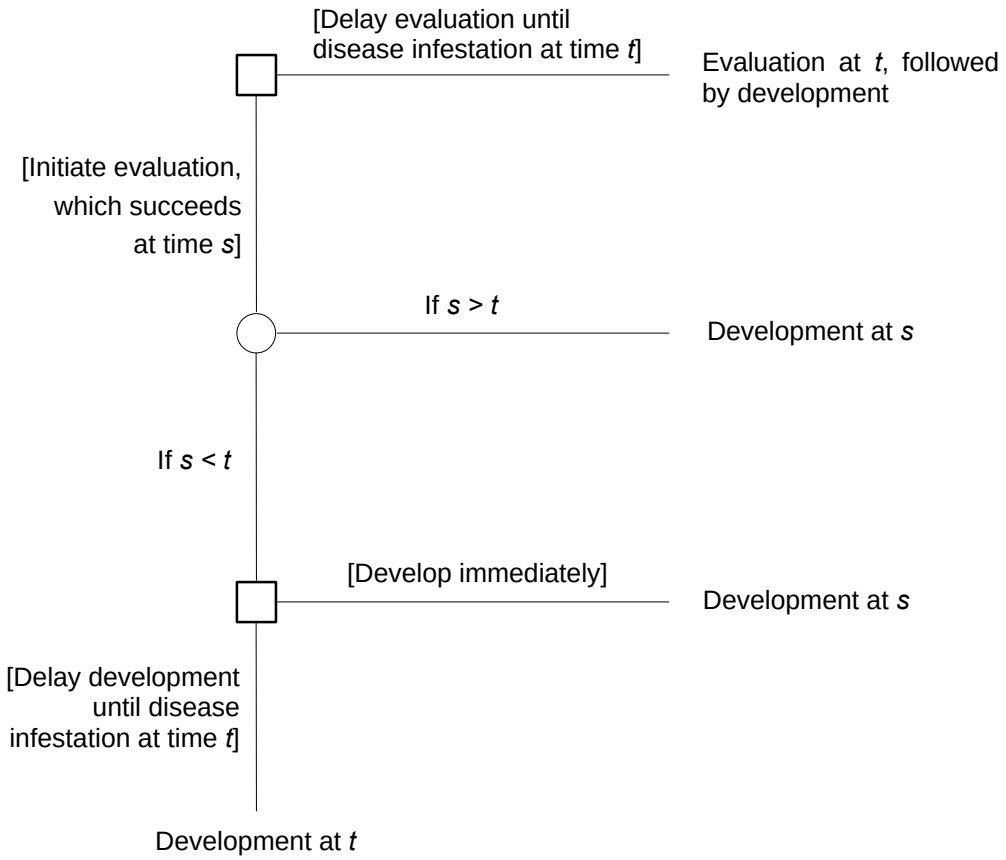
[8] This assumption implies that we ignore the possibility of other types of disease control such as chemical pesticides. Some soil-borne diseases may naturally decline in severity after seven to ten years of continuous infestation, and in other cases crop rotation can be used as a means of disease control (Leonard, personal communication 1999). Finally, substitution of a nonsusceptible crop can reduce the losses caused by the disease. The flow cost of infestation could be modified to recognize these mitigating factors.

[9] Similar qualitative results are derived by assuming a stochastic development process.

[10] Squares in Figure 1 indicate the *decision nodes* for the genebank manager, and the circle indicates the *chance node* with exogenously determined probabilities.

Figure 1: Decisions on the timing of evaluation and development



The first decision that a genebank manager should make in period zero, prior to an infestation, concerns the timing of evaluation; i.e., whether to evaluate immediately (ex ante) or delay the evaluation until the infestation of a disease (ex post). If he chooses to delay evaluation, evaluation and development should (by assumption) follow in sequence immediately after infestation. If he chooses ex-ante evaluation in period zero and the search for the traits succeeds in period s, he must decide the timing of development if the infestation has not yet occurred ($s < t$). His decision then is whether to develop immediately, before the disease infestation, or to delay until infestation

occurs. Therefore, we consider three alternatives of evaluation and development: (i) ex-post evaluation/development (P_t^t), (ii) ex-ante evaluation/ex-post development (A_0^t), and (iii) ex-ante evaluation/ex-ante development (A_0^0).

THE EXPECTED COSTS OF EVALUATION AND DEVELOPMENT

Ex-post Evaluation/Development

One option a genebank manager can choose is to delay evaluation (i.e., the search for the gene) until infestation of a disease. This is the current standard practice. (Of course, if the disease is unknown prior to infestation, there is no alternative). If the genebank starts to search for a resistant gene after the disease breaks out, society will suffer losses during the evaluation period [t, $t + s$] as well as during the development period [$t + s$, $t + s + l$]. The expected cost contingent on a search of duration s, evaluated at time zero, is

$$C_1(s) = \int_0^{\infty} \left[\frac{c+d}{r}\left(1-e^{-rs}\right) + \frac{(m+d)L}{r} e^{-rs} \right] \lambda\, e^{-(r+\lambda)t} dt$$

where $L \equiv 1 - e^{-rl}$. The expected cost of ex-post evaluation/development is[11]

$$P_t^t = \int_0^{\infty} C_1(s)\phi\, e^{-\phi s} ds = \frac{c\lambda}{(r+\phi)(r+\lambda)} + \frac{mL\phi\lambda}{r(r+\phi)(r+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)}$$

The terms on the right hand side (RHS) are the expected search cost, development cost, and disease cost, respectively. Since all of these costs are incurred only if the disease breaks out, the expected cost approaches zero as the disease hazard rate λ approaches zero.

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[11] In the following analysis, *Aij* (*Pij*) denotes the cost of *ex ante* (*ex post*) evaluation, where *i* denotes the timing of evaluation and *j* denotes the timing of

Ex-ante Evaluation/Ex-post Development

The genebank manager can also consider the option of starting before the infestation ("outbreak") of a disease in the relevant cropping area to search for a targeted gene that has resistance to the disease. If such ex-ante search is optimal, it is optimal to start searching at time zero. An example is anticipatory search for barley stripe rust resistance in germplasm relevant to the United States. When the search results in discovery *after* the disease occurs ($s > t$), development follows immediately by assumption. The expected cost when $s > t$, evaluated at time zero, is

$$C_0(s) = \int_0^s \left[\frac{c}{r}\left(1 - e^{-rs}\right) + \frac{d}{r}\left(e^{-rt} - e^{-rs}\right) + \frac{(m+d)L}{r} e^{-rs} \right] \lambda e^{-\lambda t} dt$$

If the gene is found *before* the disease occurs ($s < t$) and the genebank manager chooses to delay the development until the disease infestation, the expected cost is

$$C_2(s) = \int_s^\infty \left[\frac{c}{r}\left(1 - e^{-rs}\right) + \frac{(m+d)L}{r} e^{-rt} \right] \lambda e^{-\lambda t} dt$$

The expected cost of ex-ante evaluation/ex-post development is derived using $C_0(s)$ and $C_2(s)$.

$$A_0^t = \frac{c}{r+\phi} + \frac{mL\phi\lambda}{r(r+\phi)(r+\lambda)} + \frac{mL\phi\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)}$$

Unlike the case of ex-post evaluation/development, the expected search cost (the first term on the RHS) is incurred regardless of the disease infestation. The expected development cost is larger (in present value) than the cost under ex-post evaluation/development since it begins earlier and so is less discounted. However, the

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development. For example, *Ptt* implies the cost of ex-post evaluation where evaluation is done at time *t* and development follows immediately.

expected disease cost is smaller since the resistant variety is, in expectation, developed earlier.

Ex-ante Evaluation/Ex-ante Development

Another alternative is to develop a new variety even before the disease breaks out. There exists a practice among plant breeders called "anticipatory breeding" in which breeders try to incorporate resistance in cultivars for possible infestation of diseases. Examples of ex-ante development are Australia's development of locally adapted cultivars resistant to Russian wheat aphids (Skovmand, personal communication 1999) and to wheat stem rust (McIntosh and Brown 1997) in anticipation of infestations in the future. The expected cost of ex-ante development when $s < t$ is

$$C_3(s) = \int_s^{\infty} \left[\frac{c}{r}\left(1-e^{-rs}\right) + \frac{mL}{r}e^{-rs} \right] \lambda e^{-\lambda t} dt + \int_s^{s+l} \frac{d}{r}\left(e^{-rt} - e^{-r(s+l)}\right) \lambda e^{-\lambda t} dt$$

The expected cost of ex-ante evaluation/ex-ante development is derived using $C_0(s)$ and $C_3(s)$.

$$A_0^0 = \frac{c}{r+\phi} + \frac{mL\phi}{r(r+\phi)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi[\lambda + (r+\phi)(1-e^{-\lambda l})]}{(r+\phi)(r+\lambda)(r+\phi+\lambda)}$$

While the expected development cost is higher than for other alternatives, the expected disease cost is the lowest. If the disease cost d is sufficiently large or the likelihood of disease occurrence is high, ex-ante development can the most cost effective.

THE TIMING OF EVALUATION

Given ex-ante evaluation at the first stage, the decision on the timing of development at the second stage is determined by comparing the expected cost of ex-ante evaluation/ex-ante development (A_0^0) with that of ex-ante evaluation/ex-post

development (A_0^t). Ex-post development is preferred given ex-ante evaluation if A_0^t is less than A_0^0; that is, if condition (1) is satisfied.

$$mL > d(1-L)(1-e^{-\lambda l}) \tag{1}$$

If ex-post development is chosen at the second stage, the decision at the first stage is determined by considering the following cost difference function:

$$\begin{aligned} G &\equiv P_t^t - A_0^t \\ &= -\frac{cr}{(r+\phi)(r+\lambda)} - \frac{mL\phi\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)} + \frac{d(1-L)\phi\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)} \end{aligned} \tag{2}$$

If $G < 0$, ex-post evaluation/development incurs lower cost and delaying evaluation is optimal. The first term on the RHS of (2) is the difference in the expected search cost, which is nonpositive since the search cost is always incurred, and incurred earlier, under ex-ante evaluation. The second term, the difference in the expected development cost, is also nonpositive for a positive discount rate since development occurs earlier when evaluation is ex ante. The third term is the difference in the expected disease cost, which is nonnegative due to the longer period of delay under ex-post evaluation.

For a rare disease ($\lambda \to 0$), the cost difference is negative and ex-post evaluation is more cost effective. The expected development cost and the disease cost under both alternatives vanish when the disease hazard rate λ approaches zero, and only the expected search cost remains as an important consideration. If the disease hazard rate is high ($\lambda \to \infty$), the cost difference function G approaches zero, implying that there is vanishing difference in the expected costs. Since the disease is expected to occur very soon, the

expected timing of the evaluation process as well as the development process is almost the same for both alternatives and thus the cost difference is negligible.

Proposition 1 Optimal Timing of Evaluation and Disease Hazard Rate.

Given ex-post development at the second stage, ex-post evaluation is optimal if disease hazard rate is below a critical level λ_1 and search cost is less than a critical level c_1.

Proof

From equation (2), we can derive the range of the disease hazard rate in which ex-post evaluation is preferred.

$$0 < \lambda < \lambda_1 \equiv \frac{cr(r+\phi)}{K\phi - cr} \tag{3}$$

where $K \equiv [d(1-L) - mL] > 0$. If λ is less than the cutoff level λ_1, ex-post evaluation brings lower expected cost. In addition, the search cost should be less than c_1 to make λ_1 positive.

$$c < c_1 \equiv K\phi / r \tag{4}$$

Q.E.D.

From the genebank manager's point of view, proposition 1 implies that it is better not to evaluate accessions ex ante for a gene (or trait) that is expected to be used rarely in the future. For a rare disease, the use of the evaluated resistant gene will be long delayed and the search cost incurred at the current time is large relative to the expected present value of the benefits. For a disease that is more likely to cause an infestation soon, ex-ante evaluation may be preferred if it is cheap enough, because it reduces the expected disease cost. But the advantage of ex-ante evaluation is not monotonic in the disease hazard rate.

Proposition 2 Ex-Ante Evaluation and Disease Hazard Rate.

The benefit from ex-ante evaluation is maximized when the disease hazard rate is at an intermediate level.

Proof

The first-order condition of function G of equation (2) is

$$\frac{\partial G}{\partial \lambda} = \frac{-(K\phi - cr)\lambda^2 + 2cr(r+\phi)\lambda + r(r+\phi)[K\phi + c(r+\phi)]}{(r+\phi)(r+\lambda)^2(r+\phi+\lambda)^2} = 0$$

When equation (4) holds, only one root of λ that satisfies the condition of the above equation is positive and finite. Thus, the rate λ^*, which is associated with the maximum cost difference G (or, maximum net benefit from ex-ante evaluation) is calculated as

$$\lambda^* = \frac{cr(r+\phi) + \sqrt{J}}{K\phi - cr} > 0 \qquad (5)$$

where $J \equiv K(K + c)r(r + \phi)\phi^2 > 0$. The second order condition is satisfied around λ^*.

$$\frac{\partial^2 G}{\partial \lambda^2} = \frac{-2[(K\phi - cr)\lambda - cr(r+\phi)]}{(r+\phi)(r+\lambda)^2(r+\phi+\lambda)^2} < 0 \qquad \text{Q.E.D.}$$

If, in addition to the costs accounted for above, there is a fixed cost associated with the decision to evaluate ex ante (e.g., in terms of the genebank manager's time), then the value λ^* gives guidance to a genebank manager in forming priorities regarding evaluation for resistance to various potential diseases. *Ceteris paribus*, diseases with hazard rates near λ^* are the best candidates for ex-ante evaluation. If a disease rarely occurs (i.e., low λ), the advantage of early evaluation is less attractive. If a disease is expected to occur soon, on the other hand, the trait will be evaluated soon under either approach and the importance of decision timing is reduced.

Figure 2: A cost difference function G

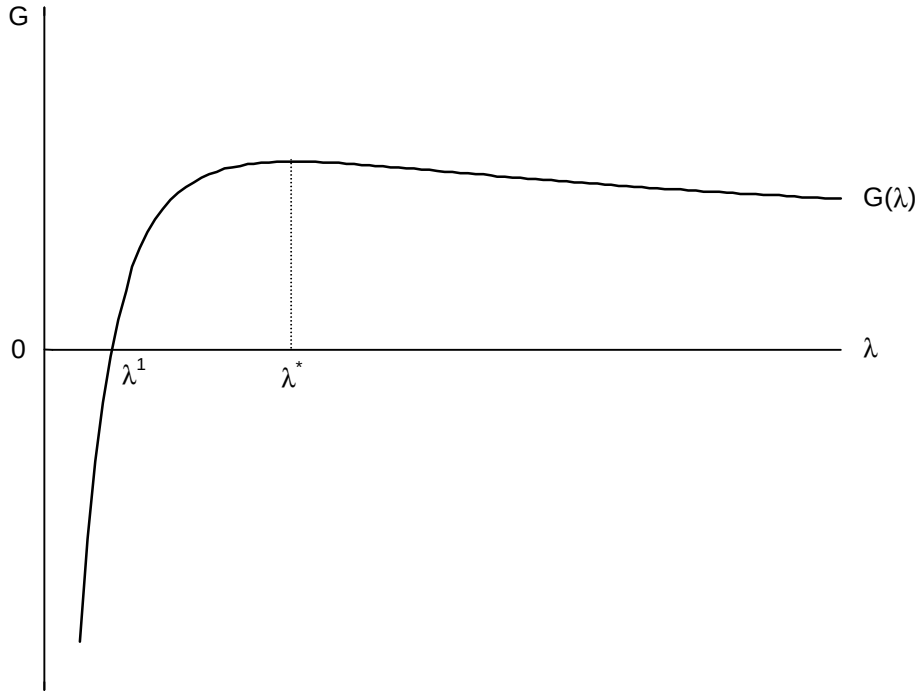


Figure 2 shows the graph of a typical cost difference as a function of the disease hazard rate. The value λ_1 defined in (3) is the cutoff disease hazard rate below which ex-post evaluation is preferred. The size of the cost difference *G* for $\lambda > \lambda_1$ indicates the degree to which ex-ante evaluation is preferred: i.e., the larger the value, the better the ex-ante evaluation approach in terms of cost effectiveness. The maximum advantage of ex-ante evaluation is attained at λ^*.

3. THE EFFECTS OF ADVANCES IN BIOTECHNOLOGY

Recently, innovations in biotechnology have occurred that can reduce the cost of the search or development process and/or speed up the processes. Here we consider how such innovations affect the decision on the timing of evaluation and development. We identify two types of technological changes for our analysis. The first type includes technologies that primarily affect the search process such as molecular genetic techniques, while the other type includes those that mainly affect the development process, such as transformation technology, cell culture techniques, and the use of molecular markers to identify transformed cultivars in the breeding process.

ADVANCES IN BIOTECHNOLOGY AFFECTING THE SEARCH PROCESS

The effects of the changes in the flow search cost c and the discovery rate ϕ on the cost difference around the cutoff value λ_1 are

$$\left.\frac{\partial G}{\partial c}\right|_{\lambda\equiv\lambda_1} = -\frac{r}{(r+\phi)(r+\lambda)} < 0 \tag{6a}$$

$$\left.\frac{\partial G}{\partial \phi}\right|_{\lambda\equiv\lambda_1} = \frac{K\lambda}{(r+\phi)(r+\phi+\lambda)^2} > 0 \tag{6b}$$

A higher search cost c favors ex-post evaluation (equation (6a)). The search cost differs by the types of traits to be evaluated. For example, Peeters and Williams (1984) report that the per-unit evaluation cost for *rhizoctonia* resistance in sugarbeet was \$175, while the cost of evaluating nematode resistance was only \$60 per unit. If the cost and probability of an outbreak of each disease were the same and if there were no economies of scope in evaluation (ignored here), then ex-ante evaluation becomes relatively more attractive for nematode resistance.

A high discovery rate ϕ favors ex-ante evaluation in terms of the search cost due to the discount factor, but it also favors ex-post evaluation since it is less costly to delay evaluation when discovery is fast. Equation (6b) shows that the first effect dominates the second effect around the cutoff rate λ_1. If modern tools of biotechnology such as genetic marker techniques and new genomic information reduce the time spent for the evaluation process of certain resistance traits sufficiently, without increasing the flow search cost, this should tend to favor ex-ante evaluation of germplasm for such traits.

ADVANCES IN BIOTECHNOLOGY AFFECTING THE DEVELOPMENT PROCESS

The effects of the changes in the development period *l* and the development cost *m* on the cost difference are

$$\left.\frac{\partial G}{\partial m}\right|_{\lambda\equiv\lambda_1} = -\frac{L\phi\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)} < 0 \qquad (7a)$$

$$\left.\frac{\partial G}{\partial l}\right|_{\lambda\equiv\lambda_1} = -\frac{(m+d)re^{-rl}\phi\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)} < 0 \qquad (7b)$$

A low development cost favors ex-ante evaluation (equation (7a)). Since timing of the development process under ex-ante evaluation is earlier than that under ex-post evaluation, a reduction in the development cost has a larger impact when evaluation is made ex ante. Modern technologies that reduce the development cost will favor ex-ante evaluation. On the other hand, if strict government regulations on the use of biotechnology increase the development cost and delay the introduction of a new variety, ex-post evaluation will be more encouraged.

A shorter development period *l* decreases the expected development and disease costs under both approaches. However, the rate of decrease in the expected costs under ex-ante evaluation is higher than that under ex-post evaluation, because the saved costs

are less discounted for ex-ante evaluation. Modern genetic engineering techniques that speed up the development process favor ex-ante evaluation. We can summarize these implications of advances in biotechnology as the following proposition.

Proposition 3—Optimal Timing of Evaluation and Advances in Biotechnology

Advances in biotechnology, which reduce the cost of the search or development process and/or speed up these processes, increase the value of ex-ante evaluation relative to ex-post evaluation.

4. THE IMPLICATIONS OF DYNAMIC TECHNOLOGICAL CHANGE: REAL OPTION EFFECTS

The fast pace of innovations in biotechnology that have made the search for traits and the development of new varieties incorporating them cheaper and faster is likely to continue. Does anticipation of further advances reinforce or offset the effects of cheaper and faster search and development on the timing of evaluation and development?

If a technological breakthrough might occur in the evaluation process, standard real option theory clearly implies that anticipation of this fact should tend to delay evaluation (Dixit and Pindyck 1994, pp. 140). If the breakthrough possibility occurs in the development process, however, the effect is ambiguous since the benefit from the technological breakthrough can be realized only after a successful search process. In this section, we focus on this interesting case by assuming that a technological breakthrough occurs only in the development process, and ask whether possibility of such a technological change tends to delay or advance the timing of evaluation.

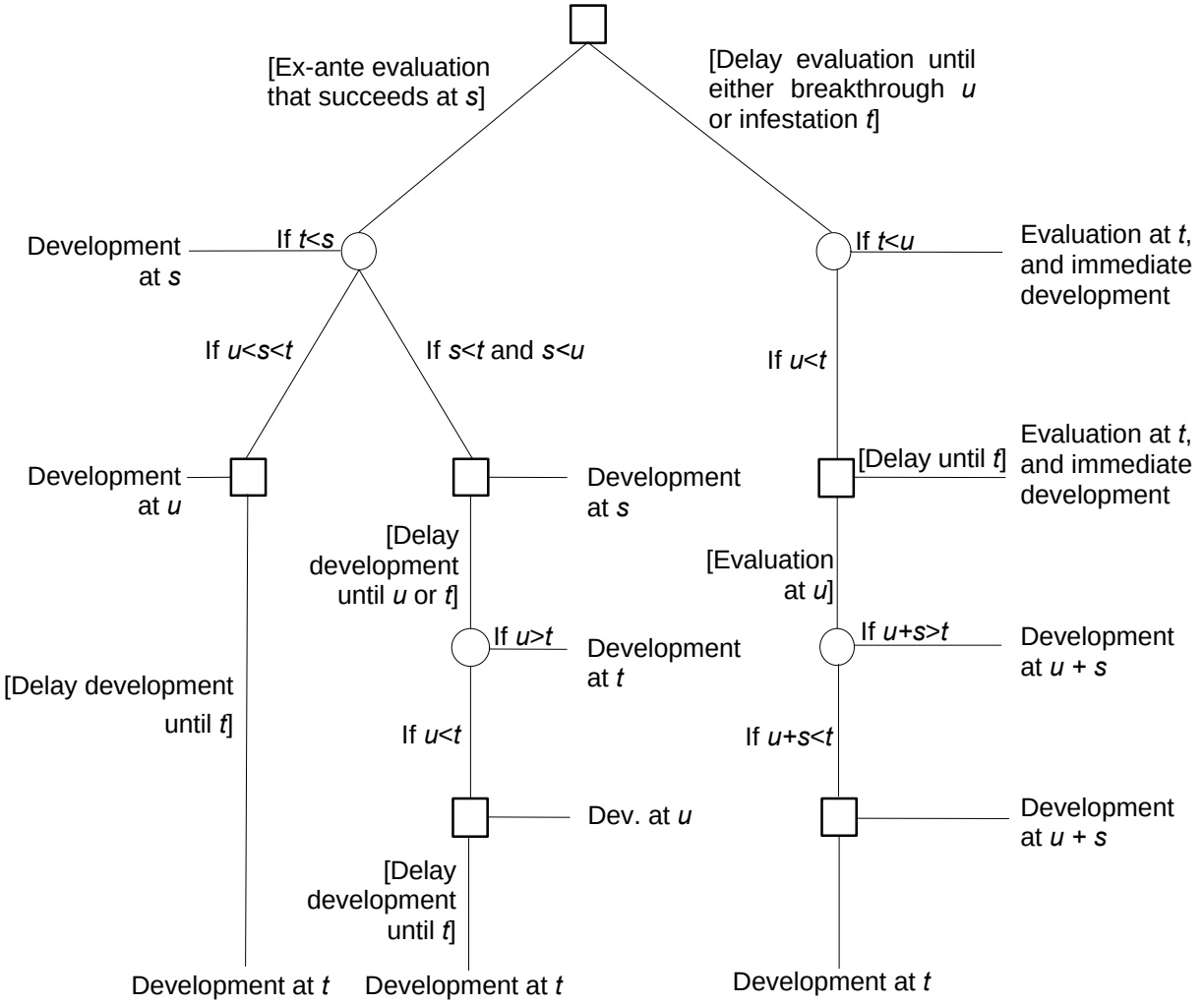
THE EXPECTED COSTS WITH A TECHNOLOGICAL BREAKTHROUGH

We now assume that a technological breakthrough reduces the flow development cost by x from m to n (i.e., $n = m - x$). The breakthrough is assumed to be discrete; it happens only once in the future at time u with a Poisson breakthrough rate β. Thus, while the flow development cost at time zero is m, the cost at time t has fallen to n with probability $(1 - e^{-\beta t})$. Another simplifying assumption is that the technological breakthrough can be utilized only if it occurs before the start of the development process. That is, we rule out converting the development process to the new technology if a breakthrough occurs in the middle of the process.

Figure 3 illustrates the decision tree of a genebank manager when there exists an anticipated technological breakthrough in development. The genebank manager now has additional decision nodes at the time of a technological breakthrough, u. The decision in period zero is whether to evaluate immediately (ex-ante evaluation), or to delay, either until a technological breakthrough ("post-breakthrough" evaluation) or until disease infestation occurs ("post-infestation" evaluation). Given ex-ante evaluation (i.e., the left branch in Figure 3), if a disease breaks out before finishing the evaluation ($t < s$), development must proceeds immediately after evaluation, by assumption. If a technological breakthrough happens before finishing the evaluation and the disease has not yet broken out ($u < s < t$), he must decide whether to develop immediately (A_0^0) or to delay until the disease outbreak (A_0^t). If neither happens before finishing the evaluation ($s < t$ and $s < u$), he can (i) delay development until the outbreak of a disease regardless of the technological breakthrough (A_0^t), (ii) delay until the technological breakthrough (A_0^u), or (iii) develop immediately (A_0^0).

On the other hand, if the genebank manager decides to delay evaluation (i.e., the right branch in Figure 3), his decision depends on the relative timing of infestation and breakthrough. If infestation occurs before a breakthrough ($t < u$), he begins evaluation immediately, followed by development. Otherwise, the decision environment is the same as the previous case without a breakthrough possibility except for the decrease in the size of development cost. One alternative is that the manager delays both evaluation and development until infestation even if the technological breakthrough has happened before the disease, in which case the expected cost is P_t^t. The second alternative is to evaluate

Figure 3: Decisions on the timing with a technological breakthrough



after the breakthrough but to delay development until the disease infestation (P_u^t), and the third is to develop immediately after the evaluation, even if the disease infestation has not yet occurred (P_u^u). The expected costs of each alternative are summarized in the following (the details of the derivations are in Appendix 1 and 2).

Ex-ante evaluation/post-infestation development

$$A_0^t = \frac{c}{r+\phi} + \frac{nL\phi}{r(r+\phi)} - \frac{nL\phi}{(r+\lambda)(r+\phi+\lambda)} + \frac{xL\phi}{r(r+\phi+\beta)} - \frac{xL\phi(r+\beta)}{r(r+\beta+\lambda)(r+\phi+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)}$$

Ex-ante evaluation/post-breakthrough development

$$A_0^u = \frac{c}{r+\phi} + \frac{nL\phi}{r(r+\phi)} - \frac{nL\phi}{(r+\beta+\lambda)(r+\phi+\beta+\lambda)} + \frac{xL\phi}{r(r+\phi+\beta)} - \frac{xL\phi(r+\beta)}{r(r+\beta+\lambda)(r+\phi+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi[\lambda+(r+\phi)(1-e^{-\lambda l})]}{(r+\phi)(r+\lambda)(r+\phi+\lambda)} + \frac{d(1-L)\phi(1-e^{-\lambda l})}{(r+\beta+\lambda)(r+\phi+\beta+\lambda)}$$

Ex-ante evaluation/development

$$A_0^0 = \frac{c}{r+\phi} + \frac{nL\phi}{r(r+\phi)} + \frac{xL\phi}{r(r+\phi+\beta)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi[\lambda+(r+\phi)(1-e^{-\lambda l})]}{(r+\phi)(r+\lambda)(r+\phi+\lambda)}$$

Post-infestation evaluation/development

$$P_t^t = \frac{c\lambda}{(r+\phi)(r+\lambda)} + \frac{nL\phi\lambda}{r(r+\phi)(r+\lambda)} + \frac{xL\phi\lambda}{r(r+\phi+\beta)(r+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)}$$

Post-breakthrough evaluation/post-infestation development

$$P_u^t = \frac{c(\beta+\lambda)}{(r+\phi)(r+\beta+\lambda)} + \frac{nL\phi\lambda}{r(r+\phi)(r+\lambda)} + \frac{nL\phi\lambda\beta}{(r+\phi)(r+\lambda)(r+\phi+\lambda)(r+\beta+\lambda)} + \frac{xL\phi\lambda}{r(r+\phi+\beta)(r+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi\beta\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)(r+\beta+\lambda)}$$

Post-breakthrough evaluation/development

$$P_u^u = \frac{c(\beta+\lambda)}{(r+\phi)(r+\beta+\lambda)} + \frac{nL\phi(\beta+\lambda)}{r(r+\phi)(r+\beta+\lambda)} + \frac{xL\phi\lambda}{r(r+\phi+\beta)(r+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi[\lambda+(r+\phi)(1-e^{-\lambda l})]\beta}{(r+\phi)(r+\lambda)(r+\phi+\lambda)(r+\beta+\lambda)}$$

THE EFFECT OF A BREAKTHROUGH POSSIBILITY

We now analyze how the possibility of a technological breakthrough in the future affects the current decision on the timing of evaluation and development. From the previous section, the conditions that ex-post development is preferred given ex-ante evaluation (equation 1) and ex-post evaluation is preferred to ex-ante evaluation given ex-post development (equation 2) can be rewritten as follows.

$$V \equiv mL\phi - d(1-L)\phi(1-e^{-\lambda l}) > 0 \tag{8}$$

$$W \equiv cr(r+\phi+\lambda) + mL\phi\lambda - d(1-L)\phi\lambda > 0 \tag{9}$$

These equations specify the parameter space in which ex-post evaluation and development is preferred without a breakthrough possibility. When there exists an anticipated technological breakthrough, ex-ante development before a breakthrough (and before an infestation occurs) is always (conditional on the chosen parameter space and ex-ante evaluation) dominated by the development at the time of a breakthrough (A_0^u) under condition (8). Since the disease cost is low relative to the development cost, delaying development until the breakthrough will bring a lower cost to a genebank manager. In addition, if the size of a technological breakthrough is large, delaying development further until the disease infestation is not optimal. That is, $A_0^u < A_0^t$ if

$$xL\phi > V \tag{10}$$

If the reduction in the expected development cost due to a breakthrough is large enough to dominate the increase in the present value of the cost due to early development, it is optimal to develop at the time of a breakthrough rather than to delay until the disease infestation. Thus, given conditions (8), (9), and (10), ex-ante evaluation/post-breakthrough development (A_0^u) is optimal if evaluation is made ex ante.

If, on the other hand, evaluation is initiated at the time of a technological breakthrough and the disease has not occurred after the evaluation ($u + s < t$), development follows immediately after evaluation if condition (10) holds: i.e., $P_u^u < P_u^t$. To find the optimal ex-post evaluation alternative, we need to compare P_u^u with the expect cost from delaying evaluation until the disease infestation (P_u^u):

$$P_u^u - P_t^t = \theta[W + V(r+\phi) - xL\phi(r+\phi+\lambda)]$$

where $\theta \equiv \beta/[(r+\phi)(r+\lambda)(r+\phi+\lambda)(r+\beta+\lambda)]$. If, given ex-post development, there is negligible difference in expected cost between ex-ante evaluation and ex-post evaluation without a breakthrough possibility (i.e., W, defined in (9), is close to zero), the sign of the above equation is negative by condition (10). Therefore, post-breakthrough evaluation and development (P_u^u) is optimal if evaluation is delayed.

Proposition 4 Optimal Timing of Evaluation and a Breakthrough Possibility

An anticipated technological breakthrough in development can advance the timing of evaluation from ex post to ex ante, which in turn advances the timing of development.

Proof

If condition (10) holds and W is close to zero, A_0^u is the optimal ex-ante evaluation alternative and P_u^u is the optimal delayed evaluation alternative.

$$A_0^u - P_u^u = \eta\{(V - xL\phi)r(r+\phi)(r+\beta+\phi) + xL\phi\lambda[\phi(\phi+\lambda) - r(r+\beta)]\}$$

where $\eta \equiv \beta/[r(r+\phi)(r+\beta+\phi)(r+\beta+\lambda)(r+\beta+\phi+\lambda)]$. Negative sign of the above equation implies that ex-ante evaluation is optimal within the parameter space where ex-post evaluation is preferred without a breakthrough possibility. The first term in the

bracket is negative by condition (10), and the second term is negative if $\phi(\phi + \lambda) < r(r + \beta)$ (and if $\lambda > 0$, assumed in equation (4)). Thus, the sufficient condition where ex-ante evaluation is preferred is $\phi(\phi + \lambda) < r(r + \beta)$. Q.E.D.

Proposition 4 implies that the possibility of a technological breakthrough advances the timing of evaluation (and development) for $\phi(\phi + \lambda) < r(r + \beta)$. If a technological breakthrough is expected to happen soon (i.e., β is high) and is likely to happen before a discovery occurs (i.e., ϕ is low), this will favor early evaluation since the breakthrough then increases the value of immediate development. If λ is high, on the other hand, immediate development is likely even without a breakthrough, so the latter has less expected effect on timing. Similarly, if the breakthrough happens after discovery (i.e., low β and high ϕ), there is no marginal advantage to advancing evaluation to exploit the breakthrough.

Figure 4: Optimal timing of evaluation with a technological breakthrough

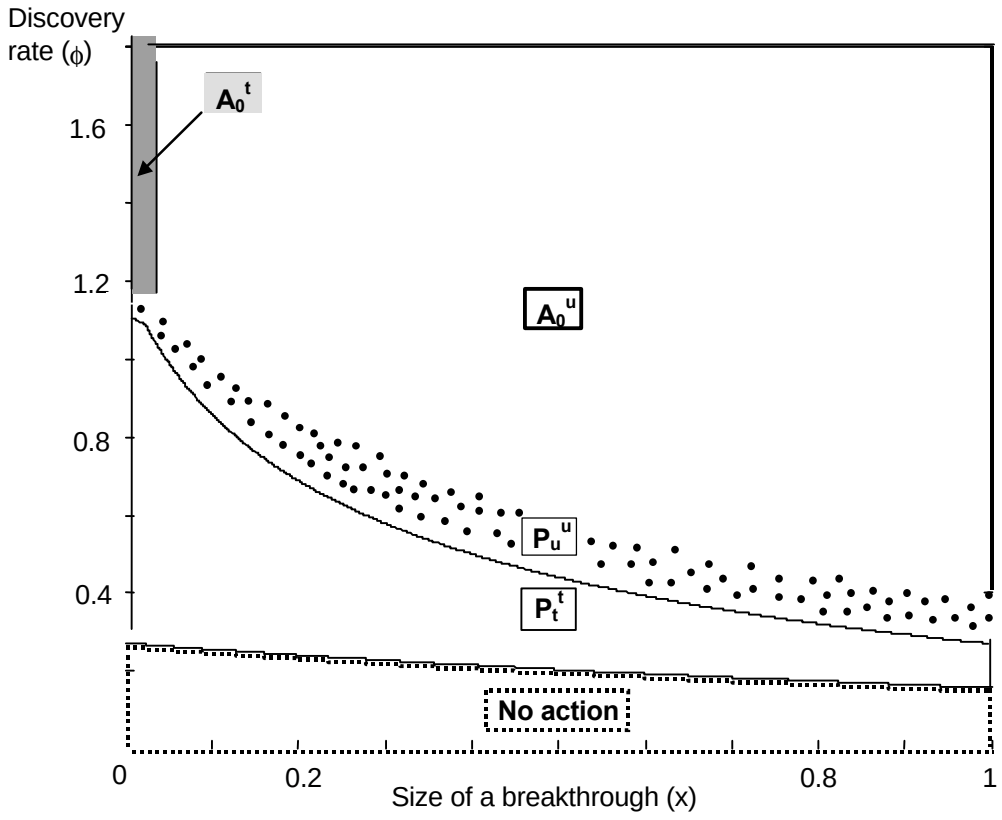


Figure 4 illustrates an example of the optimal evaluation alternatives under different parameter spaces. When there is no possibility of a technological breakthrough ($x = 0$), ex-ante evaluation/ex-post development (A_0^t) is preferred for $\phi > 1.18$ and ex-post evaluation (P_t^t) for $0.25 < \phi < 1.18$. Within this range where ex-post evaluation is preferred, as the size of a breakthrough increases, the set of optimal alternatives expands to include post-breakthrough evaluation/development (P_u^u) and ex-ante evaluation/post-breakthrough development (A_0^u). The benefit from a large technological breakthrough can be substantial if it is utilized earlier. This will induce ex-ante evaluation to capture the benefit of earlier utilization if condition $\phi(\phi + \lambda) < r(r + \beta)$ holds. Thus, continuous advances in biotechnology in the future may induce early evaluation of genebank accessions and consequently early development of cultivars.

This result is contrary to the usual argument of real option theory in which uncertain future environment delays the timing of a decision. The reason for this difference is that in this model it takes time to utilize the breakthrough—that is, the evaluation process must be successfully completed before utilizing the breakthrough in development. If the evaluation process is instantaneous or the breakthrough happens in evaluation, our model favors delaying as in standard real option theory. However, in situations where it takes time to finish the first stage of a two-stage investment process, the timing decision may be different from the argument of real option theory. The ability to delay the second stage (development) depending on the state makes early investment in the first stage (evaluation) more attractive, as in Bar-Ilan and Strange (1998). But here the real option value due to technological uncertainty actually can advance investment in both stages relative to the case of no technological uncertainty. Bar-Ilan and Strange

(table 4, p.452), by contrast, find that uncertainty (in output price) increases the “trigger price” whether the investment may be suspended after the first stage, thus discouraging early investment relative to the case with zero price variance.

5. CONCLUSION

The agricultural environment is continuously changing, and so is the demand for germplasm by plant breeders. Predicting future use of germplasm in ex-situ genebanks is increasingly difficult. One of the most important policy issues regarding management of genebank collections concerns the evaluation of their collections prior to utilization. A commonly expressed view is that all traits likely to be relevant in crop improvement should be completely evaluated ex ante to facilitate and encourage the utilization by plant breeders.

This paper examines the optimal timing of evaluation of germplasm for disease resistance traits and of development of cultivars incorporating those traits, from the social point of view. We consider the case where the disease-causing agent is known, but the date of crop infestation is stochastic. We find that for a trait that has low probability of being needed soon, ex-ante evaluation tends to be dominated by delayed evaluation. This result is especially important for the management of genebanks, which suffer chronic funding problems. Instead of spending scarce financial resources for the expensive evaluation of rarely used genes, it might well be more efficient to focus on other activities; for example, provision of basic information and construction of an information network for better information flow (Frankel 1989; Williams 1989).

Technological progress has an important influence on the timing of evaluation of accessions and of the development of cultivars incorporating traits identified in the evaluation process. Innovations that reduce search and development costs and/or speed up search and development rates turn out to favor ex-ante evaluation. The possibility of a future technological breakthrough in the cost of evaluation tends to delay evaluation, as

one might expect from the common general intuition about real option value in which prospective technological progress affecting the cost of an investment tends to delay the timing of an investment. But the possibility of a breakthrough in the cost of development may advance the timing of the whole process, contrary to real option theory.

We showed that, for the parameter space where ex-post evaluation is preferred, the breakthrough possibility may advance the timing of evaluation from ex post to ex ante. The reason is that the marginal benefit from the technological breakthrough is larger when development process is started earlier. If the initial situation favors ex-ante evaluation, the possibility of a breakthrough reinforces the effect on the earlier evaluation. We can conclude that both the level and rate of technological progress may justify advancing the search process and consequently the development process, except when the possibility of a breakthrough refers to the evaluation stage itself.

This study covers only one small aspect of the problems faced by genebank managers: i.e., evaluation for single-gene disease resistance traits. Depending on the specific cost conditions, evaluation for multiple traits simultaneously might often be optimal, complicating the above analysis. The case of a sequence of technological breakthroughs is another interesting extension. The question of evaluation for more complex quantitative traits associated with yield is the subject of ongoing research in functional genomics. As the science becomes better understood, exploration of the economics of different managerial strategies regarding genebank accessions should continue to be a very interesting topic.

APPENDIX 1:
EXPECTED COSTS OF EX-POST EVALUATION

The search cost of ex-ante evaluation is $c/(r + \phi)$. If the evaluation succeeds *after* infestation ($t < s$), then development follows immediately. The expected cost (excluding the search cost) when $t < s$ is

$$Q_a(s) = \int_0^s \left[\frac{d}{r}\left(e^{-rt} - e^{-rs}\right) + \left(1 - e^{-\beta s}\right)\frac{(n+d)L}{r}e^{-rs} + e^{-\beta s}\frac{(m+d)L}{r}e^{-rs} \right] \lambda e^{-\lambda t} dt$$

If the genebank manager delays development until infestation for $t > s$, the expected development and disease cost is

$$\left(1 - e^{-\beta s}\right)\int_0^s \frac{(n+d)L}{r}\lambda e^{-(r+\lambda)t} dt \qquad \text{for } u < s$$

and

$$\left(e^{-\beta s} - e^{-\beta t}\right)\int_s^\infty \frac{(n+d)L}{r}\lambda e^{-(r+\lambda)t} dt + e^{-\beta t}\int_s^\infty \frac{(m+d)L}{r}\lambda e^{-(r+\lambda)t} dt \qquad \text{for } u > s$$

Thus, the expected development and disease costs of post-infestation development when $t > s$ is

$$Q_1(s) = \frac{(n+d)L\lambda}{r(r+\lambda)}e^{-(r+\lambda)s} + \frac{xL\lambda}{r(r+\beta+\lambda)}e^{-(r+\beta+\lambda)s}$$

The expected cost of ex-ante evaluation/post-infestation development is derived using $Q_a(s)$ and $Q_1(s)$.

$$A_0^t = \frac{c}{r+\phi} + \frac{nL\phi}{r(r+\phi)} - \frac{nL\phi}{(r+\lambda)(r+\phi+\lambda)} + \frac{xL\phi}{r(r+\phi+\beta)} - \frac{xL\phi(r+\beta)}{r(r+\beta+\lambda)(r+\phi+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)}$$

If development is delayed until the technological breakthrough or the disease infestation, the expected cost is

$$\left(1-e^{-\beta s}\right)\left[\int_s^{\infty}\frac{nL}{r}e^{-rs}\lambda\, e^{-\lambda t}dt+\int_s^{s+l}\frac{d}{r}\left(e^{-rt}-e^{-r(s+l)}\right)\lambda\, e^{-\lambda t}dt\right] \qquad \text{for } s < u$$

and
$$\int_s^{\infty}\int_s^{t}\frac{nL}{r}\beta e^{-(r+\beta)u}\lambda\, e^{-\lambda t}dudt+\int_s^{s+l}\int_s^{t}\frac{d}{r}\left(e^{-rt}-e^{-r(u+l)}\right)\beta e^{-\beta u}\lambda\, e^{-\lambda t}dudt$$
$$+\int_{s+l}^{\infty}\int_{t-l}^{t}\frac{d}{r}\left(e^{-rt}-e^{-r(u+l)}\right)\beta e^{-\beta u}\lambda\, e^{-\lambda t}dudt \qquad \text{for } s < u < t$$

and
$$e^{-\beta t}\int_s^{\infty}\frac{(m+d)L}{r}\lambda\, e^{-(r+\lambda)t}dt \qquad \text{for } s < t < u$$

The expected cost of ex-ante evaluation/post-breakthrough development is derived using $Q_a(s)$ and above equations.

$$\begin{aligned}A_0^u=&\frac{c}{r+\phi}+\frac{nL\phi}{r(r+\phi)}-\frac{nL\phi}{(r+\beta+\lambda)(r+\phi+\beta+\lambda)}+\frac{xL\phi}{r(r+\phi+\beta)}\\&-\frac{xL\phi(r+\beta)}{r(r+\beta+\lambda)(r+\phi+\beta+\lambda)}+\frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)}\\&-\frac{d(1-L)\phi[\lambda+(r+\phi)(1-e^{-\lambda l})]}{(r+\phi)(r+\lambda)(r+\phi+\lambda)}+\frac{d(1-L)\phi(1-e^{-\lambda l})}{(r+\beta+\lambda)(r+\phi+\beta+\lambda)}\end{aligned}$$

If development follows immediately after evaluation regardless of a technological breakthrough, the expected development and disease cost is

$$\left(1-e^{-\beta s}\right)\left[\int_s^{\infty}\frac{nL}{r}e^{-rs}\lambda\, e^{-\lambda t}dt+\int_s^{s+l}\frac{d}{r}\left(e^{-rt}-e^{-r(s+l)}\right)\lambda\, e^{-\lambda t}dt\right] \qquad \text{for } u < s$$

and
$$e^{-\beta s}\left[\int_s^{\infty}\frac{mL}{r}e^{-rs}\lambda\, e^{-\lambda t}dt+\int_s^{s+l}\frac{d}{r}\left(e^{-rt}-e^{-r(s+l)}\right)\lambda\, e^{-\lambda t}dt\right] \qquad \text{for } u > s.$$

The expected cost of ex-ante evaluation/development is derived using $Q_a(s)$ and above equations.

APPENDIX 2:
EXPECTED COSTS OF EX-ANTE EVALUATION

When a disease breaks out before a technological breakthrough ($t < u$), the genebank starts to evaluate and develop a new variety without further delay. The expected cost of ex-post evaluation when $t < u$ is

$$Q_p(u) = \int_0^u \left[\frac{c+d}{r+\phi} + \frac{(m+d)L\phi}{r(r+\phi)} - \frac{xL\phi}{r(r+\phi)} e^{-(r+\phi)(u-t)} \right] \lambda e^{-(r+\lambda)t} dt$$

When the technological breakthrough happens before the disease ($u < t$), and if evaluation and development are delayed until the disease infestation, the expected cost is

$$Q_2(u) = \int_u^\infty R_2 \lambda e^{-\lambda t} dt$$

where $R_2 = e^{-rt} \int_0^\infty \left[\frac{(c+d)}{r}\left(1-e^{-rs}\right) + \frac{(n+d)L}{r} e^{-rs} \right] \phi e^{-\phi s} ds$. The expected cost of post-infestation evaluation/development is

$$P_t^t = \int_0^\infty \left(Q_p(u) + Q_2(u)\right) \beta e^{-\beta u} du$$
$$= \frac{c\lambda}{(r+\phi)(r+\lambda)} + \frac{nL\phi\lambda}{r(r+\phi)(r+\lambda)} + \frac{xL\phi\lambda}{r(r+\phi+\beta)(r+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)}$$

Given that evaluation is initiated at the time of the breakthrough, development can be started at the time of the disease infestation (if it occurs after the search is completed). The expected cost for $u < t$ is

$$Q_3(u) = \int_0^\infty R_3(s) \phi e^{-\phi s} ds$$

where

$$R_3(s) = \int_u^\infty \frac{c}{r}\left(e^{-ru} - e^{-r(u+s)}\right) \lambda e^{-\lambda t} dt$$
$$+ \int_u^{u+s} \left[\frac{(n+d)L}{r} e^{-r(u+s)} + \frac{d}{r}\left(e^{-rt} - e^{-r(u+s)}\right) \right] \lambda e^{-\lambda t} dt + \int_{u+s}^\infty \frac{(n+d)L}{r} \lambda e^{-\lambda t} dt$$

The expected cost of post-breakthrough evaluation/ex-post development is derived using $Q_p(u)$ and $Q_3(u)$.

$$P_u^t = \frac{c(\beta+\lambda)}{(r+\phi)(r+\beta+\lambda)} + \frac{nL\phi\lambda}{r(r+\phi)(r+\lambda)} + \frac{nL\phi\lambda\beta}{(r+\phi)(r+\lambda)(r+\phi+\lambda)(r+\beta+\lambda)} + \frac{xL\phi\lambda}{r(r+\phi+\beta)(r+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi\beta\lambda}{(r+\phi)(r+\lambda)(r+\phi+\lambda)(r+\beta+\lambda)}$$

If the genebank manager starts to develop immediately after the evaluation regardless of the disease outbreak, the expected cost for $u < t$ becomes

$$Q_4(u) = \int_0^\infty R_4(s) f e^{-fs} ds$$

where

$$R_4(s) = \int_u^\infty \left[\frac{c}{r}\left(e^{-ru} - e^{-r(u+s)}\right) + \frac{nL}{r} e^{-r(u+s)} \right] l e^{-lt} dt + \int_u^{u+s} \left[\frac{dL}{r} e^{-r(u+s)} + \frac{d}{r}\left(e^{-rt} - e^{-r(u+s)}\right) \right] l e^{-lt} dt + \int_{u+s}^{u+s+l} \frac{d}{r}\left(e^{-rt} - e^{-r(u+s+l)}\right) l e^{-lt} dt$$

The expected cost of post-breakthrough evaluation/development is derived using $Q_p(u)$ and $Q_4(u)$.

$$P_u^u = \frac{c(\beta+\lambda)}{(r+\phi)(r+\beta+\lambda)} + \frac{nL\phi(\beta+\lambda)}{r(r+\phi)(r+\beta+\lambda)} + \frac{xL\phi\lambda}{r(r+\phi+\beta)(r+\beta+\lambda)} + \frac{d(r+L\phi)\lambda}{r(r+\phi)(r+\lambda)} - \frac{d(1-L)\phi[\lambda+(r+\phi)(1-e^{-\lambda l})]\beta}{(r+\phi)(r+\lambda)(r+\phi+\lambda)(r+\beta+\lambda)}$$

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