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TECHNOLOGY SELECTION AND APPROPRIATE TECHNOLOGY

A. Steven Englander*

This paper provides a formal model of technology choice by a single region. Case studies have indicated that the technology acquired by LDCs often seem unsuitable, although the criteria for suitability are often unclear. The reasons which are presented for inappropriateness of the selection often rely more on political arguments then economic ones, or treat the recipient country as a passive actor in the whole process.

Can a technology actively selected by a recipient country ever by inappropriate, assuming factor cost ratios represent true relative values? A model presented by Evenson and Bingswanger (1978) indicates that a technology developed in one economic or physical environment may be 'appropriate' to a second, very different environment if the second environment can generate a very limited range of technological possibilities on its own. Ranis (1978) has emphasized the importance of information on technological alternatives flowing smoothly and accurately within the system and the need to acquire capacity for adaptive research. Both these approaches recognize the importance of indigenous research capacity, although Ranis accords more emphasis to friction and proper incentives within the system. Barring policy and management problems, their conclusions appear to be that technology choice will be efficient--the appearance of inappropriateness stems from the lack of explicit recognition of the contraints on technology generation in the system.

The model presented below builds on the early models of rational technology selection of Evenson-Binswanger and Ranis. It shares common elements with the Evenson-Binswanger model and may be regarded as a generalization of their model. It goes further, however, in several crucial aspects. It allows the extent of both adaptive and independent research to be choice variables in the technology acquisition decision. It allows for selection out of a continuum of technologies which differ in the environments for which they were designed. It allows for limits to the extent to which technologies can be adapted across environments and allows for losses because of imcomplete adaption. The public goodnature of research plays a critical role in determining the efficiency of resource allocation as well.

The model presented immediately below is couched in terms relating to agricultural technology. A reason for first presenting a model of agricultural technology selection is that many of the conceptual issues possess more intuitive natural interpretations. A second section will consider the impact of market structure on the development of technology, and a third section will broaden the basic model of agricultural technology development to one which emcompasses certain types of fixed capital investment. A fourth section discusses testing of the model.

Technology Choice in Agriculture

In the model below, the decision is made by a region as to whether to adopt technology produced in other regions or build up a stock of indigenously developed technology. The region assumes that its research policies will not affect those of any other region. In practice, especially internationally, such behavior seems the rule rather than the exception. The focus is the consideration which enter into the technology acquisition decision for a single country, not efficiency in resource allocation among a set of countries.** In discussing the transferability of technology, we can use the environmental-sensitivity measure devised by Evenson and Binswanger, which relates cost of production with a given technology in its native environment to cost of production in another environment in which it is used. The meaning of the term "environment" is also clear. In the agricultural context,

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**For discussion of this topic, see Englander, and Evenson (1979) and Englander (1980).

climatic differences will produce differing isoquants à la Riccardo, and the environmental sensitivity will depend on these differences.

For the concreteness it will be assumed that water control is the relevant environmental dimension, that environments range from desert to well irrigated, and that the percent of seasons without drought problems measures water control. Any relevant environmental dimension or an index combining several dimensions could serve as well.

Assume that research has been successfully conducted on varieties grown under various regimes of water availability. A country in which drought is a problem most of the time is attempting to choose its research priorities. It has a traditional agricultural technology which is very resilient under drought conditions but which is lacking in other dimensions. The choices available to the country are (a) ignore the research of the other regions and conduct research independently according to its own priorities and abilities and (b) adapt the research of other regions to the domestic conditions of drought.

A number of factors will determine its decision. The first is the distribution of research which is available from regions under differing water regimes. Irrigated and well-watered regions may have a preponderance of the available research and the technologies developed in these regions may have very desirable characteristics. However, the difficulty in incorporating resistance to severe drought conditions into these technologies may commend adapting a smaller research stock available from a region in which drought resistance is a greater priority.

On the other hand, it may remain advantageous to sacrifice a degree of drought resistance in order to acquire a technology which is better in other ways. However, the impact of a diminishment in the level of drought resistance on the advantages of technology superior in other dimensions must be considered. As an imported technology becomes more susceptible to drought, the benefits from improvements in other dimensions will be reduced according to the increase in damage from drought.

In making the decisions discussed above, the availability of research resources for adaptive and independent research must also be considered. If there are large numbers of well-trained researchers willing and able to create technologies specific to their environment, the technology acquired by the region, both adapted and created indigenously, will be closely tailored to the domestic environment. If such capacity is absent, there will be less concern about the completeness of adaptation since the role of independent research will be less significant relative to the research imported.

Let E_i represent the i'th environment and denote the domestic environment by E_D. Also define $E_{ki} = E_k - E_i$ as the distance between the i'th and k'th environments.

The availability of research across all other environments is expressed by

$$X_j = X_j(E_{jD}),\ X_j' > 0,\ X_j'' < 0 \tag{1}$$

where j ranges over the extent of the environmental index. It will be assumed that there are increasing amounts of research available with greater environmental distance from the domestic region, but that the rate of increase is falling.

The extent to which research can be transferred from environment j to environment k is determined by

$$t_{jk} = t_{jk}(E_{jk})\ t' < 0,\ t'' < 0 \tag{2}$$

i.e., as a function of the distance between the original environment to which the research was tailored and the environment to which it is being adapted. The extent of transferability is assumed to decline at an increasing rate as the distance between the original environment and the target environment increases. Thus, $t_{jf}X_j$ measures the total technology transferable from environment j to environment f.

The cost of incompletely adapting a stock of research available from a distant environment is the sacrifice of some environmental specificity of research. As a region compromises on the extent to which it adapts technologies to its region, it is likely to be lowering the usefulness of the technology which it has acquired. An illustration can be drawn from the water availability example discussed above. If traditional technologies are drought resistant but the newly acquired technology is not as resistant, the effectiveness of the acquired technology stock will be diminished by the extent of the added losses from drought. The reduction in research effectiveness is described by

$$a_{fd} = a_{fD}(E_{fD}),\ a_{fD}' < 0\ a_{fD}'' < 0 \tag{3}$$

where E_f is the environment to which the technology is adapted, and E_{fD}, therefore represents the extent to which the domestic region has compromised in tailoring the technology to its environment. The less the technology stock is tailored to the domestic environment, the lower the value of the stock. It is also assumed that the decline in the usefulness of the technology becomes steeper as it is less adapted. Below, when we discuss the degree of adaptation of a technology, we will be referring to the value of a_{fD}.

If a technology developed in environment j is adapted to environment k, the amount available to the domestic environment D, will be

$$a_{fD} t_{jf} X_j$$

Implicitly, this scheme disaggregates a technology package into two components. One component consists of characteristics of the technology which are relatively insensitive to environmental changes. The environmental sensitivity of any element in the technology package will be determined specifically for each region seeking to acquire technology, and will vary between regions. It is on the environmental-sensitive elements that adaptive research is conducted, and the degree to which the sensitivity is eliminated determines the extent of adaptability to the domestic region.

It is assumed that the orientation of independent domestic research is determined in conjunction with the decisions on the transfer of technology, and that the two complement each other. The former, however, is constrained by the degree of adaptability which has been built into technology acquired from other regions and will decline in usefulness the less the technology as a whole is adapted to the domestic region. In the example in which water availability is the relevant environmental index, if transferred technology has not been rendered adequately drought resistant by adaptive research, the effectiveness of technology developed domestically will suffer to the same extent. This is equivalent to the assumption that technologies combined from different sources will jointly have the minimum of their levels of adaptability. In this case, domestic research may be assumed adapted to the domestic environment but limited by the adaptability built into the transferred research. This is probably a conservative assumption. Many of the results will hold qualitatively even with more liberal assumption on the joint adaptability of technologies acquired from diverse sources.

The four decision variables are (1) the environment whose technology is to be transferred, E_j; (2) the extent to which the technology is to be adapted to the conditions of the domestic regions, E_{Df}; (3) the level of adaptive research, X_1; and (4) the level of research aimed at improving upon the acquired technology, X_2. If there is no attempt at transferring research, then only independent research, directed at improving existing technology in the domestic region, is conducted.

The formal maximization problem may be written as

$$\max L = g\left\{a_{fD}\left[t_{fj}\ (1-e^{-\rho X_{1D}})X_j + X_{2D}\right]\right\} - C(X_{1D}, X_{2D})$$

where

$g\ (.)$	is the research benefits function,
$C\ (.,.)$	is the cost function of the two research types,
X_{1D}	is the level of adaptive research conducted by the domestic region acquiring research,
X_{2D}	is the level of the independent research activity in the domestic region,
a_{fD}	is, as discussed above, the relative effectiveness of research, which depends on the degree to which the transferred research has been adapted to the domestic environment,
X_j	is the research available in region j,
and ρ	is a parameter which determines the ability of adaptive research to transfer research.

In the argument for $g\ (.)$, the research benefits function, the term in square brackets represents a stock of research which the domestic region is attempting to utilize and the factor a_{fD} discounts this technology by the extent to which it is not adapted to the domestic region.

For simplicity, much separability has been incorporated into the functional forms. Thus, X_j is the transferable research of region j, $t_{fj}X_j$ is the maximum potential transfer of research from environment j to environment f, and $(1-e^{-\rho X_1})$ measures the percentage of the maximum potential transfer which is actually transferred. The point of this formulation is to introduce the effort directed at research transfer, the extent of adaptation and the distribution of potentially transferable research of factors in the determination of appropriate technology for the region.

It would also be possible to write the transferred research component as

$$(1-e^{-\tau_{fj} X_1})\ X_j$$

where $\tau_{fj} = \tau(E_{fj}) \tau' < 0\ \tau'' < 0.$

There is little qualitative difference in the results obtained using either form. The second form allows the adaptation of any technology to any environment as long as more adaptive research is performed. The earlier form is more amenable to graphical interpretation and is used in the presentation below.

The equilibrium conditions are presented below. ε (.) refers to the elasticity of . with respect to its argument and η_t is the percentage of total research acquired through transfer.

$$-\frac{1}{\eta_t}\frac{\varepsilon(a_{fD})}{E_{fD}} = \frac{\varepsilon(X_j)}{E_{Dj}} \tag{5}$$

$$-\frac{\varepsilon(t)}{E_{fj}} = \frac{\varepsilon(X_j)}{E_{Dj}} \tag{6}$$

$$g' \quad a_{fD} = C^2 \tag{7}$$

$$g' \quad a_{fD}te^{-\rho X_1} X_j = C^1 \tag{8}$$

The conditions above are conditions for an interior solution. Examination of the nature of corner solutions provides some insight into conditions which will make a region rely entirely on transferred research or its own research. In (5), since η_t is bounded by one, if

$$\frac{\varepsilon(a_{fD})}{E_{fD}} > \frac{\varepsilon(X_{jt})}{F_{Dj}} = \frac{\varepsilon(t)}{E_{fj}},$$

then transferred technology is adapted completely to the domestic environment (or no transfer is attempted). From (6) if

$$\varepsilon(X_{jt})/F_{Dj} > \frac{\varepsilon(t)}{E_{fj}},$$

then the original environment of the transferred technology will be the one which has conducted the most research.

Figures 1 and 2 analyze some implications of these equilibrium conditions. The first quadrant of figure 1 illustrates (6). The values of $\varepsilon(X_j)$ and $-\varepsilon(t)$ are graphed against E_{fj} and E_{Dj}. From (6) locis of points of equilibrium are the points $\varepsilon(t)$ and $\varepsilon(X_j)$ which lie on the same ray drawn from the origin. For example, as the ray OR indicates, when $E_{Dj} = E'_{Dj}$, then $E_{fj} = E'_{fj}$. The former, E_{Dj}, is the distance of the domestic environment from the environment of origin of the new technology, and E_{fj} is the extent to which the technology has been adapted to the domestic environment. The distance between the equilibrium points is E_{fD}, the measure of the extent to which the borrowed technology has not been adapted to the domestic environment. The point S indicates the point where the transferred technology is completely adapted to the domestic environment. In quadrant IV, the equilibrium values of E_{fD} and E_{fj} are graphed. In quadrant III, $-\varepsilon(a)$ is graphed against E_{fD}. In quadrant II, the equilibrium values of $-\varepsilon(t)$ and (a) are shown as PP' and the equilibrium values of $-\varepsilon(t)$ and $\varepsilon(X_j)$ are shown as OQ.

In Figure 2, equilibrium values of $\varepsilon(X_{jt})/E_{Dj}$ and $\varepsilon(a)/E_{fD}$ are drawn. From (8) the increase of the slope of the ray drawn from the origin to any point along BB' can be seen to be the share of transferred technology in the total technology stock acquired by the region. This obviously precludes combinations below the 45-degree line in Figure 2, because the implied share of transferred technology would be greater than one. It also indicates that the degree of adaptation to the domestic environment will diminish as the importance of transferred technology increases. Factors which could accomplish this would include reductions in the relative cost of adaptive research and outward shifts in research availability.

By taking the differentials of (5) and (8), it is possible to examine the effects of shifts in the underlying parameters. It is possible to show that a positive shift in the marginal cost of adaptive research will induce less adaptive research on but a greater degree of adaptation of a technology drawn from a nearer environment. The level of independent research will increase. On the other hand, an upward shift in the marginal cost of independent research will induce a lower level of independent research, a higher level of adaptive research, less adaptation to the domestic environment, and selection of a technology from a more distant environment. The negatively correlated movements of the level of adaptive research, X_1, and the extent of adaptation, a_{fD}, occur because the value of the latter depends heavily on the relative importance of independent and adaptive research. As independent domestic research gains more prominence, the extent to which a technology will be adapted to the domestic environment increases.

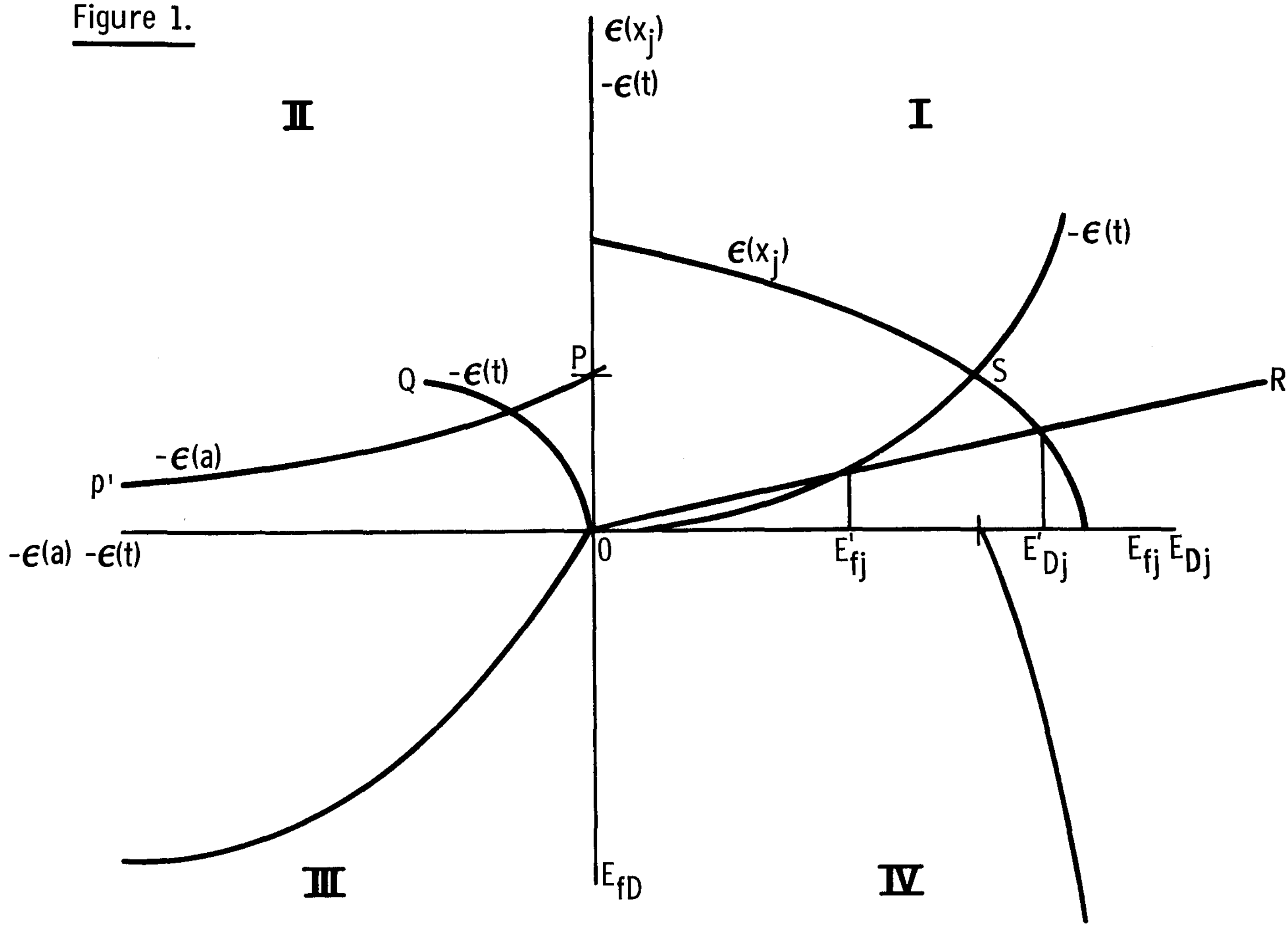
If other regions increase the transferability of their research, shifting the t schedule upwards and raising the maximum potential transferability from other environments, the effects will generally be similar to those resulting from a lowering of marginal costs of adaptive research. The exact sufficiency condition for these results is that

$$-\varepsilon(g') < \frac{1}{\eta_t}$$

where, as before, $\varepsilon(g')$ is the elasticity of marginal benefits and η_t is the share of transferred technology in the total of technology acquired. The intuitive explanation of this condition is that if marginal benefits fall very quickly, easier access to research performed by other regions may induce a cutback in the level of adaptive research. All benefits functions of the form

$g = Z^{\alpha}$ $0 < \alpha < 1$, where Z is the amount of technology acquired, fulfill the condition. Similar conditions and results emerge from an outward shift of the stock of research in other regions.

Figure 1.



A shift in the a_{fD} schedule produces ambiguous effects. The interpretation of proportionate outward shift would be that the decline in the effectiveness of a fixed research stock as it becomes less adapted to the domestic environment becomes less severe. It is clear that the marginal productivity of both adaptive and independent research would increase, holding the other two choice variables fixed. It can also be shown that if the relative share of independent research decreases, then so will the equilibrium value of $\varepsilon(X_j)$, corresponding to an increased dependence on technology developed in a more distant environment. If the share of transferred research increases, then the value of $\varepsilon(a)/E_{fD}$ must fall. The direction in which shares move would seem to depend on whether the cost of independent research increases quickly relative to the cost and availability of transferred research.

The assumptions of negative second derivatives for the $a(E_{fD})$, $t(E_{fj})$ and $X_j(E_{Dj})$ functions made interior solutions more likely. The interpretations of these assumptions are (1) the marginal losses due to nonadaptation are increasing, (2) the marginal ability to adapt diminishes more rapidly the greater the distance over which adaptation is attempted, and (3) the marginal increase in technology as one moves to more distant environments is diminishing.

Altering the third of these assumptions to allow for increasing marginal research availability with greater distance could introduce increasing returns to scale so that a region's choice would be between adapting a larger but distant stock or not doing any adaptive research at all, eliminating intermediate choices. This could also be regarded as the Evenson-Binswanger case with discrete rather than continuous technology choice sets.

Some effects of altering the first two assumptions are illustrated in Figures 3 and 4. The effect of changing the second assumption is indicated by the solid lines, while the effect of altering the first is illustrated by the dashed lines and tildas. The most striking result is that in both cases the monotonic

Figure 2.

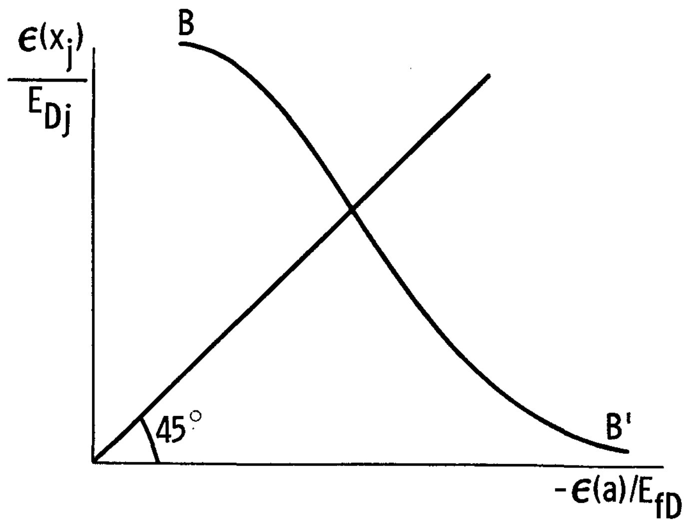


Figure 3.

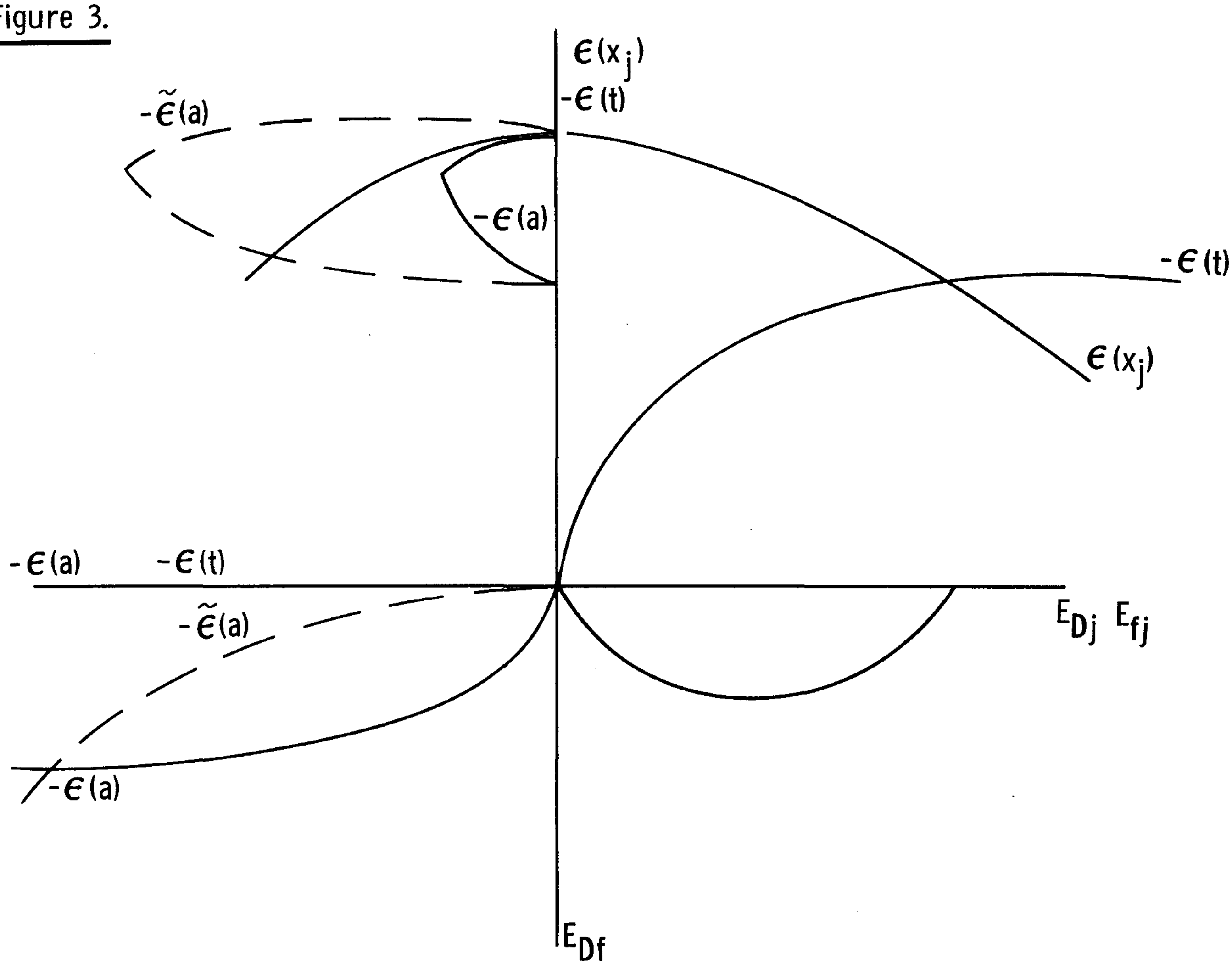
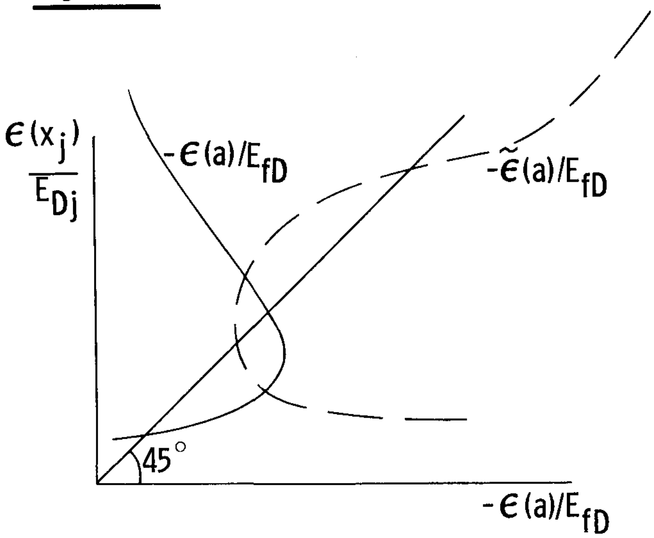


Figure 4.



equilibrium relationship of E_{Dj} and E_{Df} does not hold. Both extremely high and extremely low levels of research transfer will be associated with high degree of adaptation. Figure 4 expresses this somewhat differently, indicating that the relative importance of transferred research can be associated with two different levels of adaptability. The case illustrated by the solid lines in Figure 3 and Figure 4 can be interpreted as indicating that for any value of a_{fD} there will be two values of $\varepsilon(X)$ and $\varepsilon(t)$ which fulfill the equilibrium conditions, one which a large share of a small research stock may be transferred and a second in which a smaller share of a larger stock is available. Of these two values, one will provide a greater borrowable stock of research than will the other. For any value of a_{fD}, there will be only one efficient borrowable stock although the function relating equilibrium values of $\varepsilon(a)$ and $\varepsilon(X_j)$ need not be continuous. From Figure 4 it can be seen that of the possible equilibrium associated with any value of $\varepsilon(a)$, one will have a relatively greater emphasis on transfer and will have a more distant origin for the transferred technology than will the other possible equilibrium. As would be expected, such a system would tend to show much less regular responses to parameter shifts. In the case devoted in Figure 3 and Figure 4 by dashed lines and tildas, both t_{fj} and a_{Df} fall at a slower rate with higher values of their arguments. This case poses more complications than the one just discussed as there are likely to be potential equilibria at various combinations of extreme values of t_{fj} and a_{Df}.

Market Structure and Technology Choice

This section will consider the effect of market size on the amount and type of research which will be conducted. It is clear that the benefits of a new technology will be a positive function of the scale on which it is utilized. If the region acquiring new technology is small and homogeneous, facing elastic input supplies, it will be reasonable to associate increases in market size with outward shifts in the marginal benefits function of research. The focus of this section will be the expansion path of transferred and independent domestic research as the marginal benefits function is shifted outwards. The related, but not identical, question of how the composition of the research bundle will change as marginal costs change will also be examined. The latter issue can be related to the public good aspect of research. Although a particular region in a given environment may be interested only in its own benefits, the other regions which share the environment may come to recognize that, taken as a group, their access to research resources of mutual benefits is significantly greater than the availability of resources as perceived by each individually. The ability to benefit from the research of others may be regarded as lowering the cost of acquiring any level of research, assuming that the regions act in concert in acquiring the research.

Some of the earlier discussion is relevant to these problems. It was noted above that as the share of transferred technology increased, there would be a tendency to acquire technology from more distant environments but with less adaptation to the domestic environment. As well, there was a limit to the amount of research which was available for transfer from other environments, a limit which could stem from increasing difficulties in adapting research from distant environments as well as actual limits to the amount of technology developed at those environments. The total of technology which becomes available to the region can be represented by Z, where

$$Z = a_{fD}\left[t_{fj}\ X_j(1-e^{-\rho X_1}) + X_2\right]$$

and a_{fD}, t_{fj}, X_j, X_1 and X_2 are as defined above. Where no confusion will arise, the subscripts will be dropped in the future.

From the earlier discussion, it is known that the equilibrium values of a, t, and X_j are linked, as was illustrated in Figure 1. In fact, if we define

$$T^* = a^*\ t^* X_j^*$$

where the asterisks denote equilibrium values, it is easy to show that

$$\frac{dT^*}{T^*} = (1-\eta)\frac{X_j'}{X_j}\,dE_f$$

where, as before,

$$\eta = \frac{taX_j(1-e^{-\rho X_1})}{Z}$$

and E_f measures the extent to which technology is adapted to the region.

It is also possible to show that in equilibrium the values of t and η increase with X_j while that of a declines. An increase in E_f lowers the value of a, but raises the equilibrium value of T*. We can also define

$$T \equiv T^*(1-e^{-\rho X_1})$$

the actual amount of technology transfer, and

$$D \equiv a\ X_2$$

the level of independent domestic research diminished by the extent to which the technology as a whole is not adapted to the environment.

As E_f increases, $-a^1/a$ is also increasing and X_j'/X_j is falling. The additional amounts of technology which become available with successive diminishments in the standards of adaptation be-become lower and ultimately are zero.

We may rewrite Z, holding T* fixed, as

$$Z = T^*(1-e^{-\rho X_1}) + D$$

and compare the marginal costs of acquiring additional technology via transfer or domestic research. The marginal cost of research is

$$\frac{dC}{dZ} = \frac{dC}{dX_1}\ \frac{dX_1}{DZ} = \frac{C_1'\ e^{\rho X_1}}{\rho T^*} = \frac{C_1'\ e^{\rho X_1}}{\rho a^* t^* X_j^*} \tag{9}$$

when technology is acquired through additional adaptive research, and

$$dC/dZ = \frac{dC}{dX_2}\cdot\frac{dX_2}{dZ} = C_2'/a^* \tag{10}$$

when technology is acquired through domestic research. The equilibrium condition for an interior solution required that the marginal cost of additional technology be the same, whether acquired domestically or through transfer. Thus,

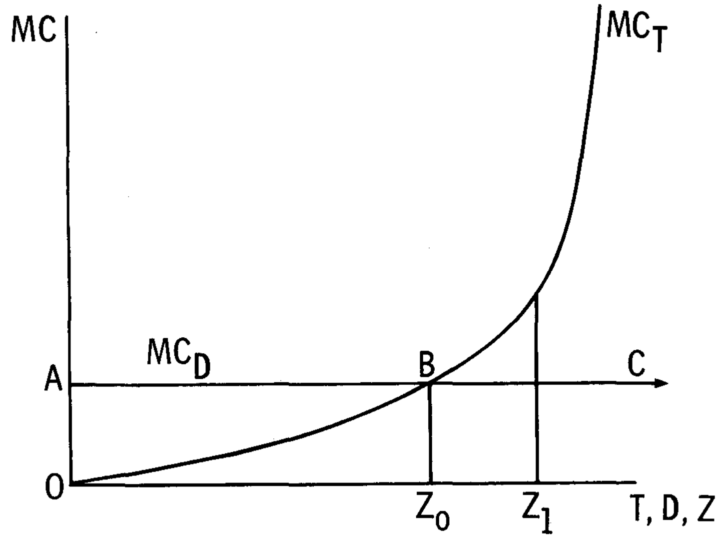
$$\frac{C_1' e^{\rho X_1}}{\rho T^*} = \frac{C_2'}{a^*}\ ,$$

whereas the marginal cost of domestic research is constant, once the level of a* (and therefore, t*, X_j*, T*, etc.) is fixed, the marginal cost of transfered research increases exponentially. Figure 5 shows the marginal costs of different levels of transferred and domestic research. It is clear that if the total amount of technology which is required is less than Z_0, transfered research will be relied upon to provide all of the technology. Any technology beyond Z_0 will be acquired domestically. For example, if Z is required Z_0 will be transfered and $(Z_1 - Z_0)$ provided from domestic sources. Because of this, the curve 0 B C is the marginal cost of research as a whole, and one could erase the portion of MC_T above B and the portion AB of MC_D and consider the remaining curve 0 B C alone.

It will be recalled that the above discussion had fixed the level of a* and, thereby, of T*. From the expression for the marginal cost of research acquired via transfer it can be seen that as T* increases (and a* falls) the marginal cost of transfered research will also fall. From the expression for the marginal cost of research acquired domestically, it is clear that the marginal cost of research acquired domestically rises as a* falls. From the relationship between T* and a*, it is clear that T* rises more slowly with successive decrements to the value of a*. These relationships are incorporated into Figure 6, which graphs the marginal cost functions at various levels of a*.

Note that a_0 a_1 a_2 a_3. The figure illustrates a tradeoff between the cost and potential of transfering research and the cost of domestic research. If g_I^1 is introduced as the marginal benefits function, one can see that there is an

Figure 5.



equilibrium corresponding to each value of a^*, and that different totals of technology will be acquired at different levels of a^*. The maximization problem is

$$\max_{a^*} \left\{ \int_{MC_{a^*}}^{g_1'} (g_1' - MC_{a^*})\, dZ \right\}$$

From the drawing, it is clear that if we restrict the available values of a to the four presented, the intersection of MC_3 and g_1' presents the greatest net benefit level.

If marginal benefits shift out to g_2', similar inspection will show the intersection of MC_0 and g_2' as providing the most benefits. When g_3' is the marginal benefits curve, the preferred value of a is not clear, although the intersection of MC_1 or MC_2 and g_3' appear most likely. With g_4' as the benefits curve, the intersection with MC_0 appears to be the optimal point.

Several generalizations emerge. First, when marginal benefits are relatively low and falling rapidly, as with g_1', there will be a greater dependence on transferred research and a greater possibility of a corner solution in which all research is acquired through transfer. If this corner solution does emerge, then the optimal value of a will be that which is consistent with the maximum potential transfer, which will be lower than any value consistent with domestic technology generation.

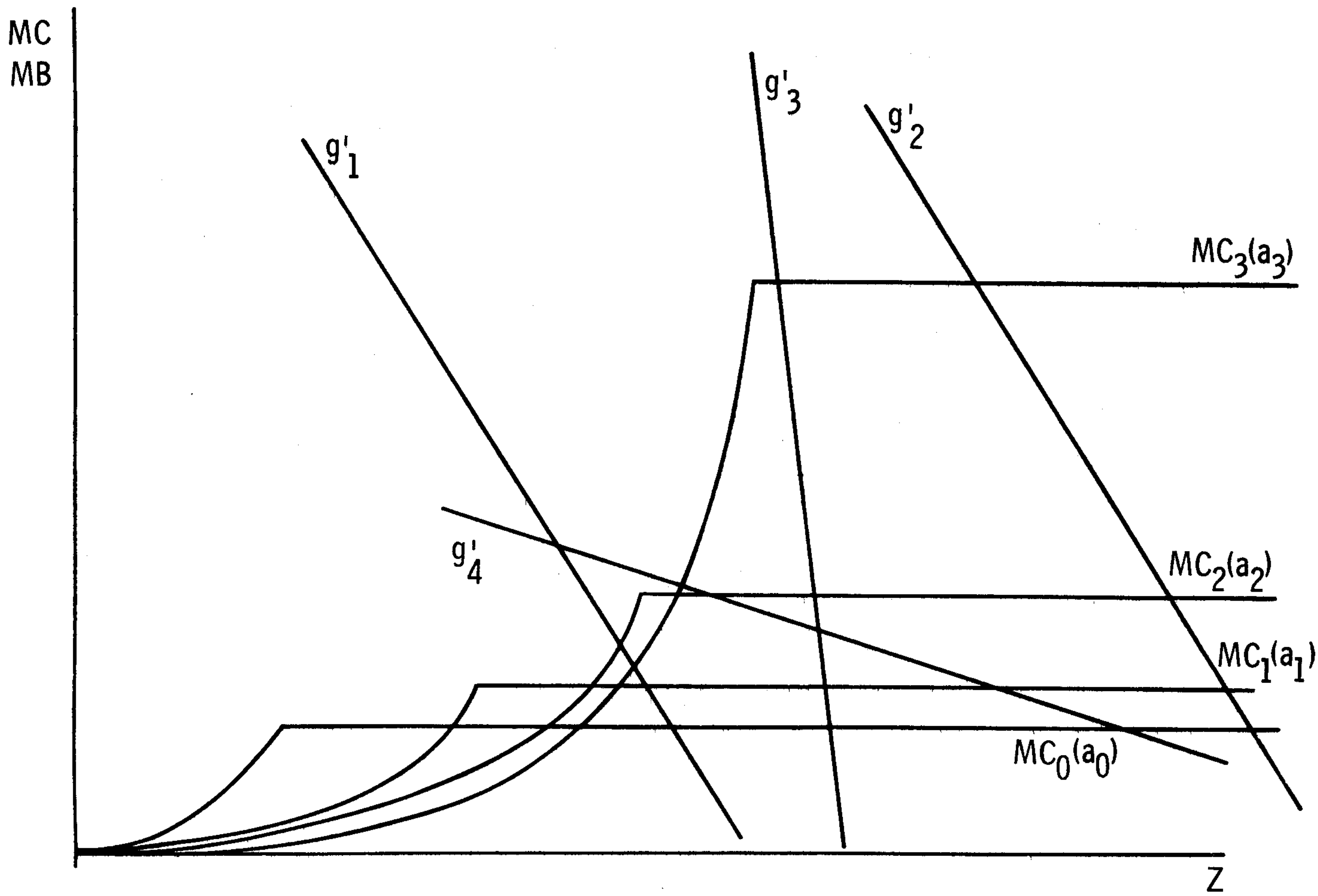
Second, as the marginal benefits function shifts outward, there will be a tendency to rely more upon domestic research and less upon transferred research. This was illustrated by the choice of a higher value of a as the marginal benefits shifted from g_1' to g_2'.

Thirdly, as the marginal benefits function becomes more elastic, even at low marginal benefit levels as provided by g_4', there will be a greater tendency to rely on domestic research.

These generalizations suggest that as markets expand, there will be a tendency to shift from a pattern of reliance on adapted foreign research to research conducted locally and aimed specifically at the region. In fact, over time a region which initially adapted the technology of another region may come to be the primary source of new technology, the original source of new technology reverting to the role of adapter. Evenson has reported on shifts of the locus of inventive activity as measured by patenting of agricultural machinery in different regions of the United States at different times. These shifts appear to behave in rough conconcordance with the predictions of this model.

One might suspect that size of market is itself endogenous, depending on the success of the research venture at least to some extent. Such

Figure 6.



interdependence is difficult to introduce into this type of model. One can envision a richer technology cycle model consisting of the following four stages. Evenson and Binswanger, have also outlined a technology development cycle.

The first stage would be direct transfer of technology into a different environment. This transfer may be a commercial experiment or a protected 'hothouse' endeavor.

In the second stage, various adaptive efforts would be incorporated into the technology.

The third stage would consist of evaluating the potential of the technology for further improvement. In many cases, this would amount to deciding whether the technology was competitive in world markets or could be with more research. This third stage can be regarded as judging whether the technology is competitive in long-run Heckscher-Ohlin terms. One can imagine that there exists a variety of long-run isoquant maps corresponding to various allocations of engineering and scientific resources. It is on the basis of these isoquant maps that the third stage decisions would be made.

In effect, the third stage would predict the scale at which improvements are to be evaluated. Anticipation of great success would increase the scale and, as shown before, lead to a greater emphasis of independent technology development.

The fourth stage implements the third stage decision. If the current or potential technology is found to be competitive, additional resources will be expended on the technology with a high likelihood that there will be a greater dependence on domestically produced, specific technology. If not, however, there may emerge a program restricted to adaptive research or even a return to, more or less, direct transfer. The world seems littered with debris from industrial and agricultural projects which, proving unviable in competitive markets, produce for a domestic market, and display little or no productivity growth over time. On the other hand, the emerging success in certain activities, leather and textiles especially, indicates that the transition to the dynamic fourth stage can be accomplished.

As mentioned before, the recognition of mutual availability and usefulness of research by countries in the same environment can be regarded as lowering research costs. As a benchmark case, the effects of a simultaneous reduction in the costs of adaptive and independent research will be considered. In general, the result is similar to that of an outward shift of the marginal benefits function. However, there is a condition which must be fulfilled,

$$(e^{\rho X_1} - 1) > (\alpha - 1)\ \xi\ (g^{'})$$

where

$$\alpha = C_2^{'}/C_1^{'}$$

and $\xi\ (g^{'})$ is the elasticity of the marginal benefits curve. The intuitive explanation is that the marginal cost of acquiring additional technology varies inversely with the degree of adaptation to the domestic environment. As the cost of domestic research rises relative to the cost of adaptive research, there will be a greater tendency to use adaptive research so that a large percentage of potentially transferable technology will be acquired. However, this limits the potential for further acquisition via adaptation with price declines, so high values of $C_2^{'}/C_1^{'}$ will encourage more use of domestic research with price declines.

The elasticity of marginal benefits enters into the condition because highly elastic marginal benefits favor domestic research, for the reasons discussed above. In general the condition would seem to be fulfilled.

This would suggest that if there are many little countries clustered in the same environment, lack of coordination in their research programs may encourage a greater dependence on adaptive research than would be efficient. Although the best solution would appear to be an increase in cooperation and information flows, this may be difficult to achieve in practice. A second best solution might be a "forced" increase in the amount of technology directed at the environment via establishment of an international center. This increase would encourage independent research in those environments through creation of a technology pole which would raise the amounts of technology available in more similar environments.

This reasoning provides a justification for the establishment of international centers which does not rely on increasing returns to scale in a research. It is difficult to measure the range over which increasing returns exist, although plausible reasons have been suggested to support their existence.

The results suggest that establishment of regional research centers, which pool the resources of countries in similar environments, may be the best policy. It also suggests that centers which focus on many crops for a single environmental niche may be better than centers which focus on a single crop for many environments (although one ought to recognize that the niches will generally differ from crop to crop). Certainly, they seem to imply that while efficiency gains may be achieved by initially providing a stimulus to development of indigenously oriented research, beyond some point one ought to expect national programs to carry on the bulk of research. The long-run strategy would best consist of improving the research capacity of national systems and establishing research centers in environments possessing low stocks of research tailored to their needs.

Investment in Research and Physical Capital

The assumption of a fixed, unchangeable domestic environment may be too restrictive. There are possibilities for changing an environment, investment in irrigation being an obvious example, although there are others. If this is the case, the problem should be restated to allow for the addition of the domestic environment as a choice variable.

Two polar cases will be of interest. The first case we will examine is one in which it is easier to irrigate a smaller percentage of a region's area to a large extent than to irrigate a larger fraction of the area to a lesser degree. Certain dam projects which benefit relatively small areas would fall into this category. More generally, if there are high fixed costs to introducing irrigation, there will be an incentive to limit the area of irrigation. For the sake of simplicity, it will be assumed that an irrigated region will have free access to all of the technology created elsewhere for irrigated regions.

The maximization problem of the first section can now be rewritten as

$$\max \left[(1 - \alpha)\alpha g_o\ (Z) + g_1\ (X_I) - C_1(X_1, X_2) - \alpha^{\theta} C_I\right]$$

where α is the fraction of land irrigated, $\alpha^{\Theta} C_I$ is the cost of introducing irrigation to percent of the region, θ is a scale parameter, $\Theta > 1$, reflecting increasing marginal costs to irrigating a larger percentage of a region, $g_1(X_I)$ are the benefits accruing to an irrigated piece of land

$$(X_I = \bar{X}_I),$$

and

$g_o(Z)$ is the research benefits function used throughout the earlier discussion.

Differentiating with respect to α, one obtains

$$\alpha^{\theta - 1} = (g_1 - g_o)/C_2$$

If we choose a value for α, say α', the rest of the maximization problem is almost exactly the same as the problem outlined in the first section. The crucial difference is that benefits are being spread over a smaller area, lowering the marginal benefits function in proportion to the reduction. In the previous section, it was seen that this would have two effects, a reduction in the total of acquired technology and a shift towards greater emphasis on transfered technology.

In (11), however, the value of g_o dependes on the level of (Z), and lower values of g_o induce higher values of Z. Whether the maximization problem presented has an interior solution will depend on whether or not the costs of extending irrigation rise faster than the marginal benefit to research falls. Otherwise the solution may be complete irrigation of the region or none.

If the interior solution does exist, we have seen that the unirrigated portion of the region will have less research and depend on transferred research to a greater extent. This may have serious consequences for inter-regional equity, the more so if the irrigated portion competes for resources with the unirrigated portion and is perceived as having greater potential.

The second case allows for irrigation benefits to be distributed over any area without increasing marginal costs. In fact, it will be assumed that the entire region is covered to the same degree by the irrigation network, and that the amount of the irrigation coverage in the region is itself a choice variable. If water control is thought of as a continuum from desert to completely and intensively irrigated, there can be many gradations in the degree of water control which can be introduced.

If we allow the subscript k to denote the extent of irrigation introduced, the maximization problem may be written as

$$\max g \left\{ a_{fh}(t_{fj}(1-e^{-\rho X_1}) X_j + X_2) \right\} - C_1 (X_1, X_2) - C_2 (E_{Dh})$$

where C_2 (E_{Dh}) is the cost of shifting the domestic environment to environment h through irrigation.

The equilibrium conditions are similar to those which emerged earlier in equations (5) - (8)

$$\frac{a'}{a} = \eta \frac{t'}{t} = -\eta \frac{X_j'}{X_j} = -\frac{C_2'}{Z} \qquad (12)$$

where Z as always is the total of acquired technology (the argument of the g(.) function) and

$$g' a \rho t e^{-\rho X_1} X_j = C_1^1 \qquad (13)$$

$$g' a = C_1^2 \qquad (14)$$

The equilibrium conditions in (12) - (14) differ from those of (5) - (8) only in the last equality of (12). The interpretation is straightforward. The last inequality serves to set the marginal value of the easier adaptation of irrigated technologies equal to the marginal cost of more extensive irrigation. The benefit obtained from irrigation in this model is that it brings the domestic environment closer to those environments in which most of the technology has been developed resulting in greater ease of adaptation of research. Looked at a little differently, it serves to allow the region to avoid difficult problems which have not been solved elsewhere by physically altering the environment.

In general, the capital investment in irrigation facilities and the investment in research appear to be substitutes, the investment in irrigation inducing a lower demand for research. One could construct isobenefit curves with investment in irrigation on one axis and research investment on the second. Convexity of these curves guarantees a unique equilibrium. The equilibrium which would emerge will depend on the relative prices of irrigation and the two research activities and would be effected by shifts in these prices. One interesting possibility is that irrigation may be the preferred investment if labor costs are low and if there is an efficient, labor-intensive construction technique. It would be especially attractive if the laborers were drawn from a pool of unemployed or underemployed workers. Hayami has suggested that such considerations played a role in the development of the Japanese irrigation network.

While this result is suggestive, it is subject to many caveats. Firstly, the currently observed range of relative costs may not be sufficiently wide as to induce major substitution between one approach and the others. More important are the abstractions required to fit reality into static models. Irrigation without additional research would produce once and for all gains, while research holds the promise of a stream of improvements over time. As well irrigation may improve research productivity by eliminating drought resistance as a necessary component of the research agenda, making other goals more easily attainable. Finally, in most developing countries the cost of research can be lowered substantially in the long run by investing in the training of native researchers and developing a viable indigenous research system. There seems less promise for the development of cheaper, labor-intensive construction techniques. One might wish, therefore, to use a lower relative price of research than is actually observed.

Measurement and Testing

One can proceed to test whether the results predicted by the model have real world counterparts. We saw that the nature of the 'appropriate' technology would be such that:

(a) as the price of adaptive research rose relative to independent research, there would be more emphasis on independent research.

(b) as the scale increased, there would be more emphasis on independent research.

(c) the degree of adaptation to the domestic environment and the relative importance of independent research would be positively correlated.

(d) as transferability increases, so would the emphasis on adaptive research.

(e) as the technology available from different regions increases, so would the dependence on transfer.

One must find measures or proxies for the levels of adaptive and applied research, the degree of adaptation, the degree of transferability, and the costs of domestic and applied research. It is possible in many research programs to obtain estimates of the numbers of foreign varieties tested in the various trials as well as the number of foreign parents used in breeding programs. If there is no reason for foreign material to be more costly in these types of experiments, we can compute the costs of adaptive research as the cost of the foreign material used in breeding and varietal trails. It seems reasonable also to assign the costs of more fundamental research entirely to the domestic portion of the program.

Let C_T be the cost of the various trials comparing varieties, C_B be the cost of the breeding program, and C_S be the cost of research on fundamental agricultural science.

Then if

α is the percentage of foreign varieties used in trials

and β is the percentage of foreign parents in the breeding program, we can set

$$V_1 = \alpha\, C_T + \beta\, C_B$$

and

$$V_2 = (1 - \alpha)\, C_T + (1 - \beta)\, C_B + C_S$$

to give us the amounts expended on adaptive and indepdent research.

If (a) - (e) are correct, we could estimate a regression equation

$$\frac{V_1}{V_2} = a_0 + a_1 R_1 + a_2 \frac{Z_f}{Z} + a_3 Q + a_4\, W_S/W_T + a_5\, W_S/W_C + \text{interaction terms}$$

where R_1 is a measure of transferability of research from other regions into the domestic region,

Z_f/Z is the ratio of foreign research to domestic research,

Q is a measure of the scale of production in the domestic region,

W_S/W_T is the cost of agricultural science research relative to yield trials, and

W_S/W_C is the cost of agricultural science research relative to breeding research.

There is some looseness in the definition provided above in terms of applicability to situations with more than two regions. In the latter case, both R and Z_f would have to be indeces of transferability and foreign research activity. The latter would have to be constructed with the recognition that an increase in research in a region with a high degree of transferability will have a greater effect than a similar increase in a region with a very different environment. Similarly, if, for some reason, transferability should shift, it makes some difference if the shift occurs in a region with a tiny research establishment or one with a larger research endowment.

Some candidates for the two-location transferability measure are (a) the simple rank correlation of yields of a set of varieties across two locations and (b) the correlation of the location by variety interaction effects of a set of varieties across two locations. The first measure has the disadvantage in that it may be dominated by varietal effects which have little relation to the transferability of material between the two locations.

Whichever measure is selected, in computing an index of overall transferability, some weighing scheme must be used. The best candidate is some measure of research inputs in the region producing the research for transfer. This could be expenditures, scientist-years, publications or some other suitable measure.

As we saw, the scale of operations itself would affect the distribution of effort between independent and adaptive research. Thus, the total production of the region or the land area should be used to represent the scale.

We also saw that the level of independent research would increase with the degree of adaptation of the technology to the environment.

If we let Y_F be the yield of varieties produced abroad and Y_D be the yield of varieties produced independently, then we would expect that Y_D Y_F would be positively correlated with V_2/V_1. Moreover, one could expect that even the varieties developed from crosses with foreign varieties would be positively correlated with V_2/V_1. This follows from the result obtained above that the research would tend to be more adapted to the specific location as the importance of independent research increased.

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