Economic modelling of plant germplasm collections in Papua New Guinea

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Abstract

Papua New Guinea has major ex situ field collections of plant genetic material in its major staple food crops (aibika, banana, cassava, sago, sweet potato, taro, yams). The PNG Government has become concerned at the cost of maintaining these collections. With limited germplasm conservation resources available, difficult choices must be made as to which plants to maintain. What resources should be devoted to maintaining plant genetic diversity in the wild or in collections? How should these resources be allocated among various plant kinds, especially when some of them are currently important in agricultural production, whereas others may only be of potential future importance. How should resources be allocated across the various methods of conserving plant germplasm? Should genetic collections only be maintained where the material has been collected, or should it also be stored in other countries.

A dynamic optimisation model is developed of the crop plant improvement process, including selection from the wild and farmers' fields, conventional plant breeding, the use of advanced plant breeding techniques, and the contribution of plant germplasm collections to the efficiency of this process. The objective of the study is to provide a better basis for evaluating the efficient allocation of resources to plant germplasm conservation in food staples in PNG.

1. Introduction

Contemporary plant breeding depends almost entirely on the availability of existing plants to provide desirable genetic traits for incorporation into new plant varieties. Plants from which desirable traits might be acquired include farmers' existing varieties (subsistence or commercial), breeders' collections, specialised germplasm collections, or wild varieties. Future plant breeding requires preservation of plants having currently useful traits, and also the preservation of plant material which may possibly be found in the future to have useful traits. From an economics perspective, germplasm preservation is an archetypal non-rival good since provision of material from a well-functioning germplasm collection to one breeder does not preclude the use of this material by another breeder. Further, as much of this material is readily reproducible, the material is largely—although not completely—non-price excludable.

Given these characteristics of non-rivalry and non-price excludability, private sector germplasm conservation activities may be insufficient to optimally preserve valuable plant material. Thus, plant germplasm conservation forms a key component of the international global commons and the public sector has become extensively involved in plant germplasm conservation. There is extensive international cooperation in plant germplasm conservation, and international networks for securing the preservation of material. Where public sector resources are constrained, such as in developing countries, funding for preservation may be provided by wealthier countries directly, or via international agencies. The greater commercialisation of public breeding, and the higher profile of private breeders supported by plant breeders' rights, has increasingly highlighted the value of genetic material used in plant breeding. Coupled with financial restrictions on germplasm conservation programs and current (and likely future) increased emphasis on the commercial value of germplasm collections, there is a need for a more systematic analysis of the optimal levels of funding, and the optimal economic organisation, of plant germplasm collections.

Papua New Guinea has major germplasm collections in its major subsistence and semi-commercial food crops aibika, banana, cassava, sago, sweet potato, taro and yams. PNG also has a collection of hybrid sugar canes for its domestic sugar cane breeding programme. Except for sugar cane, nearly all the varieties in these collections were collected in PNG. PNG is also a major centre of genetic diversity for some of these plant kinds (e.g. plantain bananas, taro, some yams and sugar cane). Since varieties of these plants are heterozygous and individual varieties cannot be stored as seed, all agricultural varieties of these plants are vegetatively propagated, and predominantly vegetatively maintained in field germplasm collections. Although the absolute costs of maintaining these collections are low, the costs are high relative to PNG's financial resources. Even if external funds could be obtained for this germplasm maintenance, economic issues still arise such as whether alternative techniques should be used to preserve existing plant germplasm resources, or whether funds should be targeted on different species.

With the exception of bananas and sugar cane, there has been much less plant breeding in the above crops than in the comparable staples of developed countries. There is thus likely to be considerable potential for plant breeding to improve the yields and other product characteristics of these crops. Plant germplasm collections are likely to play a major role in crop improvement in these species. Thus the collections that PNG holds will be of major significance to future crop improvement for both PNG, and possibly also in other countries. Some of the historical and potential benefits of this material are international—for example, some 25 per cent of the genes of modern sugar cane hybrids are derived from the PNG canes *Saccharum officinarum.* There is likely to be under-investment in conservation of

PNG's plant genetic resources (from the international viewpoint) unless mechanisms for paying PNG to maintain its genetic diversity can be established. Further, in a developing country like PNG, insufficient resources may be available for the conservation of plant germplasm even from a purely national perspective.

Maintenance of plant germplasm is an investment problem. Economic analysis of germplasm storage requires a comparison between the return from investing in the conservation of germplasm and rates of return obtainable elsewhere. The principal difficulty in evaluating germplasm investment decisions lies in being able to assess the value of the germplasm. The production process for plant breeding may conceptually be economically modelled, where germplasm provides (i) an understanding of the constraints limiting plant production; (ii) the genetic material to relax those constraints via breeding varieties with higher yields and better quality characteristics; and (iii) genetic material for maintenance plant breeding to offset declines in the resistance of commercial cultivars to scourges (i.e. pests, diseases and weeds). Such modelling would enable estimates to be made of the value of germplasm.

2. PNG agriculture[1]

Agriculture is the most important sector of PNG's economy. It provides a livelihood for about 85 per cent of the economically active population of PNG, and employment for 25 per cent of the workforce in the commercial sector of the economy. Agriculture creates about 25 per cent of Gross Domestic Product and contributes 14 per cent to foreign exchange earnings. The agricultural sector comprises subsistence, semi-subsistence and commercial sub-sectors. Smallholder farmers are the most prominent producers who produce 75 per cent of coffee production, 65 per cent of cocoa, 66 per cent of copra and 35 per cent of oil palm and almost all food crops (96 per cent of all agricultural produce). The employment structure of agriculture is 8.5 per cent purely subsistence, 87 per cent semi-subsistence or semi-commercial engaged in both subsistence and commercial activities, and 4.5 per cent purely commercial.

2.1 Food Production and Consumption

Production of staple foods remains the most important economic activity for most of PNG's rural population. Semi-subsistence food production is based upon the traditional systems of shifting cultivation. Pressures of development and modernisation, such as urbanisation, rising population pressure in some areas, and the growing desire for cash among rural people are likely to cause a gradual change towards more sedentary systems of production.

Subsistence farmers in PNG grow a diversity of food crops in their gardens. A variety of crop species are planted in a mixed cropping manner, usually at very high densities. The succulent leafy vegetables are planted first, followed by root crops and then tree crops like bananas and fruits and nuts. Sweet potato (*Ipomoea batatas* L. Lam.) is the predominant crop in the Highland areas of the country. In the Lowlands, the cropping systems are more diverse and vary among areas. The dry coastal areas of the Central Province follow a yam-banana-cassava based system. Yams (*Dioscorea spp*.) are usually harvested first, followed by a number of harvests of banana (*Musa spp*.) and cassava (*Manihot esculenta* Crantz). Taro (*Colocasia esculenta* L. Schott) is predominant in the wet lowland areas of Morobe Province and the atoll environment of the North Solomon Island. Diploid bananas are widely

[1] Based on Kambuou (1995, chapter 1).

cultivated in the Madang, New Britain, New Ireland, Morobe and the Sepik Provinces. Triploid and tetraploid bananas are more suitable to the drier areas of the Markham/Ramu valleys and the Central Province. Yam based cropping systems are practised in some inland areas of East Sepik, Madang and the Trobriand Islands of the Milne Bay Province. Sago (*Metroxylon spp*.) is predominant in low marshland areas (e.g. Fly, Sepik, Ramu and Puerari deltas) and is still harvested from the wild; root crops and leafy vegetables are grown on marginal arable land as a supplement to sago.

Despite periodic localised food shortages and a few pockets of severe malnutrition, food supplies and overall levels of nutrition appear adequate throughout PNG. Commercial production of food crops is limited by the size of the domestic market, while the marketing of traditional staple crops is adversely affected by their low value-for-weight ratio and perishability. Sugar is commercially produced in the country essentially for the domestic market and is currently completely protected by an import ban.

Domesticated pigs are the main animal used in the traditional systems, together with village fowls and chickens. The remaining livestock for food are hunted. Domesticated pigs play a significant role in the social life of the Highland areas. Pigs are regarded as a form of wealth and are used mainly in traditional marriage ceremonies and funeral feasts. Domesticated livestock are generally free ranging although supplements of sweet potato tubers and vines and split coconuts are occasionally fed to pigs. With contemporary changes in life style and greater emphasis on the monetary economy, farmers across PNG are expanding into livestock production, including cattle, sheep and goats, pigs and poultry for both layers and broilers. Changes to traditional subsistence lifestyles are necessary to accommodate these more intensive livestock industries.

The commercial livestock industry consists of a few intensive broiler chicken operations that also supply feed and chicks to out-growers, a few intensive piggeries and cattle ranches mainly in the Markham Valley. Since independence the poultry and pork industries have reached self-sufficiency levels with Government protection. The government is attempting to develop a small sheep industry in the Highlands to increase local production and consumption of meat.

The main river systems in the country include the Sepik, Fly, Ramu, Markham and Puerari river systems. The livelihood of PNG's coastal and river people revolves around the sea and the water ways. These people depend on harvests from the sea and the river systems. The coral reefs surrounding the islands and the coastal areas of PNG are rich in marine life including a diversity of fish, shells, lobsters, crabs, sea weeds and variety of other sea creatures. The waterways are also rich in freshwater fish, prawns, crabs and other river food.

Coastal and riverine people also practise shifting cultivation for production of fresh vegetables and staple root crops to supplement their aquatic diets. Sago is the main staple food crop for the people living on the plains of the Sepik, Fly and Puerari deltas. It grows wild in the river plains and swampy areas throughout the country and is harvested whenever needed. Due to the shortage of arable land for cultivation, river people establish social contacts with mountain and inland people for barter purposes. Fish and other river food are exchanged for root crops and other vegetables.

2.2 Export Crops

Crops contribute significantly to export earnings with an average of K260 million between 1985 and 1993.[2] Coffee is the important crop in terms of foreign exchange and employment with about 50 per cent of all rural households producing over 70 per cent of the crop annually. About 64,500 hectares (50,000 ha smallholdings and 14,500 ha plantations) are under coffee. Cocoa is the second most important crop with 22 per cent of the value of major agricultural exports. About 11 per cent of all rural households produce 66 per cent of the crop with the balance coming from plantations. Cocoa has an area of 116,600 hectares with 49,900 ha under estates and 66,700 ha as smallholdings. Oil palm is the third major crop with 14 per cent of the value of exports annually. It covers about 58,000 hectares (33,000 ha estates and 25,000 ha smallholders involving about 7,000 families); estates produce 65 per cent of the output and the remaining 35 per cent is from smallholders.

In the coconut industry, copra and coconut oil account for 11 per cent of the value of major agricultural exports and the industry supports about 111,000 households cultivating an area of about 100,000 hectares. Rubber and tea are small in terms of production, acreage and foreign exchange earning. About 8,000 households grow rubber and the production in 1993 was 2,800 tonnes with an export value of K2.2 million. More than 83,000 households are engaged in the growing of spice crops and other alternative cash crops. The important individual crops are chillies, cardamom and pyrethrum. The export value of these crops in 1992 was K8.2 million.

3. PNG's food plant germplasm

The selection and/or development of new plant varieties still largely depends on traditional techniques of identifying and recording superior plant material, inducing sexual reproduction using superior parent material, and selecting the elite offspring of these crosses. The continued development of superior new varieties depends on the continual search of the plant genepool for desirable characteristics that might be incorporated in new varieties. Conventional plant breeding is thus dependent on the maintenance of the existing genepool and its thorough evaluation as a source of suitable new genetic traits. The first plant varieties derived from "genetic engineering" are just beginning to become available but such varieties are also currently largely dependent on the incorporation of known genetic traits into existing plant kinds. A typical example of such search for new varieties was the screening of taro varieties for tolerance or resistance to taro leaf blight, and the incorporation of this characteristic into varieties by traditional sexual crossing of varieties in a PNG plant breeding programme.

Subsistence farmers in PNG traditionally maintain, multiply and distribute their own planting materials. Almost all the crops grown are vegetatively propagated, and planting material of crops such as bananas, taro, cassava, aibika and other leafy vegetables are maintained in old garden sites until the new gardens are made. Seeds of amaranths and other vegetables are usually wrapped in leaves and stored above fire places for up to a month before planting. Good yam tubers are selected and stored in specially built yam houses to allow the tubers to sprout before they are planted out. In the Trobriand Island of Milne Bay Province, yams are stored in yam houses for a longer period of time for eating as well as for planting.

New Guinea is a centre of genetic diversity for plantain bananas, taro, some yams and sugar cane (Kambuou 1995). Sweet potato and cassava are exotics but have been in Papua New Guinea for at least several centuries; the former flowers profusely in the Highlands and there is thus the opportunity

[2] PNG's currency unit is the kina (K). In January 1997, the kina traded approximately 1:1 with the Australian dollar. In September 1994 there was a 25 per cent depreciation of the kina.

for continued field evolution. The PNG germplasm collections of the food staples (i.e. excluding sugar cane) are of PNG origin, and little of this material has been relocated outside PNG.

Varieties of the major staples are all heterozygous and are thus vegetatively propagated in agricultural use. These varieties can only be stored as vegetative material, although seeds of some plant kinds are viable (e.g. sweet potato, taro, sugar cane) and thus gene pools can be stored using seed. Varieties of these plant kinds are currently maintained as field collections via frequent vegetative propagation. Aibika and the root crops are replanted at about 6-monthly intervals, while banana and sugar cane are replanted every few years.

The genetic diversity of edible plants in PNG is detailed in Kambuou (1995); and diversity and conservation of major species or types is summarised in Godden and Kambuou (1996). Taro is one of the major root crops of PNG, the other being sweet potato; these two comprise the most important food crops with cooking bananas being the country's third most important staple food. PNG has a relatively large germplasm collections in aibika, sweet potato and taro; and a moderately-sized collection in yams and a relatively small but important banana collection (Godden and Kambuou 1996).

4. Economic analysis of germplasm conservation

Since maintenance of plant germplasm is an investment problem, the key element of an economic analysis of germplasm conservation is evaluation of the costs and benefits of this activity. Some of the technical and financial issues involved in the provision of germplasm storage have been documented (e.g. Plucknett *et al.* 1987); in PNG's case, analysis requires comparison of the costs of field and non-field forms of germplasm conservation. Such cost analysis requires careful definition of the appropriate costs but, in principle, this is not a difficult problem. If conservation funds are unlimited, then the best strategy is to conserve all known plant germplasm (cf. pathway 1 in Figure 1), and preserve corresponding habitats to conserve currently unidentified plant germplasm.

If conservation funds are limited, however, the decision problem is much more difficult. If estimating the benefits of germplasm conservation is impossible, it is at least possible to estimate the costs of various methods of germplasm conservation, and the costs of different sized collections. It would then be necessary to develop a procedure to reconcile the known estimated costs of germplasm conservation against beliefs about the value of conserving various plant kinds, numbers of accessions and methods of conservation (cf. pathway 2 in Figure 1).

If only scientific assessment of the future value of germplasm is possible, then it may be possible to rank the importance of germplasm material, and conserve the highest ranked material until the budget constraint is reached (Figure 1, pathway 3).

Economic analysis of optimal investment in germplasm preservation requires estimates of the benefits of this storage as well as the costs of such preservation (cf. pathway 4 in Figure 1). The value of germplasm collections depends on the future incorporation of the genetic material into commercial varieties via plant breeding, and estimation of this value is not a trivial problem. Assessing the value of germplasm collections requires being able to relate existing conserved germplasm to future advances in plant breeding. Because, by definition, these advances occur in the future, a model is required to forecast the (approximate) future value of existing collections.

4.1 Germplasm conservation—a simple production model

The inputs in a plant germplasm conservation process are principally labour, and physical and human capital. In the case of in situ or field conservation of plant germplasm, land is also important. A simplified model of plant germplasm conservation is presented in Figure 2, in terms of labour, and combined physical and human capital. Consider options for maintaining a stock of plant germplasm varieties equal to N. These may be, for example, labour intensive such as field collections of growing material (e.g. point A in Figure 2) or capital intensive such as controlled environment seed storage or tissue culture (e.g. at B in Figure 2).

In PNG's case, labour is relatively cheap compared to human and physical capital, and plant germplasm is generally maintained as field collections. There are some exceptions to this generalisation, but these exceptions involve the use of external aid funds to relax the capital constraint. Some experimentation is currently proceeding to investigate the feasibility of lower-cost tissue culture storage—e.g. to develop an intermediate technology like C (Figure 2)—by extending the storage life of tissue culture specimens. There are also possible intermediate technologies available for labour-intensive germplasm conservation—for example, human capital in the form of the statistical design of field conservation may reduce the amount of labour involved while requiring higher levels of human capital.

Where the economic problem is simply to choose between discrete technologies for conserving a given quantity of plant genetic material, empirical solutions to the problem can be obtained by directly comparing costs using standard budgeting. However, economic constraints in plant germplasm maintenance do not arise simply in the form of relative resource costs. The more interesting economic problem concerns how many varieties should be conserved. Consider the choice between the number of varieties to conserve in Figure 2: how should a choice be made between conserving N or N* varieties? In a conventional neoclassical problem, relative output:input prices determine the optimal level of output. In the present case, therefore, the key issue is the "price" of the conserved germplasm. However, since there is at best a highly imperfect market for plant germplasm, there are no good market estimates of its value. Thus, the key problem is to estimate the value of germplasm.

4.2 Estimating Benefits of Germplasm Collections—modelling output of selection and breeding

Plant breeding is a production process to develop superior new plant varieties. Plant breeding may have a single objective—e.g. to breed a blue rose, or to insert the genes necessary to confer resistance to a specific disease. In general, however, plant breeding has multiple objectives because a range of characteristics contribute to a plant's value. For simplicity, in the present case, only a single trait—yield—is considered as having economic value.

A given bundle of resources devoted to improving an agricultural variety—e.g. through plant selection or purposive breeding—might give rise to a probability density function like A in Figure 3 (cf. Evenson and Kislev 1975). For a given density function like A, there will correspond a farmers' maximum yield (e.g. B in Figure 3) and an upper bound on yield (e.g. Z in Figure 3). These resources might support activities such as the search for varieties in the wild, the search for new varieties in farmers' fields, conventional plant breeding, or advanced genetic manipulation using the new molecular biotechnologies ("genetic engineering") to discover or produce varieties with yields exceeding B. Use of more resources, more efficient search techniques, more efficient resource use or improved selection technologies may result in the following opportunities:

1. to select from probability density functions defined over the existing range of yields with a higher probability of discovering varieties yielding better than existing varieties (e.g. probability density function C in Figure 3); or

2. to select from probability density functions whose range includes yields exceeding the existing expected maximum yield (e.g. probability density function D in Figure 3).

Assuming varietal improvement is analogous to sampling varieties from such distributions without replacement, Godden and Kambuou (1996) showed that the marginal expected net present value of plant selection is a decreasing function of plant breeding effort (e.g. curve MB in Figure 4). If the marginal cost of plant breeding effort is increasing (MC in Figure 4), then there will be an optimal level of effort for each type of plant breeding effort. For a given constraint of available resources for improving plant yields, there will be an optimal allocation of resources across the various types of search for improved varieties; mathematical programming methods might be used to solve this resource allocation problem.

4.3 Modelling Germplasm Collections—conservation, evaluation and breeding

Integration of models of conservation of germplasm conservation and plant breeding may be illustrated as in Figure 5. In panel A of this figure is represented the "germplasm conservation" activity. The key parameters of this activity are the type of material to be conserved (e.g. taro), the technology available to effect this conservation (e.g. field collections, tissue culture, seed collections), and the funding available which determines—in conjunction with the conservation technology chosen—the required resources of land, labour and supplies. Given the conservation technology and resource constraints, the collection size may be determined, and this collection size partitioned into the number of varieties to be conserved and the number of replicates of each variety. The interaction of the number of individual varieties chosen to maintain and the numbers of replicates of these varieties, together with environmental conditions, determines the actual number of varieties successfully maintained each period.

Panel A might be thought of as a museum of plant varieties. Us of this museum requires that the varieties within this museum be catalogued and evaluated—the "germplasm evaluation" effort (panel B). Newly discovered varieties must also be evaluated and added to the collection. The number of varieties successfully maintained in the museum collection (from panel A), the number of new discoveries, and the funding available for germplasm evaluation, determine the number of varieties that may be evaluated in a given period. The information obtained on these varieties adds to the accumulated knowledge of varietal characteristics which also contributes to the decision as to how many varieties to maintain (panel A). For example, if two varieties previously thought to be different were shown to be identical, then they can be consolidated in the collection.

Panels A and B comprise the maintenance and documentation of accessions held in the "museum" of plant varieties, and this information is valuable for scientific purposes. However, the principal *economic* reason for maintaining such collections is that germplasm maintained within them may be used in selection and/or breeding programmes to improve currently utilised varieties, whether for subsistence or commercial purposes. The number of varieties maintained (panel A) and the accumulated knowledge about these varieties (panel B) contribute to the production process for new varieties—the "germplasm utilisation" process (panel C). The degree to which new germplasm can be incorporated in economically-useful varieties not only depends on the number of varieties conserved and knowledge about these varieties, but also the funding of the plant breeding effort. Additional factors affecting the plant breeding effort are the environmental and economic conditions affecting plant production—e.g. the effect of existing or newly emerging pests and diseases, and existing or potential economic conditions affecting the value of products from particular varieties or their costs of production. Ultimately, the value of output of particular plant kinds influences the resources society is prepared to commit to preserving plant collections, additional to resources society might be prepared to commit to maintain such collections for purely scientific purposes.

The decision process represented in Figure 5 might be implemented for a single plant kind such as taro. The general framework for obtaining numerical solutions to this problem for a single crop is outlined in the next section. In the context of PNG agriculture, it is proposed to ultimately permit the integration of the consideration of all the plant kinds in which PNG has major plant germplasm collections, with an initial focus on aibika, banana, sweet potato and taro.

4.4 Optimal Germplasm Management

The decision problem represented by Figure 5 will be modelled as a stochastic dynamic programming problem. Our preliminary attempt to construct a solution framework is outlined below.[3]

The initial state of the system is state number 1—"base" germplasm exists which cannot be grown to produce useable products, but which may result in useable varieties after plant breeding. Decisions must be made now on whether to attempt to maintain this base germplasm, and whether to search for a higher value category based on it. If the germplasm is not maintained now, it is lost forever (i.e. reversion to state 0).

Expending germplasm maintenance effort does not guarantee its survival as disease, weather or other environmental conditions could lead to its extinction. Searching for a higher valued variety may or may not be successful in the next period. If a higher valued category is discovered, it will be productive on release, and no further maintenance activity will be required. Decisions still have to be made through time as to whether a search should be conducted for further higher value varieties.

The following tables outline the state and decision variables, probability parameters and return parameters which are assumed to be relevant to making optimal decisions through time, dependent on the state of the system. The objective is the maximisation of the present value of net social returns. They will be incorporated in a stochastic dynamic programming formulation of the problem. Optimal decision rules and value of the current state will be found for alternative parameter estimates.

<u>Table 1: The State Variable</u>

0	Germplasm lost
1	Base germplasm exists, yield 1 (=0)

[3] In at least two respects, the outlined model is not sufficiently consistent with the problem represented in Figure 5. Firstly, the model represented in Table 1 implies that the original germplasm does not require maintenance once a new superior variety is developed, whereas germplasm conservation continues in practice irrespective of the development of new varieties. Secondly, new varieties themselves may also be added to the germplasm collection, or new varieties may be discovered in the wild and added to the germplasm collection. Thirdly, it implies that germplasm is only valuable when its use increases future yields, whereas maintenance research—prevention of yield declines due to new or changing diseases, for example—is also important. The size of a germplasm collection is also likely to effect the outcome of the selection process.

2	Germplasm, yield 2, released commercially
3	Germplasm, yield 3, released commercially
4	Germplasm, yield 4, released commercially

In this formulation of the germplasm maintenance and plant improvement problem, the fixed environment is illustrated in Figure 6 by the probability density function of yields (A), and an upper yield limit (Z) (cf. Figure 3 and the discussion in section 4.2). The state variable is the condition of germplasm and crop yield, and takes five idealised values—non-existence of germplasm (state 0); existence of germplasm with zero crop yield; and three higher yield levels (yield 2, y2; yield 3, y3; yield 4, y4 in Table 1 and Figure 6 respectively).

For each of the states defined in Table 1, there correspond subsequent states as shown in Table 2. If the germplasm is lost or non-existent (state 0), this state is maintained with a probability of 1 given that the present model does not allow for the collection of additional germplasm material. State 1 (with zero crop yield) is followed by state 0 (i.e. loss of germplasm) with probability 1 if no action is taken to preserve it; simple preservation action is successful with probability p^s (cf. Table 3) thus there is a probability $(1-p^s)$ that the germplasm will be lost. In state 1, if breeding activity were undertaken, state 2 with yield 2 (y2 in Figure 6) would be achieved with probability p^b_{12} (cf. Table 3); alternative outcomes if breeding were undertaken are crop breeding being unsuccessful and thus remaining in state 1 (with probability $[1-p^b_{12}].p^s$) or losing the collection (with probability $[1-p^b_{12}].[1-p^s]$). In states 2 and 3 (i.e. j=2,3), no action results in reversion to state 0 (loss of germplasm) with probability 1; and breeding permits transition to the next state j+1 with probability p^b_{jj+1} or continuation in the current state with probability $(1-p^b_{jj+1})$. In the final state (j=4), no breeding action is modelled.

Table 2: Decisions and resulting probabilistic state transitions

State	Decision	Probability of following state				
		0	1	2	3	4
0	No action	1				
1	No action	1				
	Maintain	$(1-p^s)$	p^s			
	Maintain/Breed	$(1-p^b_{12})(1-p^s)$	$(1-p^b_{12})p^s$	p^b_{12}		
2	No action			1		
	Breed			$(1-p^b_{23})$	p^b_{23}	
3	No action				1	
	Breed				$(1-p^b_{34})$	p^b_{34}
4	No action					1

Table 3: Probabilities

Probability symbol	Description
p^s	Probability of base germplasm surviving for at least one more period
p^b_{ij}	Probability of successful breeding from (yield) category i to category j

Each of the states defined in Table 2 has an associated economic return. Because useable crop material is not available in states 1 and 2, there is no positive return from “no action” or “maintain” in these states; the latter incurs a cost of c_m (Tables 4 and 5). If the germplasm collection is maintained and used for breeding in state 1 (at a cost c_b) and a superior variety is discovered, its present value is r_{y1} (Table 5) and the return from this action is as defined in Table 4. Similarly, the “no action” and “breed” actions have returns as defined in Table 4. In the final period, where there is assumed to be no breeding, there is simply a zero return from the “no action” option.

Table 4: Returns from decisions

State	Decision	Return
0	No action	0
1	No action	0
	Maintain	$- c_m$
	Maintain and Breed	$- c_m - c_b + p^b_{12} r_{y2}$
2	No action	0
	Breed	$- c_b + p^b_{23} r_{y3}$
3	No action	0
	Breed	$- c_b + p^b_{34} r_{y4}$
4	No action	0

Table 5: Description of return symbols

Return	Description
c_m	Cost of maintaining germplasm
c_b	Cost of attempting to breed to next higher yield category
r_{yi}	Present value of returns to infinity from release of improved germplasm with yield i (given germplasm with yield i-1 already released, i>2)

Implementation of this decision analysis framework requires assigning values to the key transition parameters p^s and p^b_{ij} in Table 3, and c_m, c_b and r_{yi} in Table 5. Derivation of these parameters requires a detailed description of germplasm conservation, evaluation and use in a particular industry or group of related industries. The cost parameters c_m and c_b are probably the least difficult to determine but require detailed assessment of the costs of maintaining plant germplasm and undertaking plant breeding. Parameter r_{yi} requires analysis of the current and future supply and demand conditions in the relevant industry. The probabilities p^s and p^b_{ij} are likely to be the most difficult for which to estimate values. Research directed at initially implementing this model is currently proceeding for taro production in PNG (see following section).

5. Application to Taro

5.1 Background

Taro (*Colocasia esculenta*) is a highly genetically variable herbaceous root crop growing between 0.5 and 1.5 meters high. The plant consists of large leaves and petioles (woody stem) above ground, and corm and roots located below the ground; the above ground section of the plant also contains the plant's unisexual flowers, fruit and seeds.

Optimal taro production is favoured by the wet tropics, although taro is also grown in drier tropical, and subtropical, areas. The plant prefers damp shady locations, between 20 and 25 degrees Celsius with an evenly distributed level of rainfall. In Papua New Guinea taro is reported to have grown up to 2750 m above sea level. While taro can be grown in either dryland or wetland agricultural production systems, it will not tolerate extreme climatic conditions (drought and floods) on a permanent basis.

Taro can be produced on a wide variety of soil types including heavy clay loams to light volcanic soils but for optimal production highly fertile soils are preferred. High productivity of dryland cultivars requires well-drained, darkly coloured, friable soil, rich in organic matter. Dryland taro also flourishes in high rainfall areas where the soils have the tendency to become waterlogged or saturated for a significant period. The wetland varieties (or lowland varieties) prefer valleys and catchments in areas where there is access to sufficient water for irrigation and some will tolerate marshy or swampy conditions and a degree of salinity. Required soils are highly fertile, alluvial, wet and rich in humic substances.

The main taro growing areas in Papua New Guinea are:

- Bukaua and Waria areas of the Morobe province;
- the Star Mountain area of the West Sepik and the Western provinces;
- the Baining area of the East New Britain province;
- Nakanai, Kandrian and Gasmata areas of West New Britain province;
- Karamui area of the lower Simbu province;
- Upper Ramu area of the Madang province;
- inland Musa area of the Oro province;
- Jimi Valley of the Western Highlands;
- Pangia area of the Southern Province (Ivancic 1995)

Taro may be grown in special-purpose taro gardens, or mixed vegetable gardens. Land preparation is usually simple, and the taro plant is vegetatively propagated. Taro requires weeding in the early stages of growth.

PNG is estimated to harvest 32,000 hectares of taro to produce 215,000 tonnes at an average yield of 6.7 tonnes per hectare (Ivancic et al 1995). Yields appear to vary markedly. In lowland areas, average yields of 5 tonnes/ha where the crop was harvested at 6-10 months have been reported for scientific trials at Keravat on New Britain. On southern Bougainville, 13.8 tonnes/ha have been reported. In the

Western Highlands at 1200 m, yields of 7.8 tonnes/ha have been reported; in the Jimi Valley at 1650 m, yields of 4 tonnes/ha have been reported. The Baisu Corrective Institution near Mt. Hagen has reported yields between 12.1 and 22.3 tonnes/ha (Bayliss-Smith 1982).

5.2 Production constraints

Over the past 50 year the total production of taro in Papua New Guinea has fallen and output from other crops like sweet potato and rice has risen. This decline is believed to be the result of a number of factors including diseases, pests, weeds; problems of soil and plant nutrition; shortages of suitable land; availability of appropriate planting material; and genetic erosion (through increasing dominance of the variety Sigel). The significance of these problems is summarised in Table 6.

The most damaging pests are the taro beetle (corm feeder), the taro leafhopper (petiole feeder), and the taro hawk moth (leaf feeder) (Ivancic 1995). Adult taro beetles cause the damage by tunnelling into the corm, or destroy the plant's growing point which kills the plant (more probable in younger plants). The taro beetle has a greater impact on quality than quantity, and only occasionally is the crop completely destroyed. The damaged crop is not wasted, usually being consumed in the village or used as stock feed. The major problems with this pest are that it is extremely difficult to detect as the insect is underground, and the other host plants are common crops including sweet potato, bananas, oil palm and coconuts. Taro beetle control measures include husbandry (e.g. growing taro under paddy conditions), insecticides, and sanitary procedures. Both the nymph and adult stages of the taro leafhopper suck sap from petioles and leaves, resulting in the stunted growth and wilting that can kill the plants. The taro hawk moth is a leaf feeder; while this insect is generally not a great problem, in Lae and Buka regular rainfall provides ideal conditions for the taro hawk moth which may result in extreme leaf defoliation and consumption of the whole petiole, subsequently killing the plant. Control methods are simple and include handpicking and spraying of insecticides.

Fungal diseases caused include taro leaf blight, phyllosticta leaf spot, cladosporium leaf spot, phythium soft rot, storage rots including phytophthora dry rot, pythium dry rot, spongy black rot, sclerotium rot, fusarium dry rot, black rot, rhizopus rot and some leaf disease. Viral diseases include the Alomae-Bobone virus complex and dasheen mosaic virus. Diseases resulting from nematodes include Mitimiti disease, root-knot and other nematodes. Diseases caused by bacteria include corm rot and leaf blight.

Taro leaf blight is caused by the fungus *Phytophthora colocasiae.* It was first detected after the second world war in Java. All traditional varieties of taro are susceptible to leaf blight and even though new gardens may be initially free of this disease this will not last for long. Taro leaf blight is easily transferred by rain water and infected plant material (e.g. rotted corms). The virus prefers temperatures between 21-24 degrees celsius with 100 per cent humidity, and establishes quickly on the leaf margin or leaf tip where rain drops have remained (Ivancic et al. 1995). Gardens on eastern slopes are less affected by taro leaf blight as short periods of high humidity in the morning limit fungal establishment. Control measures for taro leaf blight include cultural techniques (e.g. remove all infected leaves, increase plant spacing, undertake crop rotation, and use clean planting materials). Fungicides are very effective, though not often used because of the high costs of spray equipment and fungicide. Ivancic (1995) noted that all cultivars are at least partially susceptible to taro leaf blight, although some varieties have been identified that display a type of 'self-sanitisation'. In 'self-sanitisation', the infected leaf dies so quickly that the fungus cannot spread to other parts of the plant; these dead leaves fall from the plant which then appears to be healthy.

Alomae-Bobone is a complex two phase virus. The first phase, ‘Bobone’, means a stunted plant having wrinkled and asymmetric leaves and the second phase ‘Alomae’ means a dying taro; as it is impossible to physically separate the two effects, the virus is called Alomae-Bobone. Plants with Bobone symptoms revive within six weeks, while those with Alomae symptoms die. Affected plants are stunted with significantly shorter petioles and thickened galls, the leaves are creased and rolled, and one or two lines are visible on the leaf. The Alomae-Bobone virus is not isolated to *C. esculenta* and has been identified in a number of other species. It is easily spread by insect vectors including the planthopper, *Tarophagus proserpina* Kirk, the mealybug; and aphids, and through infected plant material from suckers and corms. The virus may also remain dormant in seed and emerge in the growing plant especially when stressed. A traditional control method is to spread mulch on the soil surface which protects it from sunlight, radiation, heating and evaporation.

5.3 Taro germplasm conservation

Taro (*Colocasia esculenta* L. Schott) is the second most important root crop of PNG. A survey of wild taro by the team of taro scientists based at Bubia Agricultural Research Centre, Lae, PNG has shown that there is relatively low diversity within the wild taro population observed in 21 locations throughout the main taro growing areas. Other species of Araceae commonly grown in the country include chinese taro (*Xanthosoma sagittifolium* L. Schott), swamp taro (*Cyrtosperma chamissonis* Schott Merr.), giant taro (*Alocasia macrorrhiza* L. Schott) and elephant foot yam (*Amorphophallus campanulatus* Blume). Except for a few cultivars of chinese taro, the remaining species grow as natural stands in the wild. The polynesian arrowroot (*Tacca leontopetaloides* L. O. Kuntze) is commonly seen growing wild in the coastal areas up to 200m.

PNG has the world's largest genetic diversity of taro. The national taro collection is maintained at the Bubia Agricultural Research Centre near Lae. The original collection of about 600 accessions of mostly landraces and farmers’ varieties has been reduced by nearly 30 per cent (Table 7). There is a small taro collection from PNG islands at LAES Keravat, and a small collection of taro varieties from the Sepik at Saramandi Research Station.

The risks of plant germplasm conservation in a developing country are likely to be higher than in wealthy developed countries. Risks of maintaining whole plant conservation in the field in PNG include flood (Laloki 1994); volcanic eruption (Keravat, near Rabaul 1994); landowner disputes (at various times have affected all major research stations in PNG); accidental, careless, malicious or starvation-induced harvesting (Keravat 1994-95 in the case of the last); or inadequate resources leading to varietal losses through weed competition, inadequate irrigation, poor pest and disease control, and sub-optimal timing of relocation of collections (all stations from September 1994). The effects of these risks can be seen in Table 7 which documents recent considerable losses in PNG’s food staple ex situ plant germplasm field collections. There are also risks with other forms of plant germplasm conservation; in tissue culture, for example, the maintenance of optimal conditions depends on sometimes uncertain infrastructure such as electricity supplies.

The budgeted annual costs of taro germplasm conservation at Bubia ARC in the early 1990s is given in Table 8. An estimated gross margin budget for taro germplasm maintenance is presented in Table 9; while the latter estimate has a small estimated overhead component for capital equipment, there is no estimate for overheads in the form of salaried labour for the management and documentation of the collection. These budget estimates may be converted to a cost per accession (i.e. variety) or, since there is a standard number of replicates planted per accession, also converted to a cost per individual plant maintained.

5.4 Taro improvement

The annual cost of taro breeding at Bubia ARC in the early 1990s was about K50,000 (Table 8); this represents about 6 per cent of the research budget for PNG's Department of Agriculture and Livestock (cf. Godden and Kambuou 1996). Documentation is, as yet, unavailable as to the yield benefits of recent taro research, or of the potential yield benefits of varietal research to relax the production constraints surveyed in section 5.1 above.

Valuing either existing taro production, or the value of improved taro production or quality, in PNG is extremely difficult since much of the crop is a food staple in subsistence or semi-subsistence agriculture, and thus is not sold through markets. Taro also plays an important social role in PNG, being often used as dowry for brides, in food exchange, at feasts and other cultural activities. Indications of the prices of taro which is marketed are presented in Table 10. The wide variation in prices between centres could result from:

. local differences in the demand for taro as a food staple;
. variation in the efficiency of production;
. the possible effects of seasonal production variability in a staple commodity with a probably highly inelastic demand;
. absence of low cost transport and related infrastructure to allow interregional trade in bulky, perishable commodities such as taro;[4] and
. in the case of Rabaul, a possible effect of localised food shortages following the September 1994 volcanic eruptions on food prices.

5.5 Summary

Implementation of the stochastic dynamic programming model outlined in section 4.4 for taro germplasm conservation requires numerical data on the following: probability of germplasm survival; probability of successful breeding; cost of germplasm maintenance; cost of breeding; and present value of varieties. The information collected to date does not provide adequate estimates of the values of these parameters. Further empirical research, and model refinement, is required to provide adequate estimates of the value of taro conservation.

6. Conclusion

A theoretical framework for modelling the interaction of plant germplasm maintenance and plant improvement has been developed in this paper. The production process for plant improvement, following Evenson and Kislev (1975), was considered as a sampling process in which nature can be

[4] Where there is wide dispersion of prices geographically, crop improvement could be valued at high or low prices. Valuation at high prices infers that taro improvement is a more efficient use of resources than improving the transport/storage infrastructure. Valuation at low prices infers that taro improvement is a less efficient use of resources than improving the transport/storage infrastructure, and that the price dispersion represents the potential gains from trade arising from improving this infrastructure.

searched for varieties superior to those currently being used. Alternatively, purposive breeding by controlling plant sexual reproduction can also be conceived of as a sampling procedure. In both cases, the use of more resources, or the use of more sophisticated resources, changes the probability of discovering a superior variety, changes the probability distribution of possible new varieties by changing its shape or range, or changes the marginal cost of plant breeding effort. A plant germplasm collection may reduce the cost of searching for improved varieties, or improve the efficiency of the purposive plant breeding process. The size of a collection may also increase the efficiency of both processes, although the effect of collection size has not been considered in this paper.

Because plant germplasm collections involve a largely non-rival and non-price-excludable commodity, national and international public agencies have been extensively involved in such collections. In developed countries, where many crops are seed reproduced and germplasm maintenance costs are low, the cost of germplasm maintenance is hardly an issue—although the costs of plant breeding may be more significant. In PNG's case, where germplasm maintenance currently requires constant vegetative reproduction under field conditions, this activity is a much more significant policy issue which the current research is directed to illuminate.

Theoretical models of the integrated activities of germplasm conservation, evaluation and utilisation have been reported in this paper, and it has been shown how these activities may be quantitatively modelled using stochastic dynamic programming. A preliminary, but as yet incomplete, data set for taro has been constructed to implement this quantitative modelling. This modelling will later be extended to PNG's other major staple food crops of sweet potato and banana, and the green vegetable crop aibika.

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Table 6: Constraints of taro production in Papua New Guinea—distribution, significance and remedial measure status

Constraints	Distribution	Significance	Research Done to Address the Problem
Taro Leaf Blight	Wide spread in Lowlands	*	Yes
Alomae-Bobone virus complex	Certain areas in lowlands	*	No
Corm Rot	Widespread and Location specific	*	Yes
Taro Beetle	Widespread	**	No
Low Soil Fertility	Widespread and location specific	**	Yes
Salinity	Location specific	Minor	No
High Yield Variability	Widespread	**	Yes
Slow Sucker Regeneration	Widespread	**	No
Competition for Good Land	Widespread	**	No
Change in Dietary Habits	Widespread	**	No

Source: Ivancic et al. (1995)

Table 7: Taro Germplasm Collections in PNG, 1995

Bubia Agricultural Research Centre, Lae, Morobe Province	Lowlands Agriculture Experimental Station, Keravat, East New Britain	Laloki Agricultural Research Station, Port Moresby NCD	Saramandi Research Station, East Sepik
600 (mx) (du) (ls) 437 (mt) 360 (ft)[c]	40 (mt) (islands cultivars) 93 (ft)[f]	135 (islands cultivars)	21 (mt) (local cultivars)

Source: Kambuou (1995) supplemented by Godden (1995)
Notes: mx (maximum number of accessions); du (duplicates), ls (accessions lost), mt (accessions currently being maintained), wk (working collection), ft (information collected during field trip May 1995).

c - a large number of varieties from the taro breeding programme will soon be added to the collection

f - includes Colocasia, Xanthosoma, Alocasia and Swamp

Table 8: Cost of Germplasm Conservation and Breeding at Bubia Agricultural Research Centre, Lae, Morobe PNG

Germplasm	Taro germplasm, characterisation and evaluation	19 996
Crop breeding	Taro improvement programme	51 077
	Screening of taro varieties for resistance to leaf blight . various variety evaluation	3 396

Source: Ghodake and Wayi (1994)

Table 9 : Annual Budget for Taro Plant Germplasm Maintenance

Capital	Equipment	546
	Tools	140
Consumables	Chemicals	979
	Materials	571
Labour	6 labourers @ rural minimum wage K53.53/fortnight	8350

Source: Kalabus (1995)

Table 10: Taro Prices in Main PNG Markets, 1993 and 1994

Commodity	Quantity Offered For Sale '000	Price (Kina/kg)
Hagen	0.98	0.75
Gordons	1.07	1.30
Mendi	0.53	0.89
Goroka	1.02	NA
Kundiawa	0.43	NA
Rabaul	0.70	2.41
Lae	0.57	0.85
Koki	1.69	NA
Madang	0.17	0.4

Source: Ivancic et al. (1995)

Figure 1: Decision Framework for Germplasm Conservation

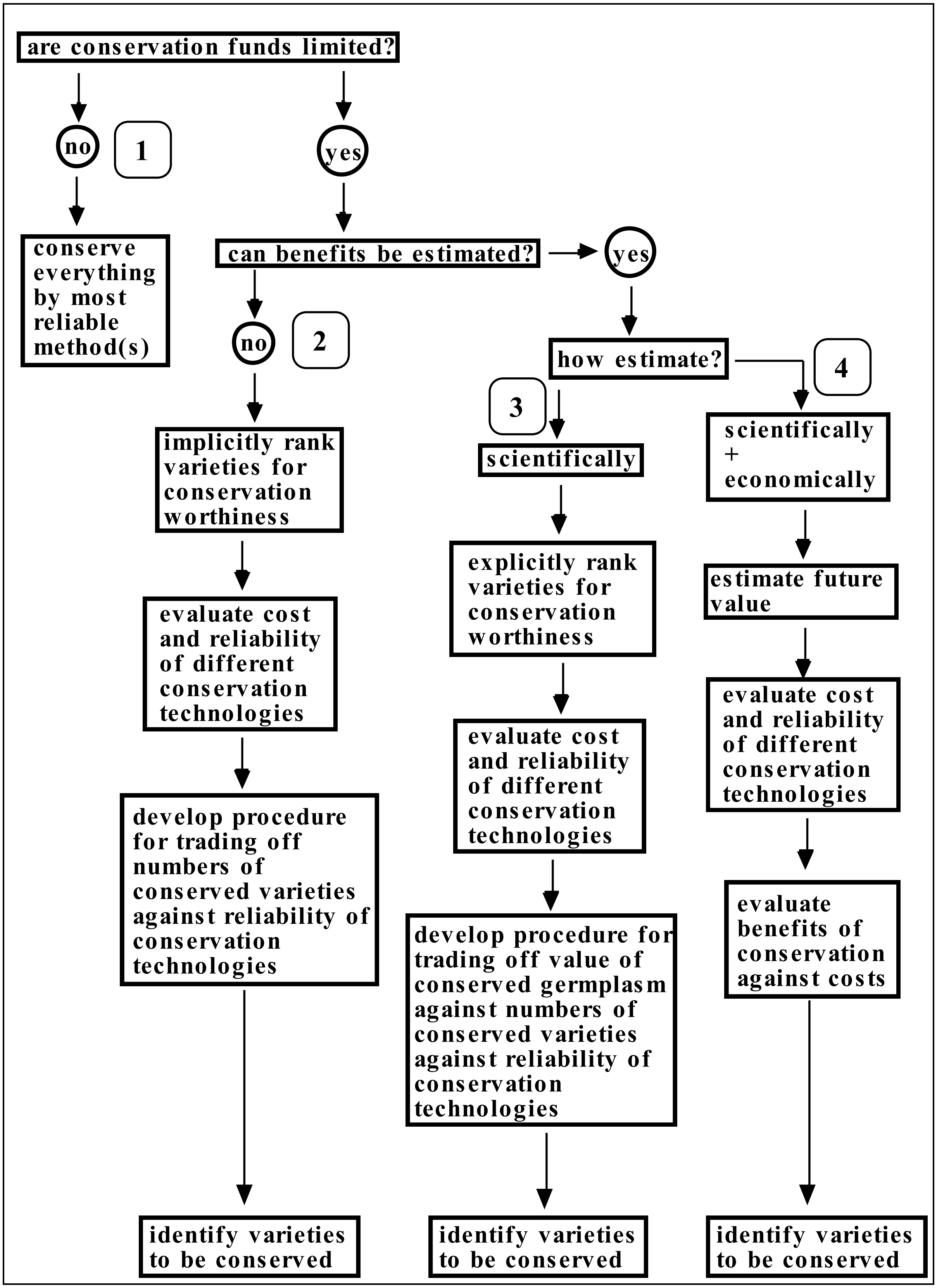


Figure 2: Plant Germplasm Conservation Production Process

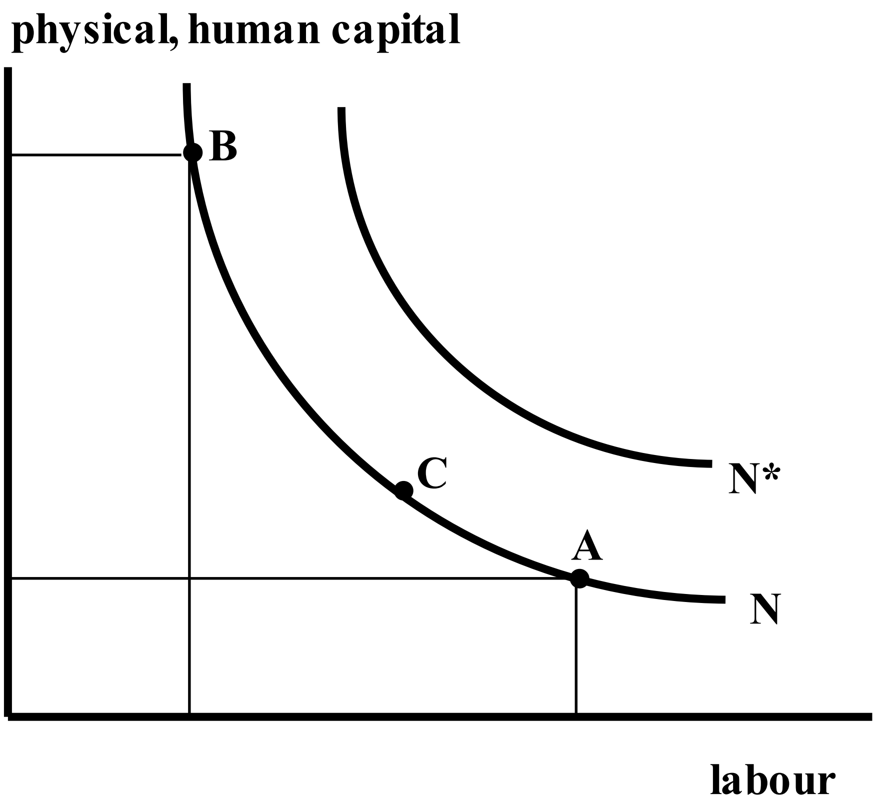


Figure 3: Plant Selection and Breeding as a Sampling Problem

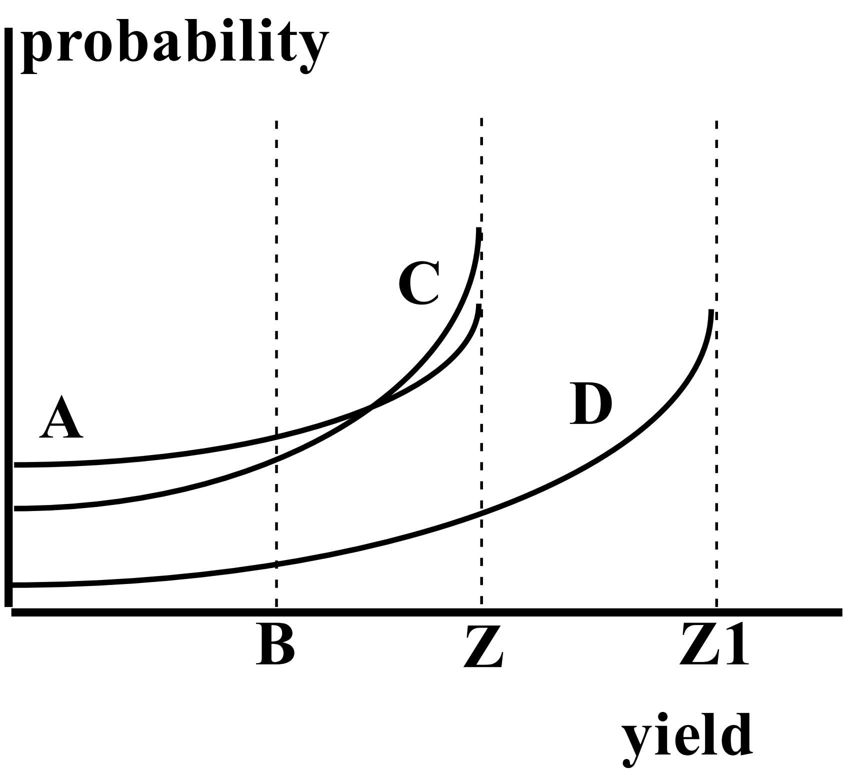


Figure 4: Conceptual Model of Optimal Selection or Breeding Effort

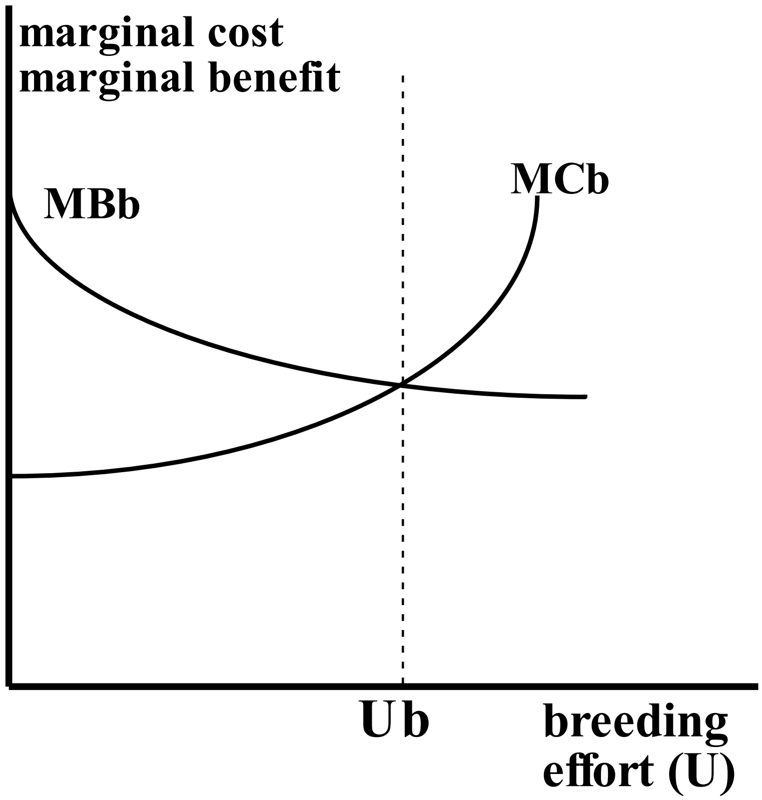
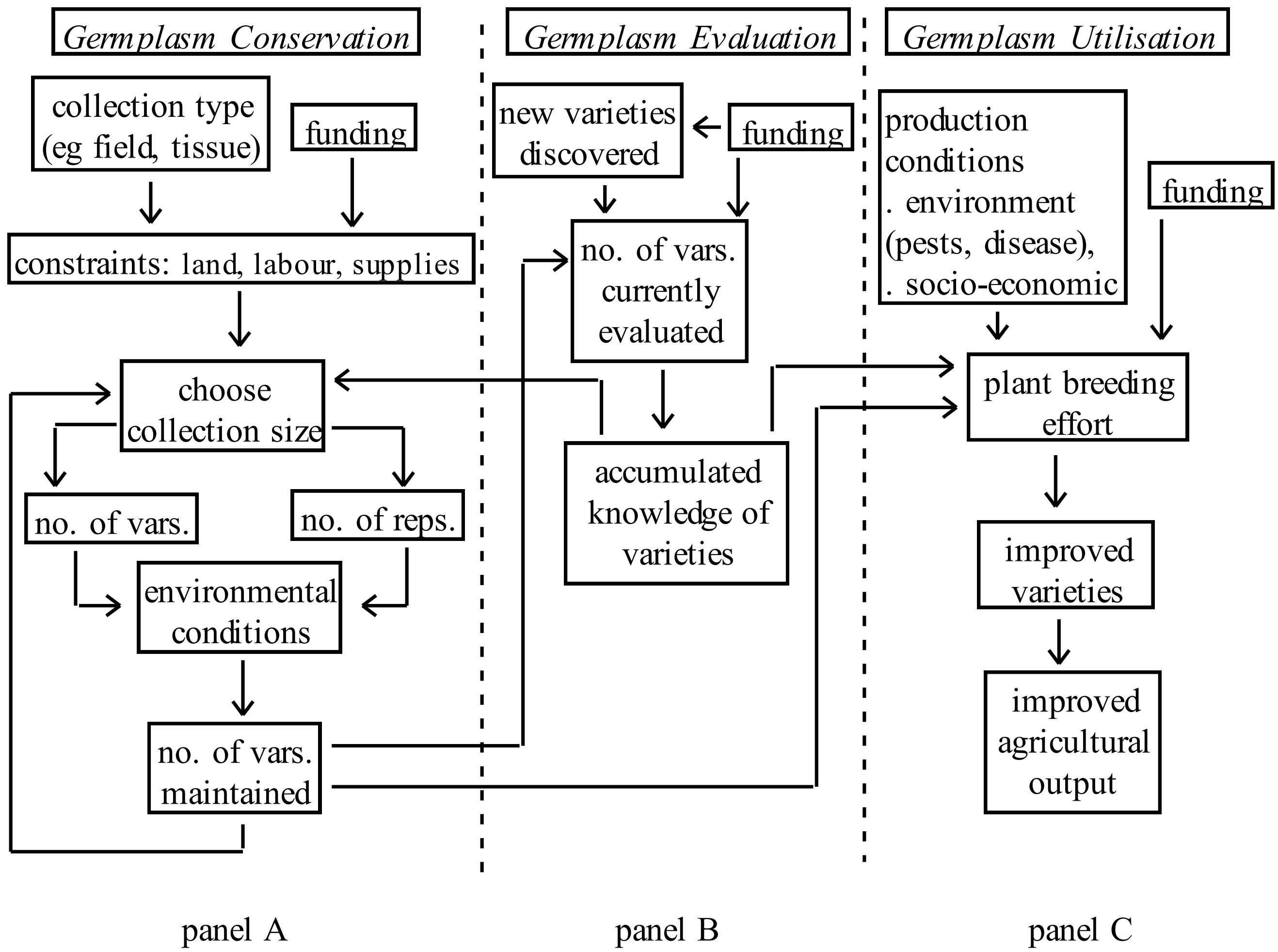
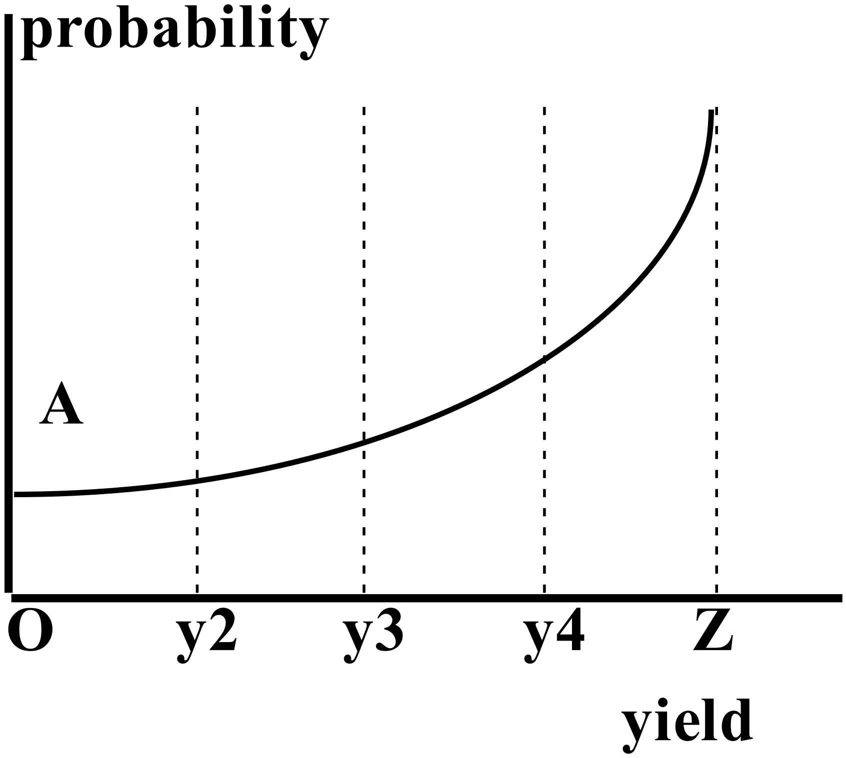


Figure 5: Integrated Model of Germplasm Conservation and Plant Improvement



vars. = varieties
reps. = replicates

Figure 6: Conceptual Framework Of Stochastic Dynamic Programming Problem



The implicit assumptions in the above analysis are:

1.

Assumptions:

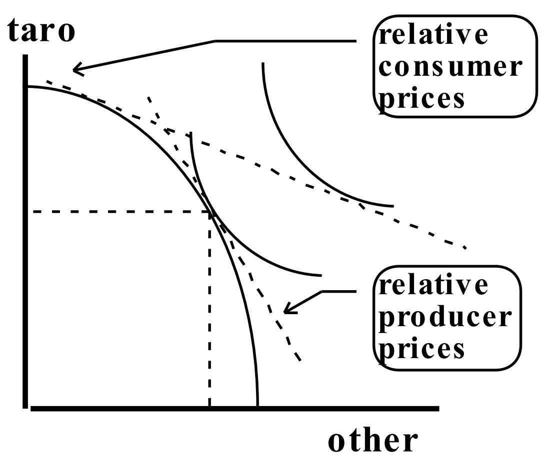
1) Base germplasm is not commercially viable in on-farm production. Must be maintained artificially.

2) Any variety with a higher yield than that for the base germplasm can be commercially released. On release, future survival guaranteed. No genetic loss even if base germplasm lost.

3) Improved varieties (here yield) discovered sequentially.

Decision interval:
6 months

Figure: No gains from trade—high transport/storage costs



Value taro at low prices, since the difference between low and high prices represents the minimum gains to improving infrastructure.