European Journal of Plant Pathology (2006) 115:75–93
DOI 10.1007/s10658-005-4039-x

Establishing priorities for plant science research and developing world food security☆

Robert W. Herdt
Adjunct International Professor of Applied Economics and Management, Cornell University, Ithaca, NY, 14853, USA (Phone: +1-607-255-8802; E-mail: rwh13@cornell.edu)

Accepted 30 September 2005

Key words: congruence, crop loss, development assistance, hunger, research priorities, technological change

Abstract

This paper begins with a broad review of food security in the developing world. I argue that technological change has made a key contribution to improving food security wherever it has been achieved and that plant sciences can contribute in the future. Potential contributions by plant scientists will have to be funded through development assistance. A perspective on development assistance and the role of assistance to agricultural research in particular provides a useful background to the consideration of how to set priorities for research using information on *what is needed and what can be done*. Optimizing the contributions of research entails five steps: (1) determine the specific objective, (2) identify alternatives to address the objective, (3) choose a method by which to set priorities, (4) apply the selected method to quantify priorities, (5) allocate available funds among the priority alternatives. Finally, it is important to take a long-term view and continue supporting the research long enough to make a difference. The paper discusses these steps, illustrates how such an approach might be applied and demonstrates the importance of applying economic criteria to research resource allocation.

Introduction

There are nearly 800 million hungry people including 185 million seriously malnourished preschool children in the developing world. All lack adequate food, water and protection from food-related disease, but without the great strides that have been made in reducing hunger in Asia and Latin America over the past 50 years, there would be millions more. Unfortunately, progress has not been achieved everywhere; in many African countries food output per person has fallen over the last decade and in India and Bangladesh large numbers of hungry people remain despite the substantial gains in per capita food production.

Analysis of food production growth of the past 50 years shows that increases in land, labour, irrigation and fertilizer have contributed to the progress that has been made; in addition, intangible factors like efficient marketing systems, dynamic production technology and higher education have played an equally important role in generating long-run growth in agricultural production (Eicher and Staatz, 1998; Hayami and Ruttan, 1985; Mellor, 1966). These intangible factors are the major differences between the low-productivity, traditional production systems that still prevail in much of Africa and the dynamic, high-input, high-output systems that increasingly prevail in Asia. Development assistance has contributed to Asia's ability to keep pace with its demand for food by helping Asian scientists develop suitable new agricultural technology; appropriate development assistance could help Africa begin the same process and agricultural research could play a part (Sachs, 2005).

☆ Prepared for the International Epidemiology Workshop, Rennes, France, April 13, 2005

This paper briefly reviews the process by which most of the world has achieved food security, identifies the focus of remaining needs, sketches the contributions of development assistance and considers how agricultural research priorities should be established. It discusses five steps involved in priority setting: determining the objective, identifying alternative activities, choosing a method for setting priorities, implementing the method, and allocating resources among the alternatives according to the priorities established. The importance of using economic considerations along with crop loss estimates for establishing research priorities is demonstrated.

Food security and development assistance

The long view

Before the middle of the nineteenth century 'hunger and premature death' was the norm for most of humanity. Eighty percent or more of all people in Europe, North America and elsewhere in the world were farmers, as in today's poor countries. A gradual process of agricultural development and demographic transformation from 1800 to 1950 was required to largely achieve food security in industrialized Europe and North America nearly doubling life expectancy from 35 to 68 years (Fogel, 2004). But in 1950 'hunger and premature death' was the norm in Egypt, India, China and most of the rest of the developing world, with life expectancy hovering around 40 years. Hunger, stunting, nutritional deficiencies and diseases were widespread. Then around the middle of the 20th century this began to change for many poorer countries; average food consumption increased by 20%, real prices of food fell despite a doubling of population and life expectancy increased from 40 to 64 years (FAO, 2002). This remarkable achievement took one-third the time required by the industrialized countries of the north. Chronic food shortages, as manifested in protein-energy malnutrition, fell in much of Asia and Latin America, in large part because grain yields and farm incomes increased through a very similar process used in Europe, North America and Japan during the previous 150 years. Products of the industrial and scientific revolutions were applied to food production; farm incomes grew and per capita food supplies increased (Johnson, 2000).

Today the developing world has twice the population it had in 1960, 150 million fewer hungry people, real prices of food grain one-third as high, and 20% more food available per person. These great advances in food security resulted from a combination of technology, policies and institutions that encouraged production growth in agriculture. As explained by T.W. Schultz, developing world farmers while poor, use the resources and technology available to them efficiently, but without the innovations in policy, institutions and technology needed to generate the ability to accelerate food production and the incentives to use those innovations they are unlikely to increase production much faster than needed to meet their own needs (Schultz, 1964).

Technology embodied in fertilizer and machinery drove the increases in food security in the industrialized countries from about 1850 onwards. But when high rates of fertilizer were applied to rice grown in the tropics at mid-20th century, they caused the plants to grow rank and fall over rather than produce more grain (Herdt and Mellor, 1964). It took the green revolution of the 1970s to provide new varieties sufficiently productive under tropical conditions to generate a growth spurt in Asian agriculture.

Complementary policies to assure greater security of tenure and more stable prices helped. As farming becomes more technologically advanced it requires capital investments like wells and buildings that are attached to the land. To encourage farmers to make such investments they must have assured rights to the land; alternatively, governments may invest in irrigation systems and otherwise subsidize agricultural investments. The institutions that assure land rights, incentive prices and a steady stream of new technology are critical for agricultural development. All these requirements can only be achieved in a stable, non-oppressive political, social, and economic context. Hence well-functioning governments that understand the importance of agriculture, make the necessary investments in agricultural infrastructure and human capital, and encourage a balance between markets and the state, are critical (Hayami, 2001).

International contributions

Crop yields in the developing world have increased substantially over the past 50 years. Wheat, maize and rice yields have more than doubled in most regions with greater increases in Asia and Latin America than in Africa; yields of other crops like sorghum and potato have also increased significantly. New modern crop varieties together with fertilizer and irrigation drove these gains; the greater the adoption of these technologies, the greater the yield increases. Fertilizer consumption grew at over 10% per year in the 1990s and reached 225 kg per hectare of arable land in East and South East Asia and 110 kg in South Asia; it was stagnant in Sub-Sahara Africa at less than 10 kg in 2000 (FAO, 2005a). From 1960 to 2000, public breeding programmes in over 100 developing countries released over 8,000 new varieties of the major food crops (Evenson and Gollin, 2003). More than 35% of these varieties were based on crosses made at the international agricultural research centres funded by development assistance and many of the others were made by plant breeders trained at those centres or stimulated to emulate or exceed the achievements of the centres. Since the 1990s private, local and international seed companies have begun creating varieties for developing countries based on 'platform' varieties generated by these public sector breeding programmes.

In sub-Saharan Africa there were limited contributions from the green revolution. New varieties of most crops did not exceed 30% of planted area and fertilizer application rates remain at five to 10% of the levels used in Asia. Much of the output increase that did occur was achieved by extending the area under cultivation and mining the soil of plant nutrients through shorter fallow periods. Food production did not keep pace with population growth and a decade-long drop in per capita food production continues. Today, Africa faces a food crisis and an environmental crisis, both resulting from low input, low yield agriculture.

While technological change was central to agricultural development, aid for technological change has been a small fraction of agricultural aid and agricultural aid has been a small fraction of total aid. Between 1973 and 2005, total development assistance varied between about $40 billion and $60 billion annually in 2002 dollars, according to data compiled by the Organization for Economic Cooperation and Development (OECD Development Assistance Committee). Development assistance to *agriculture* from all wealthy countries grew from $4.7 billion in 1973 to over $12 billion per year in 1983–87 but since then has fallen back to about the 1973–1977 amounts (Table 1). In the most recent period around one-quarter of all aid to agriculture went to what OECD calls 'agricultural sector policy, planning and programmes; aid to agricultural ministries; institution capacity

Table 1. Official development assistance to agriculture sub-sectors, annual average constant $ 2002, million

	1973–1977	1978–1982	1983–87	1988–1992	1993–1997	1998–2002
Agricultural policy & administration	421	359	857	1468	562	1614
Agricultural water resources	1097	2207	2114	1699	1061	660
Agricultural development & general	735	1251	2307	1188	1081	647
Forestry, not research	149	369	613	880	468	354
Crop production	331	1173	1028	724	388	258
Fisheries, not research	192	471	400	408	285	235
Research	63	275	456	375	184	201
Agricultural inputs	313	684	552	317	309	186
Agricultural land resources	204	253	795	417	271	178
Agricultural finance and coops	425	1127	1549	895	209	132
Extension	104	235	514	230	77	99
Livestock production + vet services	274	379	331	312	124	94
Agricultural services	426	544	1035	840	167	71
Agrarian reform	0	38	31	440	143	63
Total agriculture	4735	9371	12596	10201	5353	4813
Food Aid (not included above)	2681	2858	3000	1502	524	1383

Source: Extracted from OECD (2005), deflated by the total DAC deflator.

building and advice; unspecified agriculture.' The second largest amount went to 'agricultural water resources,' and the third largest to 'integrated projects' and 'farm development.' Agricultural research has received modest support over the years, seldom exceeding 10% of agricultural aid. It is, however, impossible to identify the development assistance support for the plant sciences, which presumably is a fraction of research.

The effect of agricultural development assistance

The effect of this development assistance varies across sub-sectors of agriculture. Irrigation and drainage projects were the largest sub-sector for thirty years through the mid-1980s and evaluation indicates aid for irrigation was usually effective. USAID evaluations of irrigation projects showed that while many problems had to be overcome, the results encouraged continuing investment. For example, a report that summarized the agency's 30 year experience, including evaluations of AID's projects in Sudan, Senegal, Egypt, Morocco, Turkey, Pakistan, Korea, The Philippines, and Indonesia avoided any quantitative generalizations about the rates of return to the aid investments but indicated that while there was evidence that irrigation's contribution to rice yields accounts for about 30% of the factors involved in the Philippines, it is dangerous to generalize about the returns for other areas or other crops (Steinberg et al., 1983).

A 1995 review of irrigation project evaluation by the World Bank focused on 208 Bank-funded irrigation projects. Evaluations rated 67% satisfactory, comparable to the average of 65% for all Bank-supported agriculture projects but worse than the average of 76% for all Bank projects (World Bank Operations Evaluation Department, 1995). A later review of the Bank's strategy for water management summarized results for 336 World Bank water projects completed from 1988 through to 1999 and indicated that their performance was below the Bank average, based on the assessment of project results along three related dimensions – outcome, institutional development impact, and sustainability of project benefits (Pitman, 2002). Just over 40% had satisfactory ratings in 1988; that increased to 53% by 1996. By the 1990s the World Bank considered water projects as part of the social support system rather than as investments intended to generate additional income and low economic rates of return were of much less concern than several decades earlier.

Integrated agricultural or rural development projects made up the second largest area of agricultural development assistance in the 1960s and 1970s. USAID experience was positive but after emphasizing such projects in many countries for about a decade, they fell out of favour (Kumar, 1987). Such projects achieved roughly the same rate of 'success' in World Bank evaluations as irrigation projects. In 1993 the World Bank's data indicated an overall success rate of 49% for such area development projects (World Bank Operations Evaluation Department, 1993). On average they generated a 10.4% economic rate of return, with just over half giving an economic rate of return over 10% (the other half characterized as 'failures' because they produced below 10%). Failures in area development projects were most frequent in Eastern and Southern Africa. Area development projects went out of favour in the 1980s but recently have reemerged in the form of participatory rural development and poverty alleviation work.

Projects to provide subsidized credit and build agricultural cooperatives comprised the third largest proportion of development assistance to agriculture – over 10% of the development assistance portfolio in the 1970s and 1980s. A summary view of experienced analysts based on many evaluations of such projects found that despite the optimistic expectations of their sponsors, the results of such programmes were disappointing. Loan-default problems were serious, poor farmers remained unable to obtain loans, and those who did get credit were often unnecessarily and inequitably subsidized. Many agricultural banks and other specialized formal lenders serving rural areas were floundering as a result of the requirements of the programmes and as a result often limited the range of services they provide (Adams et al., 1984; Meyer and Nagarajan, 1996). Credit projects lost favour in the late 1980s and 1990s and currently make up less than 3% of the agricultural assistance portfolio.

Assistance to agricultural research absorbed around 4% of agricultural development assistance over the past 25 years. Many analytical estimates of the economic rates of return to agricultural research have been made and, contrary to the conclusion reached for other kinds of agricultural assistance, over 95% of the studies show substantial positive economic return on investments (Alston et al., 2000). Careful examination of nearly 300 studies reporting over 1800 individual rates of return indicate no support for the idea that returns have fallen over time, but rather that returns vary in other ways that make intuitive sense. In particular, research on commodities with longer production cycles like livestock and more diffuse effects like natural resource management have lower rates of return. Overall, the median rate of return to agricultural research investments is nearly 50% and the median rate of return to research and extension combined is nearly 40%. Studies examining the relationship of agricultural growth to research, education, roads, and other important factors in India and China reinforce the importance of research for growth (Fan et al., 1999, 2002; Rosegrant and Evenson, 1992). Much attention has been focused on variety development but it is clear that pathology, entomology, epidemiology and other plant sciences play an important role in the development of new crop varieties.

Establishing priorities for plant science research

Plant scientists interested in contributing to food security in the developing countries face a simple question: 'What should we do?' International assistance can most effectively address research questions while control of epidemics is largely the responsibility of national authorities and except for certain critical pests like desert locust. In contrast, research has been one of the most effective areas of development assistance. The question of how assistance might be allocated to various research options in the plant sciences is the subject of the balance of this paper.

The question of 'how' to allocate research resources is difficult to separate from 'who' should allocate them and there are two views on who should set priorities. One holds that priorities should be set by those who do the research while the other holds that priorities should be set by those who benefit from it or by those who pay for it. But 'who' largely implies 'how.' If researchers decide, they will favour what they believe they can most effectively do. If users decide they will favour research on their 'most important' unsolved problems; but if researchers have no way to address the unsolved problems, there can be no effective research. On the other hand if researchers discover something for which users have no need, it is of no value (although it adds to knowledge and may be valuable 'basic' research).

Having users decide seems eminently reasonable, but in the case of publicly funded research, becomes circular as the bureaucracy involved in directly funding research seeks the optimal allocation by appealing to both the users and doers of research. Dalrymple (2005) provides a useful discussion distinguishing between researchers who provide the supply of scientific goods and the users who represent the demand for such goods. The best approach would take both positions into account, perhaps through a process something like that reflected in Figure 1.

Figure 1 identifies a 'political-bureaucratic structure' that interprets the latent demand for innovations generated by farmers, consumers, processors and other actors in the ' socio-economic structure.' This political-bureaucratic structure might also be characterized as a decision-maker who generates the actual demand for innovations. This structure distributes funds to the 'innovation-producing institutions' that pay researchers to conduct research and thereby generate the supply of innovations. As those innovations are used by the socio-economic structure they generate actual payoff. The supply and demand analogy has some appeal, but even the elaborated view depicted in Figure 1 breaks down because there is no equilibrating price mechanism for publicly funded research so supply and demand are not the right terms. Nonetheless, it seems clear that the two aspects – what new knowledge is *needed by users* and *what can be done* – should be considered in setting research priorities. In the procedure outlined here, both are. Five steps are required to produce an answer to the question of how resources should be allocated:

1. Determine the objective,
2. Identify alternatives, assemble data for each,
3. Choose a method for setting priorities,
4. Establish priorities among the alternatives,
5. Allocate available resources among alternatives.

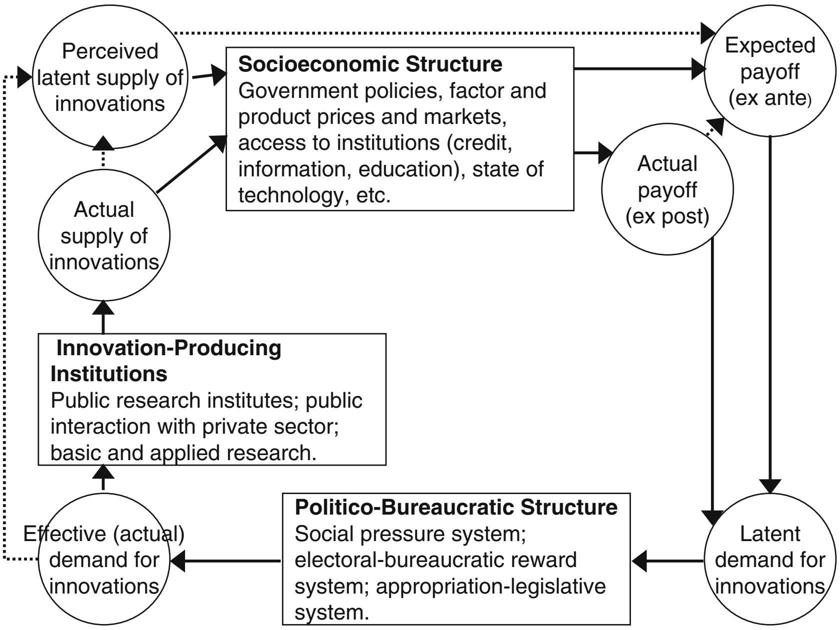

Figure 1. Generalized model of the supply and demand for technological innovation in the public sector.
Source: Adapted by Dalrymple (2005) from: Alain de Janvry, "Social Structure and Biased Technical Change in Argentine Agriculture," in Hans Binswanger and Vernon Ruttan (eds.), *Induced Innovation: Technology, Institutions and Development*. Johns Hopkins University Press, Baltimore, 1978, pp. 301–303. Original referred to both technological and institutional innovation.

Determine the objective

The objective of the whole exercise is presumed to be to put available plant science research resources to their 'best use.' That is, to optimize the use of those resources in generating 'something' – but, exactly what is the something? One option might be to maximize *added output and loss prevented for all crops*. But crops are different, so it is not appropriate to simply add together the prevented losses of grains, vegetables, coffee, and cotton. It is easy enough to aggregate different crops by valuing each agricultural product at its price and adding to get total value of agricultural output. However, production of different crops requires different inputs. For example, it takes much more capital to produce a ton of wine grapes than a ton of rice; more to produce a ton of coffee than a ton of lentils. Such differences in costs suggests the objective to be maximized might be the value remaining after subtracting the cost of inputs, in other words the net value of farm output or *net farm income*.

Some advocate that publicly-supported research should have a special focus on the poor, arguing that maximizing net farm income of the poorest people should be the primary objective. One might accommodate this concern by weighting the income of the poor more heavily in setting priorities, or consider only the farm income of the poorest farmers, ignoring the income of others. If so, it is important to define who the poor are. Some analysts focus on the one-fifth of the population with the lowest incomes – the low income quintile. But is this the low income quintile in each country or in the developing world as a whole? An alternative is to consider the contribution to equity – that is the *income of the poor relative to the wealthy*. This is sometimes done by considering the ratio of incomes of the lowest income quintile to that of the highest income quintile. The Gini coefficient is a measure of equity that reflects the relative income of all units in the population, not just the highest and lowest quintiles. However, it is seldom practical to use the Gini coefficient because of the difficulty in obtaining the data to calculate it.

One might prefer to focus directly on the contribution of research to *nutritional adequacy* of the poor. Like the income of the poorest quintile, this avoids data problems associated with measuring equity but introduces complications associated with defining nutritional adequacy. How can improvements in calories be aggregated with gains in vitamins or increased protein intake? An index of contribution to nutrition might be devised but in reality the contribution of any particular food to any individual's nutrition depends on that individual's current nutritional status, and, using such a set of weights for aggregating different nutrients is no less arbitrary than applying a set of prices to aggregate across commodities and involves many more computational steps.

These complexities and others lead to using monetary terms to value the productivity of research, which are in any case needed to account for input costs. It introduces the challenge of defining the price for each commodity and input. Commodity prices are different in every territory and most fluctuate on a day-to-day basis and over longer periods. Surprisingly, there is no readily applicable set of international prices by which to value agricultural commodities. The World Bank tabulates monthly prices for rice, maize, wheat, soybeans, rubber, sugar, but not for all agricultural commodities.

Another issue is which price along the marketing chain should be used for aggregation. Price to producers differs from price to consumers by the amount of marketing costs. Marketing costs are likely to be relatively similar among the grains but marketing costs for perishable fruits differ significantly from those for grains. Low income consumers may have different relative values for grains and fruits than high income consumers. A commodity's value in one country may differ from its value in another. Finally, the poorest consumers use a high proportion of their incomes simply to obtain food so the purchase price of food is an important factor in the real incomes of the poor.

For the purpose of this discussion it is assumed that the issues identified above are resolved and there is agreement among the stakeholders and decision maker that the objective to be maximized is the *contribution of each alternative to the real net income of the lowest income quintile in the least developed countries*. For convenience, call this the **real income of the poor.**

Identify alternatives

It is essential to begin with a comprehensive list of research alternatives. The allocation process requires that similar information on all options be considered together. An omitted option cannot simply be added later because all interact and, depending on relationships, an allocation to a new option does not necessarily reduce all others in the same proportion. The scope of alternatives will depend on how broadly one defines the problem. For example, if plant science is taken to include the economics of plant protection, such matters must be included as alternatives. If sociology research on movements to ban chemicals in favour of green agriculture is an alternative that might be funded by the decision maker, then research on such topics must be on the list. If plant breeding for genetic resistance is an option, it must be included. Whether such topics should be included in allocating research resources for plant sciences is a prior decision. Here we make the assumption that the universe of alternatives can be defined along the dimensions of: pest or causal organism, crops/host plants, locations, tasks and approaches.

Manageable interest

In abstract terms, there is almost no limit to the alternatives that might be considered. In practical terms, however, one should restrict the alternatives considered to the set over which the decision-maker has a manageable interest. A manageable interest is the set of issues over which a decision-maker can make and implement a decision. In other words, a decision-maker with responsibility for one province has a manageable interest in alternatives for that province and should restrict considerations to alternatives within the province, while a decision maker with responsibility for a nation must deal with all alternatives relevant for that nation. Likewise, a decision-maker responsible for cereals should deal only with alternatives relevant for cereals, while one with responsibility for all crops has a much larger set of alternatives.

In recent times agricultural research decision-makers have become more attuned to the views of a broad range of people and groups who express interests in food-related matters because of their interests as consumers or simply as members of civil society. These groups, together with farmers, food processors, researchers, taxpayers, research organizations and others are considered as 'stakeholders' in the decisions made about the allocation of public resources and decision-makers often seek ways to incorporate stakeholder views into both the definition of alternatives and in setting priorities among the alternatives.

Plant hosts

One dimension defining the universe is the set of crops or plant hosts that will be included. It is presumed that the interest is with plants of economic importance, but this covers a wide range. Even limiting consideration to agricultural crops is challenging because there are many 'minor' crops that are of importance in some particular situations. A recent global effort to define plants of international agricultural importance resulted in a list of 64 species (FAO, 2005b). For this exercise the number of host plants is called: H.

Organisms included

A second dimension is the set of pest and disease causal organisms to be included. That is, are all plant diseases to be included – bacterial, viral, fungal and idiopathic? What about nematodes? Will vectors of all diseases be included or only vectors of major diseases? If vectors carry human or animal diseases as well as plant diseases, will research on those animal diseases be included as part of the allocation problem? Will priorities be defined strictly for plant diseases or will non-vector insects and weeds be included? In reality it is difficult to separate out these causal organisms, especially because when a new epidemic breaks out the causal organisms are largely unknown and in many cases a single event has multiple causes. For convenience of discussion call the number of causal organisms: N.

Geography

The third dimension is geographic: over what set of agroecologies, countries or territories are the allocations to be made? Assuming an interest in developing countries, are all developing countries to be covered? The World Bank defines least developed, low-income and middle-income developing countries. Should only countries with a defined minimum amount of crop land be included? Should the former Eastern Bloc countries included? Given the importance of climate in plant diseases, one might argue that it makes most sense to use agroecological regions. Logical though it is, the problem introduced by this is that most data are available for political regions and must be transformed into agroecological categories if they are to be used in that way. For our discussion the number of territories is called: G.

Possible research activities

Contemporary efforts to understand the challenges plant diseases pose to the global food supply roughly follow the above approach of identifying the gains (and losses prevented) from controlling specified sources of loss on specified plants in specified countries. For example, the objective of one ambitious study on the subject reports the scale of losses caused by plant pathogens, animal pests and weeds on eight crops in seven global regions (Oerke et al., 1994). It seems appropriate to follow this lead and define research activities through the target intersections of causal organism, plant host and location. For convenience we call the intersections 'research tasks,' and their number is: R.

Hence:

$$R = N \times H \times G \tag{1}$$

Diseases are controlled through host resistance, pesticides and cultural practices, but all three are probably involved in most successful control systems. Each of the technological control approaches may entail distinctly different activities. For example, host resistance may be pursued through conventional plant breeding or through genetic engineering and may be polygenic or monogenic (Sorho et al., 2005). Biological control may be pursued using native or exotic organisms. The technology for each approach requires quite different resources and, most effective control entails several approaches. The number of such technologies is called: T.

The total possible number of *research activities*, A, is then:

$$A = T \times R \quad \text{or:} \quad A = T \times N \times H \times G \tag{2}$$

A useful notation is to allow each of the elements T, N, H and G assume the form of a subscript that runs from 1 to t; 1 to n; 1 to h and 1 to g. Then any individual research activity can be designated as A with the appropriate subscripts, or in general as:

$$A_{\text{tnhg}}$$

The allocation problem is: to determine the priorities for research among all possible research activities, that is, among all possible intersections of causal organisms, host plants, geographies, and technologies. To get some idea of the magnitude of the allocation task, suppose that for the whole developing world, there are 50 major causal organisms, 25 plant hosts, 10 territories and 5 technologies, then there will be 62,500 research activities among which to allocate resources. This appears to be an overwhelming task, but of course, some combinations will be 'empty' and others will most efficiently be combined into one activity thereby reducing the number of alternatives. Still, the number will be large, requiring a systematic procedure for organizing all the applicable information.

Priority setting methods

Three broadly different methods have been used to set priorities among research alternatives: scoring, congruence and benefit:cost approaches (Norton and Pardey, 1987). Each has a number of variations.

Scoring approaches

The simplest possible approach is to group alternatives in priority categories such as high, medium and low or rate each alternative on a one to five, one to ten, or some other numerical scale that directly indicates priority by the score of each alternative. More challenging is *ranking* alternatives numerically from the 'most important' to the 'least important,' giving each alternative a unique numerical rank indicating its priority.

Often people are not comfortable with a single number because they believe either there is 'no basis' for making such a judgment or there are several different dimensions to alternatives that would rate differently. They prefer scoring or rating the contribution each alternative is expected to make to several *dimensions* and then aggregating those contributions. For example, individual scores could be assigned to dimensions like output, equity, geographic distribution, women's income, food security or others, and those scores aggregated. The aggregation may be through simple addition or alternatively through weighted aggregation. Table 2 shows how such a system might work.

The first section shows the scores for two research activities; one is high on women's income and low on output and food security; the second alternative scores high on output and food security and the same as the first alternative on the other three characteristics. The aggregate is the simple average or the aggregated value using equal weights. The second section illustrates the effect of differential weights where equity and women's income have higher weights and other characteristics have lower weights. With the unequal weights the aggregate score of the first research alternative is much closer to the second, reflecting the greater weights given for two of the characteristics. In this system both weights and the scores each contribute to the aggregate score.

Any number of variations of scoring approaches can be devised. For example one might use data on production in geographic regions to score the geographic characteristic and value of output to score the output variable. A number of possible weighting schemes may be devised; and a large number of different characteristics may be used as weights. The weights can be determined in a separate exercise from the scores so stakeholders can be involved where they have special knowledge or interests (e.g. in the scores) without completely determining the outcome.

The same versatility that permits the introduction of many characteristics and variations on weighting is one of the limitations of scoring

Table 2. Illustration of alternative scoring approaches

	Activity	Output	Equity	Geo-graphic	Women's income	Food security	Aggregate score
Simple average							
Score	1	2	2.5	3	4	2	2.7
Score	2	4	2.5	3	4	4	3.5
Weighted							
Weight		0.1	0.3	0.1	0.4	0.1	
Score	1	2	2.5	3	4	2	3.05
Score	2	4	2.5	3	4	4	3.45

approaches. One must be careful not to design the weights to skew the results in a particular direction and recognize that the greater the number of weighting characteristics, the more difficult it is to trace the links between characteristics, weights and aggregate score (Alston et al., 1995).

Congruence-based allocation

Another approach is based on the view that research resources ought to be allocated in proportion to the 'importance' of each activity as reflected in the value of crop production or, in the case of plant protection, the value of crop losses attributed to various problems. This approach is known as the 'congruence' method of allocating research resources.

Using Y to represent production loss prevented or yield increase obtained, for every A_{tnhg} there is a corresponding $Y_{tnh.}$ A critical relationship is the contribution each research activity (A_{tnhg}) is expected to make to increasing Y_{tnh} and in turn, the contribution that increased output makes to the incomes of the poorest quintile. Implementing this approach requires information like: applying \$$X$ to A_{tnhg} over a period of Y years will prevent losses or increase production by Y_{tnh} and raise real income of the poor by \$$Z_{tnh}$ per year over subsequent years.

An obvious starting point is to know the Y_{tnh} – the yield loss or potential yield increase – for each of the A intersections defined in (1) above. Intuitively, crop losses are the amount of crop lost to various pests or because production factors are used at less than maximum output levels. Here the focus is on losses from pathogens and pests. As with most seemingly simple concepts, complexities lie below the surface, as the literature on crop losses makes clear. Figure 2 illustrates this point.

For any crop a physiologically defined theoretical yield potential can be associated with any genotype and climate regime, unimpeded by limitations of water, nutrients and pests. In any practical situation there is some *unavoidable crop loss*, given the impossibility of controlling all factors that lead to losses. This defines an attainable yield. In general, attaining that yield requires expenditures on inputs or control measures in excess of the profitable levels and so one can define *economically non-recoverable loss* and hence an economic yield. That is the level one would expect to observe if all farmers applied all crop loss control measures at the economically optimal level, but generally the actual yield is somewhat below that level. The actual yield reflects the yield response to crop protection actually used that is, the *prevented loss*. Still lower, assuming some effectiveness of current practices is the yield without crop protection. The distance between these differently defined yields reflect the various loss concepts.

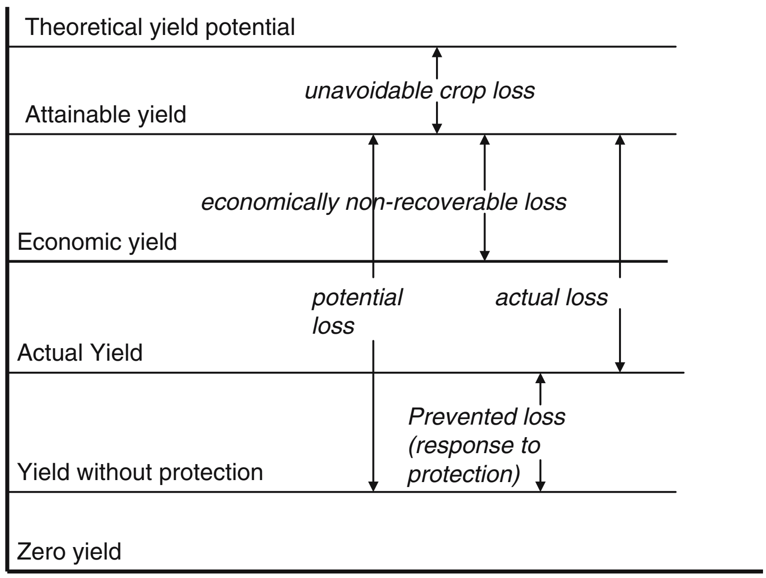

Figure 2. Conceptual model for crop loss assessments (adapted from Oerke et al., 1994 modification of Zadoks and Schein, 1979).

Of course, except for actual yield, all the yield levels and losses identified above are concepts that cannot be observed under production agriculture. But the concepts are so intuitively helpful that some broadly accepted conventions have been developed that permit estimates to be generated. In studies of crop losses, 'attainable yield' is defined or computed using crop growth models taking into account the climate, water availability, yield potential of varieties grown, rates of fertilizer application and other cultural techniques like seedbed preparation and crop density (Oerke et al., 1994). The difference between the estimated attainable yield and actual yield provides an estimate of '*actual loss*' attributed to pests and pathogens. It is also possible to estimate the '*prevented loss*' from knowledge about the plant protection measures used and their effectiveness. In many cases the results from plant protection experiments are used in making such estimates.

An alternative, more participatory approach to using crop modelling and experiments is to draw on the knowledge of farmers who are producing crops in the areas of interest. Clearly, those who make their livelihoods through farming have an interest in anything that reduces yields and they would seem an important resource for identifying yield losses and potentials for increases. As intuitively appealing as this is, a review of the literature reporting such activities identifies at least six limitations (Dalrymple, 2005). First, farmers are likely to be highly influenced by their immediate and highly visible problems and are likely to have a short-term outlook and be less concerned with or aware of the opportunities offered by longer-term research. Second, farmers are more likely to favour research that generates benefits they receive rather than broadly-adapted research that generates product price reductions and benefits to consumers. Third, in most developing nations elites dominate and will naturally direct attention to research that favours them over less powerful groups. Fourth, those who favour participatory approaches in setting priorities generally ignore consumers and consider only farmer participation, despite the evidence showing that consumers are the main beneficiaries of much agricultural research. Fifth, as the geographic scope of the allocation exercise is enlarged it becomes increasingly difficult to get a comprehensive and unbiased view from farmers and consumers. Finally, the wide diversity of clientele and the complexity of the systems necessary to integrate the number and diversity of client views make such approaches inherently difficult to structure. These difficulties could, of course, be overcome and estimates of the relative importance of conducting research in each of the A_{tnhg} could be generated using participatory methods. In practice, more efforts seem to have been devoted toward participatory research than toward participatory priority setting.

Estimated crop losses

An important stimulus to crop loss measurement was given by several major symposia on the subject in the last century. The first was organized in the 1960s by the Food and Agriculture Organization (FAO, 1967) and a second took place in the 1970s in honour of E.C. Stakman (Teng and Krupa, 1980). A more recent study of crop losses (Oerke et al., 1994) provides access to a large amount of systematically organized information. This work was designed to stimulate research on the causes of losses, improve methods to protect crops, enhance the effectiveness of control methods, integrate plant protection with other management practices to optimize methods of crop production, and help generate support for research on effective crop protection. Table 3 provides a summary.

The immense amount of work and detailed, country-by-country, crop by crop information that lies behind the table cannot be overstated. Based on that work, global crop losses are estimated to be about 75% as large as actual production, with the losses almost equally attributed to pathogens, pests and weeds. The lowest estimated losses, about 30%, are in Europe and North America, while Africa and Asia each are estimated to lose nearly 50% of their attainable production. Nearly 60% of global losses occur in Asia, far more than in any other region. This is because Asia produces nearly half of global agricultural production and has a higher rate of loss than other regions.

Using a simple congruence approach to set priorities based on these data would suggest that 60% of research resources should be allocated to preventing losses in Asia and within that allocation, the resources allocated to pathogens, animal pests and weeds should be in the ratio of approximately 14:18:14, the proportion of loss to the three main causal agents. The balance of available resources

Table 3. Estimates of crop losses, in financial terms (US$), occurring during the production of the eight principal food and cash crops in the years 1988–1990, by continent

Continent	Actual production		Loss (%) of production due to			Loss, overall		
	$ bn.	%	Pathogen	Animal pests	Weeds	%	$ bn.	% of global total
Africa	13.3	4.0	15.6	16.7	16.6	48.9	12.8	5.3
N. America	50.5	15.1	9.6	10.2	11.4	31.2	23.0	9.4
L. America	30.7	9.2	13.5	14.4	13.4	41.3	21.8	8.9
Asia	162.9	48.6	14.2	18.7	14.2	47.1	145.3	59.6
Europe	42.6	12.7	9.8	10.2	8.3	28.2	16.8	6.9
U.S.S.R.	31.9	9.5	15.1	12.9	12.9	40.9	22.1	9.1
Oceania	3.3	1.0	15.2	10.7	10.3	36.2	1.9	0.8
Total	335.2	100.0	13.3	15.6	13.1	42.1	243.7	100.0

Source: Oerke et al. (1994, p. 749); final column added by the author of this paper. Prices used in valuing production (by Oerke et al.) were: wheat: US$ 136.2/t; rice: US$ 209.1/t; barley: US$ 79.5/t; maize: US$ 98.1/t; potatoes: US$ 128.7/t; soybeans: US$ 236.1/t; cotton: US$ 490.6/t; coffee: US$ 1934.4/t.

would be allocated similarly, following the proportion of losses in each region to each source.

One can argue that congruence with crop losses is a good approach if dollars spent on every A_{tnhg} have the same effectiveness in increasing the incomes of the poor (given that objective). This is likely to hold if no A_{tnhg} are 'harder' or 'easier' than others so that a given amount of money spent on each would make the same contribution to the value of each crop and that each commodity makes the same contribution to real incomes of the poor. But, the relationship between research input and loss prevented is likely to be complex – some research challenges are harder than others. The research continuum from basic through applied to adaptive implies that a higher degree of uncertainty is associated with 'more basic' research activities that are likely to take longer. 'More difficult' research problems are likely to require more resources and time to generate usable results but are also likely to have the potential to generate higher returns. The contribution of losses prevented for a commodity important in the consumption of the poor or in generating income for the poor is more important for the objective than for a commodity not important to the poor. Technologies not well-suited for adoption by the poor would contribute less than those especially well-suited.

Input–output function of A_{tnhg}

The relationship between research input, expressed in researcher time and funds, and the expected findings or 'solutions' that prevent loss, is defined as the research input–output function. The input–output function for each A_{tnhg} should reflect the difficulty and time required to find a solution through that activity; input–output functions for different activities will reflect differences in the difficulty or time needed for various A_{tnhg}. The input–output function provides an estimate of what research may actually contribute towards the objective while crop loss estimates represent the opportunity for research to contribute – these are the two key factors: *what can be done* and *what is needed*. In Dalrymple's terms, the input–output function reflects the supply of research findings while increased real incomes of the poor from the crop loss thereby prevented reflect the demand for research findings.

To illustrate: a set of pesticides can be screened for their effectiveness against a particular pest in a relatively few growing cycles, say in a matter of 2–5 years. If the pesticide has been approved, a control practice can be recommended to farmers shortly thereafter. An alternative approach, the development of cultivars with genetic resistance to the pest, may take 6–10 years from the beginning of research to release to farmers. Even if the two activities give the same yield effect and remain effective for the same period, they have different input–output functions. Some kinds of research may have a greater inherent requirement for inputs such as laboratory equipment, experimental fields and labour; costs of land, labour and capital vary across locations and other factors affect the cost of any particular research activity, but these differences can be incorporated in an input–output function.

A number of things can be inferred about the relationship between research input and expected prevented yield loss or expected output (Y_{tnhg}). First, at the beginning of the process and with zero input, expected prevented loss is zero. Second, no matter how great the resources or time taken, there is some maximum value of expected Y_{tnhg} depending on actual losses or yield potential for each $A_{tnhg,}$. Third, at the beginning of the research with small inputs the probability of finding a successful 'solution' is small and therefore the expected prevented Y_{tnhg} is small. The expected value likely increases slowly until some critical minimum amount of resources are applied and at that point increases rapidly over some range of research inputs. Beyond some level of resources the expected Y_{tnhg} is likely to begin to increase at a declining rate.

Figure 3 illustrates a few of the many possible input:output relationships consistent with the inferences stated above. Each curve portrays the relationship for a different research activity designed to prevent losses experienced in a particular intersection defined by equation (1). Research input consists of money, people and time reflected on the horizontal axis as cost per year. Curves A1 and A2 use the same research approach but with more resources applied each year in the case of A1, so the solution is expected to be found sooner. Both are expected to generate knowledge to prevent the entire loss. Curves B1 and B2 represent a different approach expected to be less successful in preventing the yield losses; B2 is expected to take less time than B1 but the latter will ultimately prevent more of the losses, although not as much as the approach used in A1 and A2. Intuitively, such ideas seem consistent with the ways scientists think about research alternatives and incorporate more information in the allocation process than the congruence approach.

Benefit:cost

In addition to incorporating the effects of different input–output relationships, benefit:cost approaches can incorporate variations in resource use, time lags and uncertainty into priority setting. To illustrate, the following example may be helpful. Suppose two different research activities could be targeted at preventing a \$900,000 annual crop loss. Suppose the first, A_{tnh1}, costs \$50,000 a year, will be completed in 5 years and is expected to prevent half the potential loss while A_{tnh2} costs \$25,000 a year, will take 10 years and is expected to prevent 80% of the potential loss after 10 years. In both cases the technologies are assumed to remain effective for 10 years after introduction. They are illustrated in Table 4.

The first line in the Table shows the research cost per year (all numbers in '000). For simplicity cost is assumed to be constant for a defined number of years, but that assumption is easy to relax. The research is aimed at preventing the potential loss depicted in the second line. The percent expected prevented loss shown in the third line is the concept introduced in Figure 3, in percentage

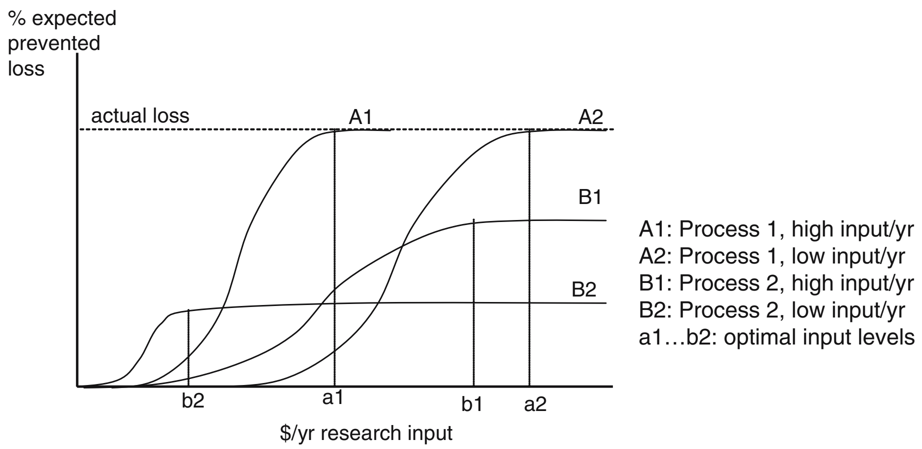

Figure 3. Hypothetical research input/output relationships.

Table 4. Illustration of the calculation of present value of net benefits of two research alternatives at a discount rate of 10%

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Alternative 1																				
1. Cost	50	50	50	50	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Potential loss	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
3. % exp. Prev loss	0	0	0	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0	0	0
4. Loss prevented	0	0	0	0	450	450	450	450	450	450	450	450	450	450	450	0	0	0	0	0
5. Adoption %	0	0	0	0	0	0.3	0.6	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9					
6. Expected LP	0	0	0	0	0	135	270	405	405	405	405	405	405	405	405	0	0	0	0	0
7. Exp. net benefit	−50	−50	−50	−50	−50	135	270	405	405	405	405	405	405	405	405	0	0	0	0	0
8. PV of net benefit	−45	−41	−38	−34	−31	76	139	189	172	156	142	129	117	107	97	0	0	0	0	0
NPV	1134																			
Alternative 2																				
1. Cost	25	25	25	25	25	25	25	25	25	25	0	0	0	0	0	0	0	0	0	0
2. Potential loss	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
3. % exp. Prev loss	0	0	0	0	0	0	0	0	0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
4. Loss prevented	0	0	0	0	0	0	0	0	0	720	720	720	720	720	720	720	720	720	720	720
5. Adoption %	0	0	0	0	0	0	0	0	0	0	0.3	0.6	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
6. Expected LP	0	0	0	0	0	0	0	0	0	0	216	432	648	648	648	648	648	648	648	648
7. Exp. net benefit	−25	−25	−25	−25	−25	−25	−25	−25	−25	−25	216	432	648	648	648	648	648	648	648	648
8. PV of net benefit	−23	−21	−19	−17	−16	−14	−13	−12	−11	−10	76	138	188	171	155	141	128	117	106	96
NPV	1161																			

terms for ease of computation. For a greater research cost the expected prevented loss will be achieved sooner and possibly to a greater extent so that for every different research input:output relationship the values of the first and the third lines of the table will be different. The fourth line is the quantity of loss prevented (LP), the product of lines 2 and 3. The time path of expected farmer adoption is incorporated in line 5 of the analysis and reflects the percent of line 4 that is realized each year. If adoption of the results of various A_{tnhg} takes different time paths, incorporating the adoption lag will differentially affect the benefits obtained in any year. The sixth line is the product of lines 4 and 5 and reflects the expected amount of loss prevented each year. Multiplying this line by the output price would give value but for simplicity here we assume a price of 1 per unit of output. The seventh line is line 6 minus line 1, the value of expected net benefit in the year in which benefits are expected to be obtained. Net benefits are, of course, negative in years 1 through 5 until results are obtained; zero in year six when the research is completed but the results have not yet been adopted; and are assumed to reach 30%, 60% and finally 90% over the next three years as adoption occurs. Thereafter net benefits are constant for the next 6 years after which the technology is assumed to be obsolete and no longer prevents yield losses (one could, of course, have a technology with slowly declining benefits). Line 8 shows the 'present value' of expected net benefits, a concept designed to reflect the idea that preventing losses sooner rather than later is better and that money spent today in preventing such losses is worth more than money spent for the same purpose in the future. The 'discount rate' reflects the relative value of solutions today compared to solutions in the future. If it makes no difference when the solution is obtained the discount rate is zero, but in most cases, people would prefer solutions sooner rather than later and the stronger that desire, the higher the discount rate. Of course, all the relationships and parameters in the table are illustrative and the result of simplifying assumptions.

The top part of the table illustrates the early return case: $50,000 is expended each year for 5 years, at which point the expected results are obtained. In years 6 through 15 the loss prevented could be $450,000 but because adoption takes time the expected loss prevented is as shown in line 6. The expected net benefit, the difference between cost and expected LP, is equal to cost in the first 5 years; afterwards costs go to zero and net benefit is the loss prevented. The values in line 7 are 'discounted' at 10% to get the present value (PV) in line 8 and those values are added together to get their sum for the entire period, called the net present value or NPV. In the bottom panel alternative 2 is shown. In terms of Figure 3, alternative 1 might be represented by a curve like B2 while alternative 2 is more like curve B1.

In the numerical example the NPV of the first alternative is 1134 and the NPV of the second is 1161. Thus, even though the first alternative has a shorter time to solution (5 vs. 10 years), the second has a slightly greater present economic value, in part because it is lower cost (25 vs. 50) and in part because it prevents a greater proportion of the potential loss (80% vs. 50%).

Each of the numbers that goes into the computation has an impact on the NPV. For example, if the discount rate is 5% rather than 10%, the NPV of the first alternative is 1936 and of the second is 2506 – with a lower discount rate the NPV of the first alternative increased by 70% and that of the second by 115%, illustrating the differential effect discount rate has on more distant income. In the extreme case, if future costs and benefits are not discounted then the NPV is simply the sum of the stream of expected net benefits; in this case 3395 and 5582.

With the discount rate at 10%, if the time to success and adoption are shortened by one year and obsolescence still occurs after 10 years, then the NPV of the first alternative is 1266 rather than 1134. If the solution using the second alternative is found after 8 years rather than 10 and adoption and obsolesce patterns are unchanged, its NPV is 1543 rather than 1161. If, in the second alternative, costs increase to 30 in year two, 35 in year 3, 40 in year 4, 45 in year 5 and 50 in year 6 and beyond, NPV becomes 1068 rather than 1161. Hence, different time paths to success or adoption or costs generate different patterns of returns and higher or lower NPV. While the approach seems complex and requires the specification of numerical values to concepts that normally are little more than 'hunches' of scientists, it has successfully been applied to *help* guide resource allocation in a $110 million programme (Herdt, 1991).

Elaborations to benefit:cost

Increases in output that are large relative to current supply may have the effect of reducing the price of the commodity in question. In fact, the global long term downward trend in grain prices has been ascribed to the success of research in increasing the productivity of grain production in many locations throughout the world. In contrast, the prices of food legumes show no such long term decline, in part because there have been relatively modest productivity gains.

By incorporating appropriate assumptions about the way consumers respond to additional supplies (demand elasticities) it is possible to estimate the impact of a productivity gain on prices and incorporate that into the estimates of benefits and costs. In addition it is possible to calculate how much of the productivity gain remains in the hands of producers and how much goes to consumers. Economists call these the producers' surplus and consumers' surplus and commonly use such concepts in estimating the benefits from technological change (Alston et al., 2000); they can also be used in research resource allocation.

An additional elaboration has been developed to accommodate the idea that it is difficult to give a point estimate of the likelihood that any particular research activity will be successful. This incorporates a 'triangular distribution' into the input–output function using estimates of the maximum likelihood of success, the minimum and the most likely probability of success (Mills, 1998). These numbers are then aggregated into a single one used as the 'probability of success' in the table.

Allocate resources among alternatives

As illustrated, priorities can be established in several ways, from categories to rankings to benefit: cost (with or without considering economic surplus) to subjective scores. Regardless of the method the result will be a set of numbers representing the priority of each A_{tnhg}. However, no matter which approach is used, that set of numbers does not imply any specific allocation of resources. Any of the sets of numbers *could* be used to allocate resources proportionately, but each would be arbitrary, given what is recognized about the research input–output function. Alternatively, the numbers generated *can be* interpreted as a *ranking* of importance if a technique is consistently applied, however such a ranking still does not translate into a particular resource allocation.

Various options might be used to translate the priority into an allocation. One extreme would be to allocate all available resources to the top ranked activity – a position not likely to get much sympathy. In a strict capital budgeting problem where the NPV is independent of the size of the investment, funds would be allocated to the alternative with the highest NPV, then the second highest, etc. until all funds are used up. Another option is to argue that all alternatives should get equal allocations. This may be the most politically appealing and would make much of steps three through to five unnecessary! However, using some concepts from economic theory, one can easily show that a non-equal allocation can generate higher benefits.

Economic theory shows that the optimal pattern of investment would be to invest in each alternative just the amount that provides an equal incremental (in economic jargon, marginal) return to each alternative and at the same time uses up all the available resources. Applying this concept requires data on the marginal return to each alternative, which can be derived as follows. A larger annual investment in a particular alternative is likely to shorten the time until success (although there is a limit to how short the time can get). On the other hand, a smaller annual investment is likely to lengthen the time to success (although if the annual investment gets too small the probability of success may become zero). The following illustrates what larger or smaller annual investments would do for one research alternative.

Suppose that with a larger annual investment ($50,000) the research phase can be shortened from 10 to 8 years and adoption speeded up so that 10% of farmers adopt in the 8th year and 40% in the 9th, etc. As a consequence the NPV would increase from 1161 to 1605 (details not shown). On the other hand, if the annual investment is smaller ($10,000) and the research phase is consequently stretched out to 15 years with a similar relative pattern of adoption as originally, then the NPV falls to 517. Following this procedure one can estimate the NPVs that correspond to a series of different annual research investments for a given research alternative. These values can be plotted as in Figure 4, alternative 2. In a similar way, for each research alternative there exist a series of NPVs corresponding to different levels of research investments.

Figure 4 shows NPV curves for three research alternatives. Alternative 2 is the case we have been following with NPV of 1161 at $25/year, 1605 at $50/year and $517 at $10/year. Although we computed the NPV for alternative 1 only for one investment level in Table 4, other levels would generate a series of NPVs to trace out the curve shown. A similar curve of NPV vs. annual research investment is shown for one additional alternative and could be plotted for every possible research alternative.

Such curves provide the key to solving the resource allocation problem. Notice that each curve is increasing but at some point the rate of increase falls and the curve eventually flattens out as researchers run out of good ideas to investigate and the work becomes less productive. In other words, the increase in NPV for higher and higher increments of investment eventually declines (and may even become zero or negative). Economic theory says that the greatest total expected gain will be obtained when the additional NPV from each alternative is equated and all resources are used. This can be illustrated as follows.

Suppose the research manager has $150 to invest each year among the three alternatives shown in Figure 4. If it is invested equally, $50 in each alternative, Alternative 1 generates an expected NPV of 1134, alternative 2 an expected NPV of 1605 and alternative 3 an expected NPV of 1175. The total of the three is 3914. On the other hand, if instead of equal allocation, alternative 3 gets $75/year its NPV goes up quite a lot (the curve is steep) and if at the same time alternative 1 gets $25/year its NPV goes down by a lesser amount (its curve is less steep).

The changes in NPV are given in Table 5; each column shows the change in NPV from the lower

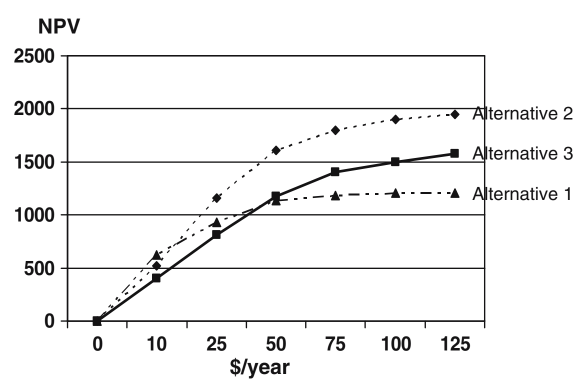

Figure 4. Hypothetical net present value (NPV) of three research alternatives.

Table 5. Change in NPV from changing annual research investment

Investment	0	10	25	50	75	100	125
Alternative 1		625	309	200	50	20	0
Alternative 2		517	544	444	195	100	50
Alternative 3		400	410	365	225	100	75

investment level to the specified one. For example, the first $10 of investment generates additional expected NPV of $625 in alternative 1, $517 in alternative 2 and $400 in alternative 3. Consider $50 invested in each alternative: switching $25 from alternative 1 to alternative 3 reduces expected NPV from alternative 1 by $200 and increases expected NPV from alternative 3 by $225 – a net increase of $25. Of course, if the research decision maker had more funds available, say $225, it would be better to invest $50, $75 and $100 in alternatives 1, 2 and 3 respectively. The differences are modest because the three curves are quite similar; the more different the input–output curves are, the greater will be the difference in expected output from applying the economic decision rule compared to equal allocation.

In this example, the three alternatives (A_{tnh1}, A_{tnh2}, A_{tnh3}) all apply to preventing losses from a single Y_{tnh} of 900 per year. Incorporating all possible Y_{tnh} and all possible research alternatives to prevent those potential losses would provide a full solution to the allocation problem that follows the rule suggested by economic theory and would maximize the expected value of prevented losses. Of course, implementing such an allocation procedure requires input–output functions for all possible research alternatives and a computational algorithm to solve the entire system. But with modern computers this is possible.

Summary

In 1800 most people in most countries were chronically hungry, life expectancy was 35–40 years and misery was the accepted lot of most people. By 1950 a few countries in Europe and North America had achieved a remarkable improvement in living standards; food production and consumption reached adequate levels for most and people lived to their mid-60s on average. But in Asia, Africa, most of Latin America and the Middle East, things were not much changed from 150 years earlier. Poverty, short lives, high rates of hunger and low-yield, low technology agriculture prevailed except for a few enclaves. A remarkable change has occurred since 1950. The world's population has doubled but there are 150 million fewer hungry people; per capita food availability in the developing world has increased by 20% and the real price of food worldwide has fallen by half. World food production has more than kept pace with growing food demand. Still, there are far too many poor, hungry and ill-clothed people in developing countries, with by far the greatest proportion in sub-Saharan Africa and South Asia.

Technology, policies and institutions designed to encourage economic growth of agriculture and ensure the poor are included in growth are the important necessary conditions to overcome hunger and poverty. Far from being tradition-bound and resistant to change, millions of farmers in poor countries have accepted new technologies in the form of seed varieties, fertilizers and irrigation and driven the rate of food production ahead of the demand for food. Experience shows that such technology must be carefully designed to fit the situations where it is to be used, but once systems for doing such research became operational, a green revolution spread through Asia and Latin America. But the necessary combination of policies, technology and government institutions have proven elusive in sub-Saharan Africa. That part of the word remains the challenge for the 21st Century.

Development assistance from wealthy countries has contributed in significant ways to help improve conditions in poor countries with agricultural research among the most successful of aid efforts. The technology and cultivation practices developed by the international agricultural research centres of the CGIAR spread widely through Asia, the Middle East and Latin America and provided the basis for a green revolution in many countries. While poverty still is the lot of too many, food availability and incomes are much improved.

Plant science research has contributed to the improved management and control of many plant pests and diseases but crop losses continue to claim over 40% of potential production having an estimated value of nearly $250 billion. Appropriately directed research could develop systems and products to save much of that potential. In order to best allocate available research resources to address those challenges, decision makers must: carefully define objectives; specify possible research alternatives in quantitative terms; choose among several different approaches for setting priorities; apply the method to establish priorities; and allocate the resources among alternatives. The optimal allocation of research resources can only be established by applying economic principles to estimates of the research input–output functions that quantify how alternatives are expected to prevent crop losses.

Most allocations simply take the previous year's resources and make small adjustments; some allocations use scoring approaches; some allocate resources in proportion to value of production, contribution to incomes of the poor or in proportion to the value of crop losses. These intuitively appealing procedures all have the drawback of failing to take into account either the likely degree of success research may have in addressing each alternative or the importance of each possible solution to poor farmers and consumers.

Economic principles offer tools that can incorporate many considerations important to stakeholders. Allocations that use marginal productivity variations on benefit:cost approaches require large amounts of data and require researchers to make their assumptions explicit. These are difficult to apply and are seldom used. However, they would keep decision makers from overlooking potentially large contributions to the ultimate goal of improving the lives of the poor through agricultural research. The paper demonstrates that two aspects related to future research – *what can be done* and *what is needed by users* of new knowledge – should be considered by any decision-maker in setting research priorities and that using economic principles together with such information generates a higher expected return on research investments than alternative methods.

References

Adams DW, Graham DH and Pischke JDV (eds.) (1984) Undermining Rural Development with Cheap Credit. Westview Press, Boulder, CO

Alston JM, Chang-Kang C, Marra MC, Pardey PG and Wyatt T (2000) A Meta-Analysis of Rates of Return to Agricultural R&D: Ex-Pede Herculem? International Food Policy Research Institute, 113, Washington, DC

Alston JM, Norton GW and Pardey PG (1995) Science Under Scarcity: Principles and Practices for Agricultural Research Evaluation and Priority Setting. Cornell University Press, Ithaca, NY

Dalrymple DG (2005) Setting the agenda for science and technology in the public sector: The case of international agricultural research. Science and Public Policy, forthcoming

Eicher C and Staatz J (1998) International Agricultural Development. The Johns Hopkins University Press, Baltimore and London

Evenson RE and Gollin D (eds.) (2003) Crop Variety Improvement and its Effect on Productivity. CABI Publishing, Wallingford, United Kingdom

Fan S, Hazell P and Thorat S (1999) Linkages Between Government Spending, Growth, and Poverty in India. International Food Policy Research Institute, 110, Washington, DC

Fan S, Zhang L and Zhang X (2002) Growth, Inequality, and Poverty in Rural China. International Food Policy Research Institute, 125, Washington, DC

FAO (1967) Background Papers for the Symposium on Crop Losses. FAO Symposium on Crop Losses. Rome. Food and Agriculture Organization of the United Nations

FAO (2002) World Agriculture: Toward 2015/2030. Food and Agriculture Organization of the UN, Rome, Italy

FAO (2005a) Compendium of Agriculture – Environmental Indicators (1989–1991 to 2000). Food and Agriculture Organizations of the United Nations

FAO (2005b) International Treaty on Plant Genetic Resources. Food and Agriculture Organization of the United Nations

Fogel RW (2004) The Escape from Hunger and Premature Death 1700–2100: Europe. America and the Third World. Cambridge University Press

Hayami Y (2001) Development Economics: From the Poverty to the Wealth of Nations. Oxford University Press, London

Hayami Y and Ruttan V (1985) Agricultural Development: An International Perspective. The Johns Hopkins University Press, Baltimore and London

Herdt RW (1991). Research priorities for rice biotechnology. In: Khush G and Toenniessen G (eds.) Rice Biotechnology CAB International, Wallingford, UK

Herdt RW and Mellor JW (1964) The contrasting response of rice to nitrogen: India and the United States. Journal of Farm Economics 46: 150–160

Johnson DG (2000) Population, food and knowledge. American Economic Review 90: 6–21

Kumar K (1987) AID's experience with integrated rural development projects. USAID Program Evaluation Report No. 19, July 1987, Washington, DC

Mellor JW (1966) The Economics of Agricultural Development. Cornell University Press, Ithaca, NY

Meyer RL and Nagarajan G (1996) Evaluating credit guarantee programs in developing countries. Department of Agricultural Economics and Rural Sociology Working Paper 2322 . Ohio State University, Columbus, Ohio

Mills B (ed.) (1998) Agricultural Research Priorities: Information Investments for the Improved use of Research Resources. International Service for National Agricultural Research, The Hague

Norton GW and Pardey PG (1987) Priority-setting Mechanisms for National Agricultural Research Systems: Present

Experience and Future Needs. International Service for National Agricultural Research, 7, The Hague

OECD Development Assistance Committee (2005) International Development Statistics on-line; CRS online database in aid activities. Organization for Economic Cooperation and Development

Oerke E-C, Dehne H-W, Schonbeck F and Weber A (1994) Crop Production and Crop Protection: Estimated Losses in Major Food and Cash Crops. Elsevier, Amsterdam

Pitman GK (2002) Bridging Troubled Waters: Assessing the World Bank Water Resources Strategy. The World Bank, OED, Washington, DC

Rosegrant MW and Evenson RE (1992) Agricultural productivity and sources of growth in South Asia. American Journal of Agricultural Economics 74: 757–761

Sachs JD (2005) The End of Poverty: Economic Possibilities for Our Time. The Penguin Press, New York

Schultz TW (1964) Transforming Traditional Agriculture . Yale University Press, New Haven

Sorho F, Pinel A, Traore O, Bersoult A, Ghesqiere A, Hebrard E, Konate G, Sere T and Fargette D (2005) Durability of natural and transgenic resistances in rice to *Rice yellow mottle virus*. European Journal of Plant Pathology 112: 349–359

Steinberg DI, Clapp-Wincek C and Turner AG (1983) Irrigation and AID's Experience: A consideration based on evaluations. USAID, Washington, DC

Teng PS and Krupa SV (1980). Assessment of crop losses which constrain production and crop improvement in agriculture and forestry. In: Teng PS and Krupa SV (eds.) E. C. Stakman Commemorative Symposium. University of Minnesota, Minneapolis, Minnesota (pp. 327) Department of Plant Pathology, University of Minnesota,

World Bank Operations Evaluation Department (1993) Annual Review of Evaluation Results 1992. The World Bank, Washington, DC

World Bank Operations Evaluation Department (1995) The World Bank and Irrigation. The World Bank, 14908, Washington, DC