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Operationalizing Sustainability: A Total Productivity Approach [1]

Larry Harrington [2]
Peter Jones [3]
Manuel Winograd [4]

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[2] Manager, Natural Resources Management Research Group, CIMMYT, Mexico.

[3] Land Use Program, CIAT, Colombia

[4] GASE, Argentina

Rationale and overview

The notion that agriculture should be sustainable is irrefutable. Research on ways to foster a sustainable agriculture is flourishing, partly driven by a widespread perception that this research is important for the future of humanity. Noble goals, however, are not enough. Despite current enthusiasm, a time will come (all too soon) when awkward questions will be asked about the effectiveness of this research, questions such as, "How do you know that progress is being made toward sustainability objectives?", and, "How can you tell when agricultural systems are becoming more or less sustainable?". Now is the time to begin to prepare for these questions. Assessing the impact of research to foster sustainability requires the ability to detect progress toward sustainability goals. Researchers need indicators of sustainability.

This report is the product of a joint endeavor by CIMMYT and CIAT to design "a common research agenda to develop sustainability indicators for tropical American agroecosystems." Expected outputs were to include:

- basic agreement on the meaning of sustainability, in the context of agricultural development processes and for selected agroecoystems,
- suggestions on how to operationalize the concept of sustainability at different levels of agricultural system hierarchy and for identified purposes (e.g., diagnosis, impact assessment, and impact prediction),
- a tentative list and characterization of possible sustainability indicators, and
- a research agenda, identifying areas of mutual complementarity between CIMMYT and CIAT in future empirical work aimed at describing past (and forecasting future) trends associated with the sustainability of agricultural systems.

Overview of the paper

This paper deals with a number of themes. First, the notion of sustainability is discussed and some desirable characteristics of sustainability indicators are described. Then, the concept of total productivity (TP) is introduced. The TP of a system is defined as the sum of the value of all outputs divided by the sum of the value of all inputs, including all economic and environmental costs. Index numbers are used to assess changes over time in TP, thus removing the effects of changes in relative input and output prices. It is suggested that, in principle, TP should be used as the primary indicator of sustainability. Agricultural systems are deemed sustainable when TP shows a non-declining trend. Components of TP can be used as secondary indicators of sustainability. A better understanding of TP trends can be achieved by taking account of several processes:

- technical change within farming systems, including the adoption of new productivity-increasing inputs as well as adjustments in input use rates,
- changes in the quality of the agricultural resource base (and the effect of agricultural production practices on the resource base),
- changes in the external environment (and the effect of agricultural production practices on the external environment).

In practice, estimating and forecasting trends in TP is unlikely to be simple. This paper argues that researchers probably will wish to develop "proxy indicators" -- readily observed variables, possibly qualitative, that are closely linked to components of TP. Issues in the use of proxy indicators at various system levels and by different users are then explored. A number of methods are described that have been used to estimate TP, along with alternative approaches to the development of proxy indicators. Finally, suggestions are made for a research agenda, with an emphasis on ways in which CIAT, CIMMYT and other institutions in Central America may collaborate in the measurement of TP and its components, and in the development and testing of proxy indicators.

The notion of sustainability and the role of indicators

Sustainability

The number of definitions of sustainability (or sustainable agricultural systems) that have emerged during the last several years is too large to count. Nonetheless, many if not most of these definitions fall into several broad approaches. It should be noted that the approaches or conceptualizations described below are not mutually exclusive. Indeed, many observers (ourselves included) emphasize one of them, while recognizing the validity of others.

1. ***Agroecology***. Sustainability is interpreted as system resilience, or the ability of a system to recover from stress or perturbation, largely due to system diversity featuring multiple pathways for the cycling of energy and nutrients (Conway 1986).
2. ***Stewardship***. Sustainability is interpreted as human stewardship of Earth's resources, with a responsibility to non-human species as well as to future generations, to use and conserve these resources wisely. A major implication is that the real incomes of future generations should be no lower than those enjoyed by the present generation. This may further imply that growth in human populations and human economic activities should be restricted (Batie 1989).
3. ***Sustainable growth***. Sustainability is interpreted as a need to minimize damage to the natural resource base while meeting growing demands for agricultural products. The CGIAR definition falls primarily into this category (CIMMYT 1989). This is the interpretation of sustainability that is emphasized in this paper.

The sustainable growth approach emphasizes the need for increased agricultural production to meet growing demands for food. This does not imply that production can continue to increase forever and, fortunately, it is not necessary to assume that it can. The developed world has shown that population growth is closely linked to development and human welfare. Higher incomes, improved education (especially for women) and availability of family planning information all contribute to reduced birth rates and slower population growth (Poleman 1989; Robey, Rutstein, and Morris 1993). As this phenomenon proceeds in the developing world, increases in the demand for food driven by population growth will gradually level off.

In general, an understanding of the causes of sustainability problems is exceedingly important, because sustainability concerns quickly become enmeshed with broad developmental issues. Sustainability problems have been traced to population pressure on resources, poverty and marginalization, insecure land use rights, short-term profit maximization, behavior of large landholders, and certain kinds of public policy. The interactions among these factors are fairly complex, and space considerations prohibit a full discussion. Some of the more important interactions, however, are summarized in Figure 1 (Harrington 1993).

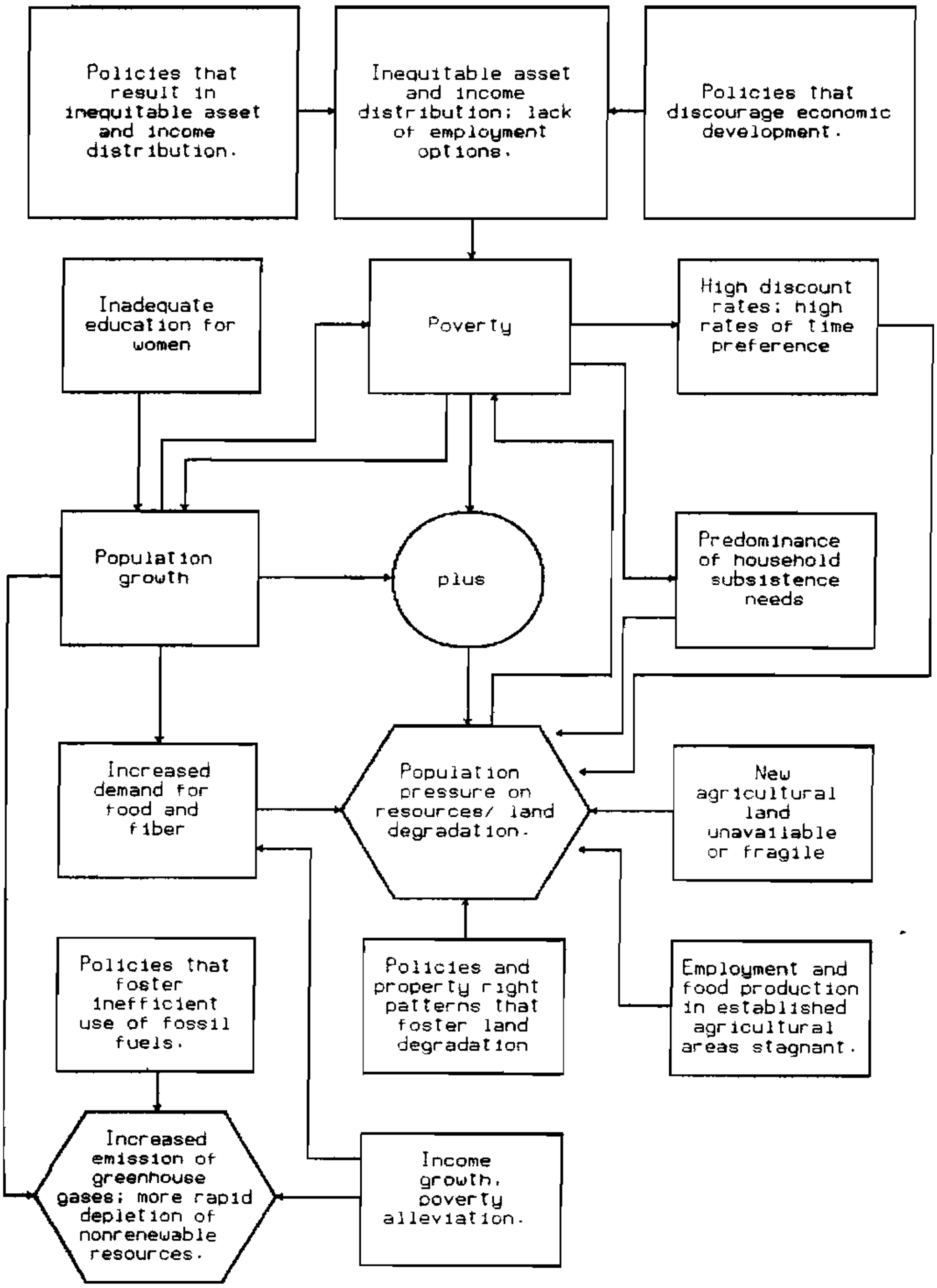
One specific definition of a sustainable agriculture (falling primarily into the "sustainable growth" category) is thought by many to be of particular interest and relevance: "*A sustainable agricultural system is one that can indefinitely meet increasing demands for food and fiber at socially acceptable economic and environmental costs*" (Crosson 1992). Note that "economic and environmental costs" include the full range of on-farm as well as off-farm costs associated with production. Examples of economic and environmental costs are given in Table 1.

The advantage of the Crosson definition is that it stresses the fact that demands cannot be met, nor production increases achieved, without cost. It further highlights the notion of trade-offs among different kinds of costs, and the option of incurring costs in one region in order to reduce costs in another. As a consequence, the definition allows for the prospect that a system may be sustainable even if some of its components are not, and that a system may be required to adapt dynamically to changing external circumstances in order to be sustainable.

Table 1. Economic and environmental costs of meeting growing demands for agricultural products: some examples.

On-site economic costs	Off-site economic costs	Environmental costs
Near-term: • Current costs of external and farmer-supplied inputs, e.g., fertilizer, labor, land, crop residues **Longer-term:** • Losses in productivity through soil erosion and soil fertility loss, or gradual salinization	• Lost productivity through siltation of irrigation infrastructure in lowlands, associated with soil erosion in uplands • Lost productivity in power generation through poor water quality, associated with soil erosion in uplands	• Reduced water quality and effects on public health: pesticide residues, nitrates, etc. • Loss of biodiversity through area expansion, deforestation • Increased emission of greenhouse gases and possible contributions to global climate change

Figure 1. Poverty, income growth and problems of sustainability.



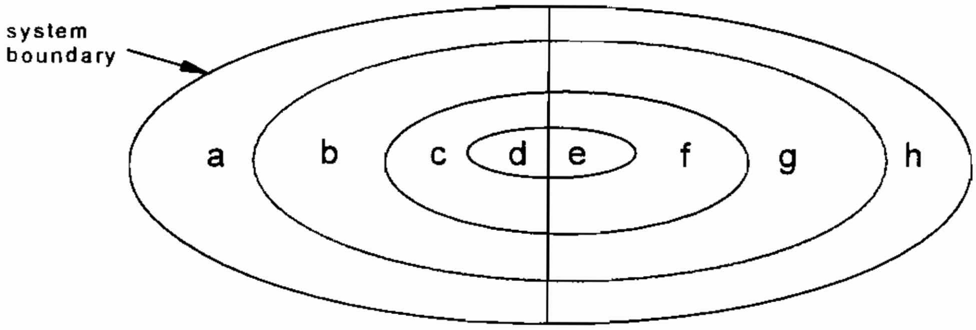
Indicators

Indicators and measures

An indicator can be defined as a variable that points out or directs attention to something. Indicators of sustainability, then, may be defined as variables that point out or direct attention to processes, states, or trends associated with the sustainability of a system. Such indicators may be based on "measures" (quantitative variables) or "non-measures" (qualitative variables). Net soil erosion (net tons of soil lost per hectare per year) is an example of a measure. The perception of a group of farmers regarding changes over time in land quality is an example of a "non-measure". Indicators need not be based on measures. Similarly, not all measures are necessarily indicators. A precisely estimated change in soil nutrient status is not an indicator when sustainability is threatened by groundwater depletion, not by soil fertilizer loss.

Figure 2 illustrates the relationship between measures and indicators. Variables that describe the workings of a subsystem may be based on measures or non-measures. Some of these variables, because of their relevance to sustainability, possibly may be useful as indicators ("possible indicators"). Among these, a small subset may be found that are particularly useful ("viable indicators"). Finally, it may even be possible to identify an even smaller subset of what might be termed "universal indicators" that indicate sustainability (or unsustainability) for all systems or subsystems, regardless of level.

Figure 2. Indicators of sustainability: measures and non-measures.



measures = a+b+c+d
non-measures = e+f+g+h
possible indicators = b+c+d+e+f+g
viable indicators = c+d+e+f
universal indicators = d+e

Desirable characteristics of indicators

It seems reasonable that a good sustainability indicator should:

1. change as a system moves away from equilibrium (provide a clear indication when the performance of a system is declining because of resource degradation),
2. give particular warning of degradation processes that are irreversible (or where the costs of reversing the process are likely to be socially unacceptable),
3. take account of the full cycle through which a system moves through time (indicators should reflect the effects, if any, of long-term crop rotations),
4. highlight links to other system levels at which degradation processes might most readily be addressed,
5. distinguish clearly between causes and effects: processes of system decline (effects) should not be confounded with system characteristics that make a system vulnerable to decline (causes),
6. feature relevant, complete geographic coverage,
7. be easily detected, relatively simple, and cost effective, taking advantage where possible of available information, and
8. provide a means of forecasting future trends in resource quality and agricultural system productivity, as well as tracking corresponding trends from the past.

This latter point is particularly important in relatively new systems, or in land types where intensification of farming is just beginning, where few (relevant) trends from the past are available as a basis for forecasting the future. Moreover, if the future is more turbulent than the past, e.g., because of climate change, then past trends may be of limited usefulness in developing indicators.

Total productivity

The principal indicator of sustainability used in this paper is *total productivity* or TP. This is a measure introduced by Lynam and Herdt (1988) and Crosson and Anderson (1993) that serves to operationalize the Crosson definition of a sustainable agriculture presented earlier. The TP of a system is defined as the sum of the value of all outputs divided by the sum of the value of all inputs, including all economic and environmental costs. Index numbers are used to assess changes over time in TP, thus removing the effects of changes in relative input and output prices.[1] It is recognized that environmental costs can be difficult to quantify and value (Pearce 1993), even though considerable methodological progress recently has been made in this area (Winpenny 1991). Agricultural systems are deemed sustainable when TP shows a non-declining trend. Declining TP trends point to resource degradation or undesirable environmental spillovers as agricultural systems strive to meet growing demands for agricultural products. Mathematically,

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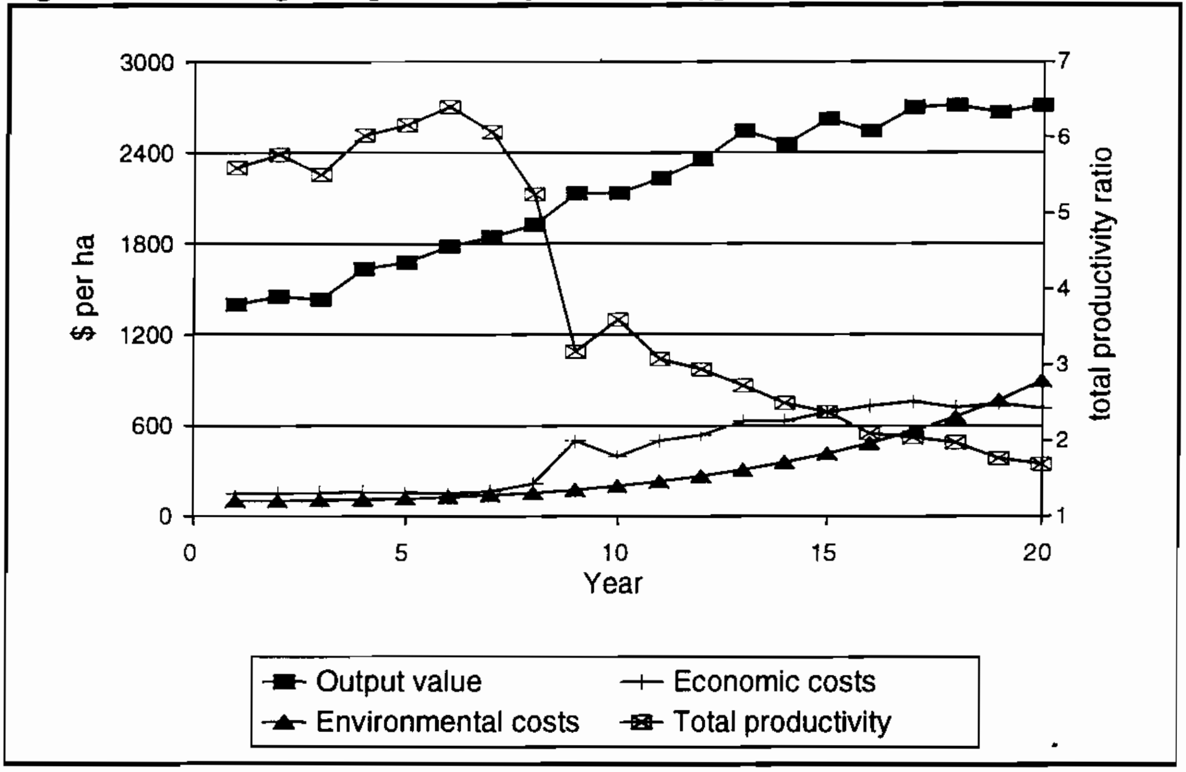
[1] The Thornqvist-Theil approximation to the Divisia continuous index is commonly used for aggregating discrete input and output data in productivity analysis. The Divisia index is exact for the case of translog production functions and is considered one of the most defensible methods of aggregation for use in productivity analysis (Ehui and Spencer 1990).

$$TP = Y / (C + F + X + E) \qquad (1)$$

where TP = total productivity; Y = value per ha of all outputs from a system including the value of all byproducts; C = near-term on-site economic costs including the opportunity costs of farmer-owned resources; F = longer-term on-site economic costs including "user costs"; X = off-site economic costs; and E = environmental costs. Note that Y and all cost categories are valued at social prices, i.e., with policy-induced price distortions removed. A hypothetical example of an unsustainable system, featuring declining TP associated with increasing economic and environmental costs, is given in Figure 3.

Figure 3. Estimating total productivity trends: a hypothetical illustration.[a]



[a] In this hypothetical example, it is assumed that prices do not change over time.

There is another way to interpret TP -- it is the inverse of the unit cost of agricultural production. As TP declines, unit costs increase. Note that a higher unit cost (i.e., a lower TP) may come from increases in environmental costs or off-site costs that are not fully compensated by a higher value of production.

Total productivity meets most of the characteristics listed above that are desirable for sustainability indicators. Nonetheless, a number of concerns may be raised:

- Empirical estimation of TP trends requires immense amounts of information. All outputs and all inputs (including off-site economic and environmental effects of a production system) first must be physically measured, then they must be valued. TP is not "easily detected and relative simple".

- Estimates of TP can exaggerate the sustainability of a system when technical change is rapid (leading to a rapid increase in the value of output) and when, at the same time, off-site economic and environmental costs are difficult to measure and as a consequence are overlooked.
- Estimates of past trends in TP may shed little light on the future if resource degradation accelerates (increasing economic and environmental costs) while productivity growth stagnates (slowing growth in the value of output).
- It is assumed that environmental values can be compared with economic values, i.e., that the environmental costs of a production system can be combined with the economic costs to estimate total costs. This implies that the costs of meeting increased demands for agricultural products are "socially acceptable" when these costs are minimized, regardless of the relative importance of environmental and economic costs. When it is argued that some kinds of environmental damage are inherently unacceptable, the implication is that the associated costs are infinite and that TP in these cases is virtually zero.

Clearly, TP is most helpful as a sustainability indicator when good estimates of important off-site and environmental costs and benefits of agricultural production systems are readily available, and when likely sources of productivity growth as well as likely effects of resource degradation are taken into account when projecting TP trends into the future.

Proxy indicators

The complexity and cost associated with estimating TP as such is cause for concern. As researchers estimate total productivity trends they may also wish to develop "proxy indicators" -- readily observed variables (possibly qualitative) that are correlated with TP or its components. A good proxy indicator will be characterized by trends that are very similar to those associated with TP or its components. Identifying proxy indicators and establishing their correlation to TP or its components should form a substantial part of any research agenda that aims to make it possible for numerous actors, farmers as well as researchers, to participate in the assessment of sustainability trends. Several alternative approaches to developing proxy indicators are discussed near the end of this paper.

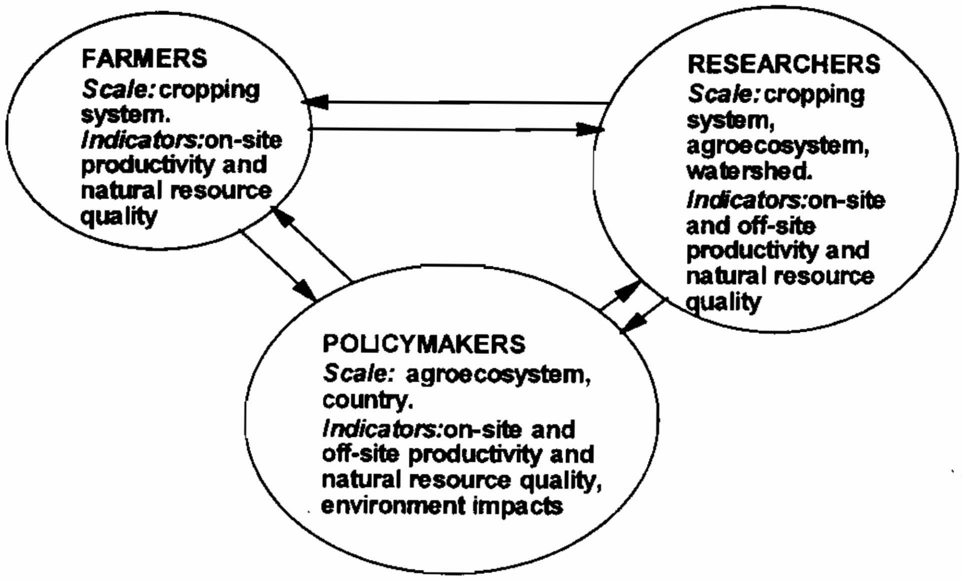
Proxy indicators, system typologies and system levels

Appropriate proxy indicators may vary over ecosystems and possibly over production systems within an ecosystem. In order to use proxy indicators, a typology of systems may be needed. Where production systems are similar and where threats to system sustainability are similar, proxy indicators will also tend to be similar. For example, an indicator based on the dynamics of fallow regrowth (linked to soil fertility trends and system productivity) would only apply to subsystems that feature fallow. Similarly, an indicator based on key weed species would only apply where those species are endemic. Research should aim to identify proxy indicators with as wide an application as possible.

Proxy indicators of sustainability are best developed and used in light of a broad understanding of agricultural development processes and of how these processes unfold at different system levels (e.g., farm, community, country, ecosystem). As system levels vary, the range of factors that mold sustainability also varies. In addition, they should provide information tailored to the needs of different system actors operating at different levels (Figure 4).

- Indicators at the agroecosystem to national levels should be useful to policymakers as they engage in policy analysis and planning.
- Indicators at the plot to agroecosystem levels should be useful to researchers as they evaluate trends and assess alternative interventions to reverse unfavorable trends.
- Indicators at the plot to community level should be useful to farmers and to farmer and community organizations, as they seek to understand what is happening to the state of their resource base and the productivity of their system.

Figure 4. Users, scale of application, and indicators.



Effects of links between system levels

Agricultural systems are deemed sustainable when total productivity shows a non-declining trend. Declining TP trends are associated with resource degradation or undesirable environmental spillovers. However, these conclusions only hold true for a given system level. When an "unsustainable" system interacts in significant ways with higher system levels, the conclusion on "unsustainability" may need to be adjusted. The following mechanisms should be kept in mind:

- a higher system level may provide opportunities for *input substitution*, e.g., declining soil fertility in a particular field may be ameliorated by application of farm yard manure (made available at the whole farm level) that otherwise may have been used for other purposes (e.g., as a fuel);
- a higher system level may provide opportunities for *enterprise substitution*, e.g., soil erosion associated with field crop production may be ameliorated by a shift to perennial horticultural crops made possible by investments in rural infrastructure (road, bridges);
- a higher system level may take advantage of opportunities for *trade-offs among subsystems*, e.g., investment in intensive agriculture in favored agricultural areas (accompanied by environmental pollution) may, through income and employment generation and poverty alleviation, reduce the need for poor people to rely on subsistence farming of fragile hillsides.

This latter point is of some interest. The question may be raised for Latin America whether an effective way of forestalling land degradation in the uplands and forest margins is to promote expanded employment through investments in favored agricultural areas, such as the highly productive valleys. Such a strategy would be most effective (and equitable) when employment and income effects are large and broadbased and when poverty alleviation is swift.

In conclusion, when assessing the sustainability of a subsystem, attention must be paid to the possibility that links with higher system levels may help ameliorate declining subsystem performance or deteriorating resource quality. The sums associated with estimating TP may be substantially different at a higher vs. a lower system level.

What about indicators for policymakers?

Policymakers comprise an important audience for indicators of sustainability, given the importance that policies can have in causing land degradation or in fostering adoption of resource-conserving techniques. Policies can contribute to "unsustainability" in two ways: *directly*, or *indirectly* through their effects on population growth, poverty, common property resources and externalities. Here are some examples of policy actions that directly contribute to unsustainability:

- Deforestation and subsequent soil erosion have been linked with policies that directly favor commercial logging (low tax rates or overt subsidies, public road construction in forested areas, poor enforcement of forestry regulations) (Repetto and Gillis 1988).
- Policies that directly restrain farmer adoption of erosion-controlling practices include subsidies on external inputs, interventions that increase interest rates, and policies that reduce the security of land tenure (Anderson and Thampapillai 1991).

Policy change can foster resource conservation. For example, policies that prohibit the burning of maize stover, along with subsidies on backpack sprayers for herbicide application, have helped transform farmers' maize stover management practices in areas of southern Mexico. As a consequence, erosion rates have dropped dramatically (van Nieuwkoop 1993). Similarly, the transfer of ownership and management of common property resources (e.g., forests) from government agencies to effective community institutions has been shown to foster more appropriate resource use (Lurie 1991).

It is often suggested that indicators be developed for the purpose of providing information to agricultural policymakers, particularly when alternative policies differentially favor resource-conserving vs. resource-degrading production practices or land and water use strategies. It is entirely suitable -- indeed, exceedingly important -- that indicators be used to inform policymakers of the economic and environmental costs associated with alternative resource use strategies.

However, the broad categories of indicators developed for policymakers need not differ from those developed for other audiences. These categories include trends in TP, the effect of changes in agricultural resource quality and in the external environment on TP, and the effects of agricultural production practices on resource and environmental quality. Indicators of sustainability can be exceedingly useful to policymakers. Equally important, however, is information on how policy alternatives affect farmer adoption behavior and thereby the underlying processes of productivity improvement or resource degradation that indicators are designed to reflect.

Categories of indicators and components of total productivity

Those who would develop indicators of sustainability must avoid the easy descent into a mere "shopping list": a detailed but unstructured conglomeration of any and all variables that conceivably may be related at one time or another, in one way or another, to sustainability. Endowing such a list with the power to "measure sustainability" only serves to confound relevant indicators with irrelevant ones, without providing guidance about which is which.

Categories of indicators

Primary, secondary and tertiary indicators

Fortunately, the concept of total productivity is helpful in establishing sensible categories of sustainability indicators. It was noted earlier that agricultural systems are deemed sustainable when TP shows a non-declining trend. Trends in TP, then, comprise the *primary* indicator of sustainability. It should be clear, however, that trends in the components of TP are useful as *secondary* indicators. Components of TP include:

- Y - value per hectare of all outputs from a system including the value of all byproducts,
- C - near-term on-site economic costs, including the opportunity costs of farmer-owned resources,
- F - longer-term on-site economic costs,
- X - off-site economic costs, and
- E - environmental costs.

Finally, variables that influence TP and its components may serve as *tertiary* indicators. These include:

- changes in agricultural technology (and factors that affect farmer adoption decisions),
- changes in agricultural resource quality (and effects of farm-level practices on resource quality), and
- changes in the quality of the external environment (with an emphasis on those changes that may affect the productivity of agriculture).

Interactions among primary, secondary and tertiary indicators of sustainability are illustrated in Figure 5. Note that the framework described in Figure 5 can be adapted to serve at any level of system hierarchy, from plot level to the global level.

Problems, causes, solutions and effects

This framework also can help sort out the links between information on sustainability *problems*, their respective *causes* and *effects* and possible *solutions* as sustainability trends are assessed. Here are some examples:

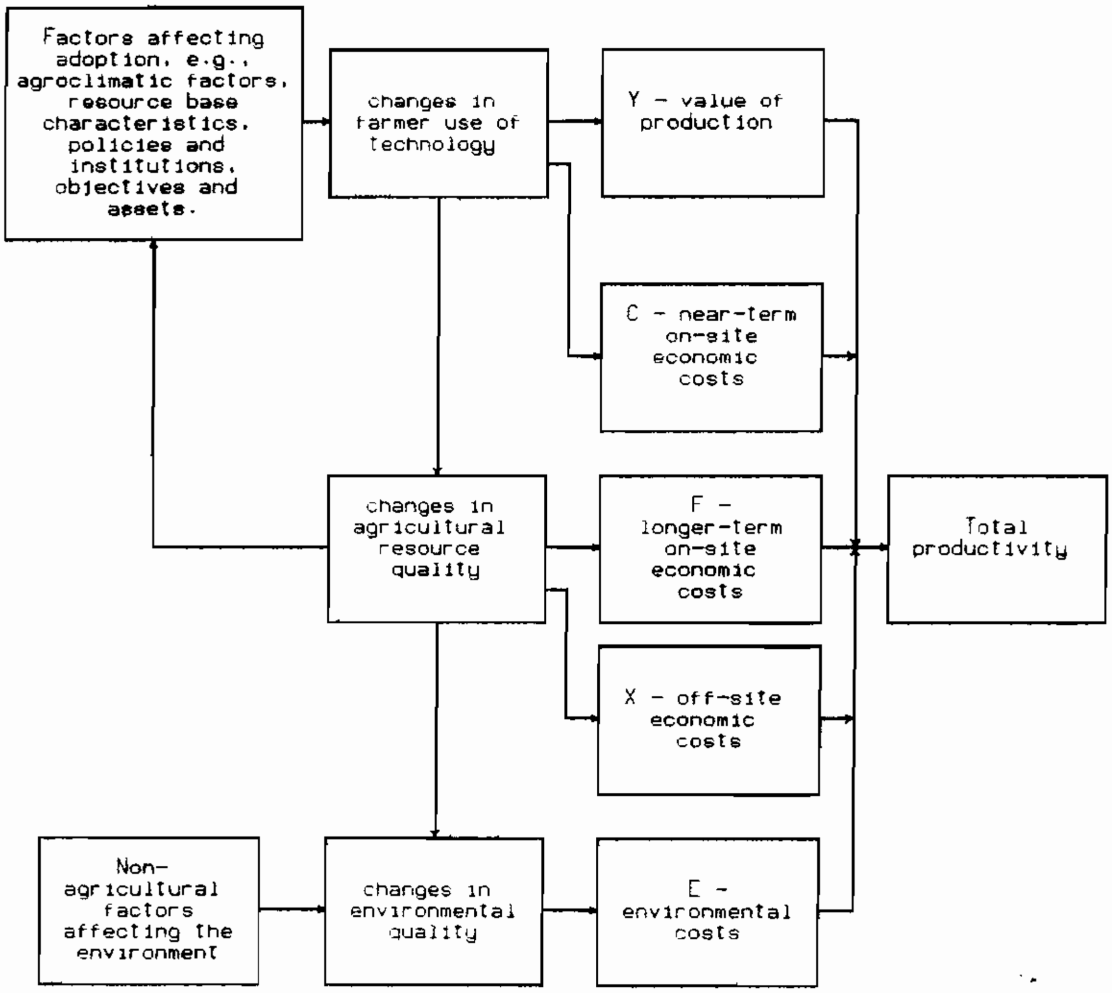
1. Many analysts have pointed out the threat to the sustainability of intensive rice systems in South Asia associated with the depletion of groundwater reserves. They are implicitly warning that:

depletion of groundwater,	problem	tertiary indicator
associated with unregulated tubewell installation and heavy subsidies on electricity,	causes	tertiary indicator
will increase longer-term on-site costs (e.g., higher pumping charges for *an individual* farmer), and in	effect	secondary indicator
higher external costs (higher pumping for *all* farmers)	effect	secondary indicator
and will result in declining trend in total productivity.	effect	primary indicator

2. In the case of hillsides in Central America:

erosion and soil fertility loss	problems	tertiary indicator
associated with burning of crop residues and intensive tillage	causes	tertiary indicator
lead to increased longer-term on-site costs (declining output over time with constant levels of inputs),	effect	secondary indicator
as well as higher off-site economic costs (wear and tear on hydroelectric plants),	effect	secondary indicator
and declining total productivity.	effect	primary indicator

Figure 5. A simplified model of processes that affect components of total productivity.



3. Conservation tillage enthusiasts often claim that sustainability is enhanced to the extent that conservation tillage practices are adopted. They are implicitly claiming that:

adoption of conservation tillage practices	solution	tertiary indicator
will increase yields	effect	secondary indicator
while reducing erosion and soil fertility loss	problems	tertiary indicator
and therefore reduce longer-term on-site and external costs	effects	secondary indicator
and improve total productivity.	effect	primary indicator

Clearly, the usefulness of tertiary indicators hinges on their ability to faithfully track important components of total productivity.

Similarly, the usefulness of combinations of secondary indicators hinges on their ability to unambiguously distinguish whether TP is increasing or decreasing.

For example, if value of output is stable but near-term costs are increasing, and there is reason to believe that off-site costs are also increasing, then TP is almost certainly falling. In this case, *qualitative* information on secondary indicators is exceedingly useful. However, if the value of output is increasing rapidly but with higher near-term costs, while off-site costs and environmental costs appear to be going down, then it is important to work through the sums and examine a *quantitative* estimate of TP.

In the following sections, issues associated with the estimation of longer-term on-site economic costs (F), off-site economic costs (X), and environmental costs (E) are discussed in more detail.

Estimating the components of total productivity

Agricultural resource quality and longer-term on-site economic costs (F)

Agricultural resource degradation may result in several different kinds of costs:

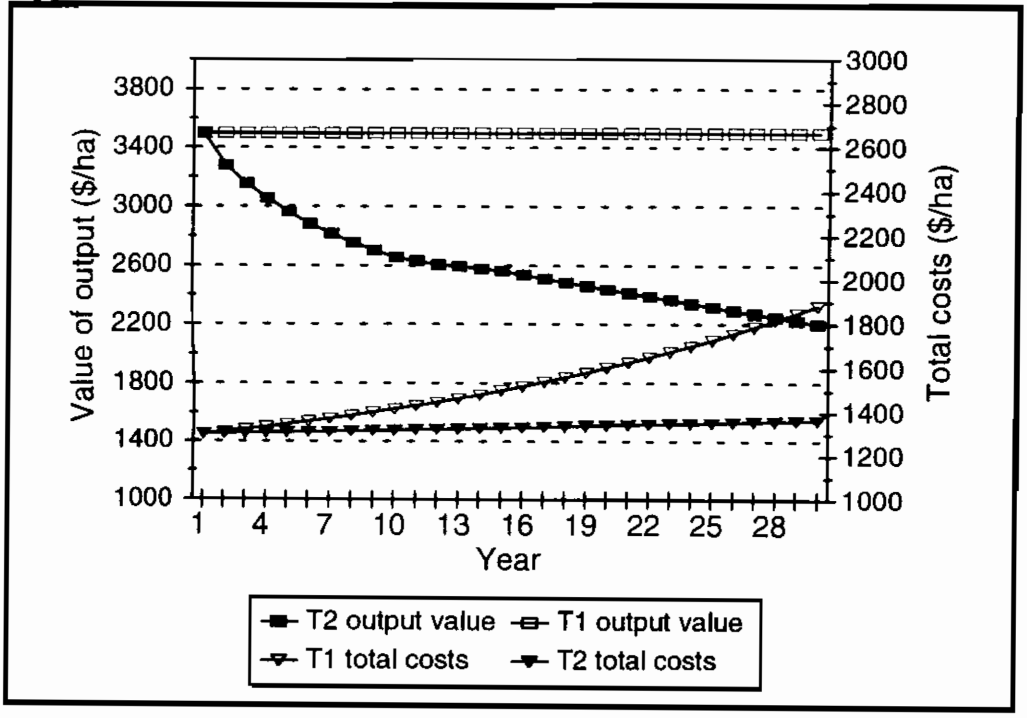
1. *Foregone output.* It can cause a decline in output compared to what would have been the case without degradation. This kind of cost may be estimated by the difference in the value of output in the presence versus absence of resource degradation. This analysis is complicated when continuous resource degradation is not expected to lead to any measurable productivity loss for a considerable period of time.
2. *Replacement costs.* It can compel farmers to spend additional money on inputs to maintain output levels. This kind of cost is estimated by the cost of additional inputs required to bring a degraded resource back up to the quality of an undegraded resource. If replacement costs are estimated that the value of foregone output should be ignored and vice-versa. (Otherwise, costs will be "double-counted".)

3. *User costs.* It can lead to an permanent reduction in the productive capacity of the resource base, reducing the economic value of the resource stock. This kind of cost is estimated by assessing the salvage value of the resource (at the *end* of the period of analysis relevant to foregone output or replacement costs), with versus without degradation. When this salvage value differential is annualized, it may be called a "user cost".
4. *Option and existence values.* It can reduce the array of options available to future generations, e.g., when a resource is degraded to such an extent that it can no longer be used for certain purposes. This kind of cost requires assessment of society's willingness to pay to maintain the resource (or willingness to be compensated for a reduced level of options).

For simplicity, the remainder of this section focuses on estimating F by means of the value of foregone output. It should be noted, however, that data from other cost categories associated with F can be readily incorporated if available.

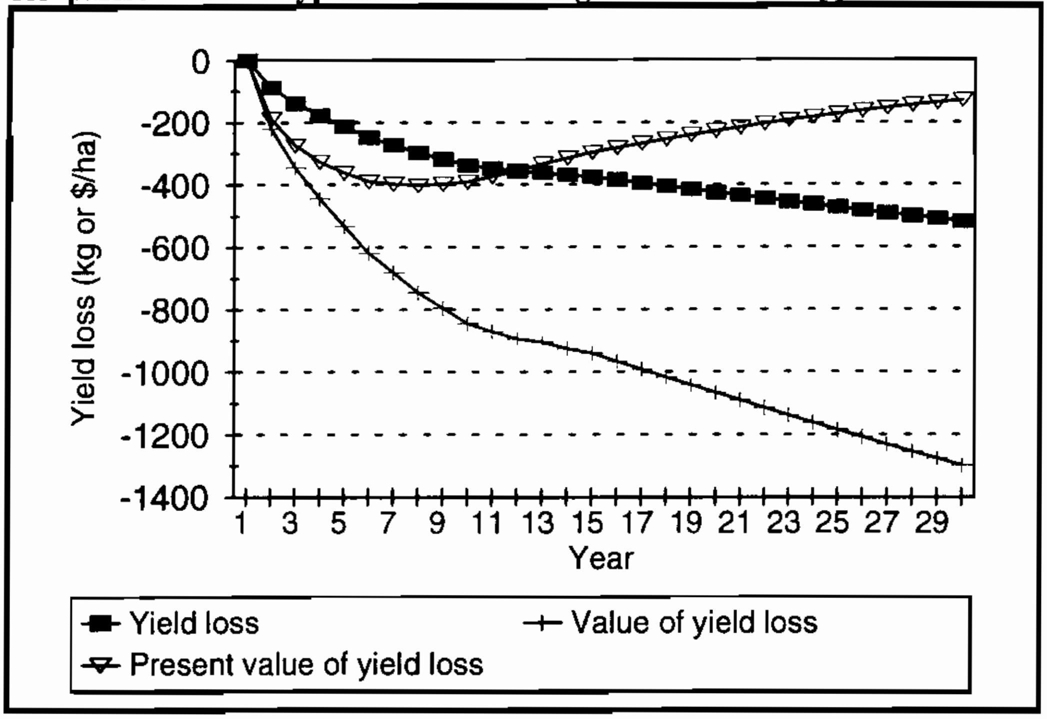
To begin, a hypothetical example of trajectories for output value and total cost (including external and environmental costs) is given in Figure 6. T2 is a land-degrading technology with falling value of output and rapidly increasing costs, whereas T1 is a relatively sustainable alternative. It should be noted, however, that T1 is not entirely sustainable given our definition -- with constant output value and gradually increasing total costs, total productivity for T1 is gradually declining.

Figure 6. Output value and total costs (including external and environmental costs) for two hypothetical technologies over a 30 year time period. Data are taken from Appendix Tables 1 and 2.



A naive measure of F would be the difference in the value of output between T1 and T2, calculated for each time period. Conceivably, the value of foregone output could be discounted back to the initial time period (Figure 7).

Figure 7. Foregone output for T2-T1, and its undiscounted and discounted value: a comparison of two hypothetical technologies. Data from Appendix Tables 1 and 2.



However, this approach has a major drawback: processes of resource degradation *are not synchronized* with their resulting losses in productivity. If, for example, a farmer were to shift from T2 to T1 in year 10, the value of T1 output for that year would remain *well below* the value of output associated with continuous use of T1, even though the "same technology" is being used for that time period. In other words, *for each point in time*, the value of F should be estimated as the discounted value of foregone output for a selected number of future time periods. That is:

- "F" for period 1 . . .	should be estimated as the present value of foregone output T2-T1 for periods 1-15,
- "F" for period 2 . . .	should be estimated as the present value of foregone output T2-T1 for periods 2-16 (base period = year 2),
- "F" for period 3 . . .	should be estimated as the present value of foregone output T2-T1 for periods 3-17 (base period = year 3),
- "F" for period 4 . . .	should be estimated as the present value of foregone output T2-T1 for periods 4-18 (base period = year 4).
- "F" for period 5 . . .	should be estimated as the present value of foregone

output T2-T1 for periods 5-19 (base period = year 5), and so on . . .

An example of results (using the same data set used in the preparation of Figures 6 and 7) is shown below in Table 2.

Table 2. A hypothetical example of estimating "F", future on-site costs of land degradation, by means of present values of yield loss for different base periods (discount rate = 8%)

	Base year for discounting				
Year	**1**	**2**	**3**	**4**	**5**
1	0				
2	196	212			
3	288	312	336		
4	348	376	406	438	
5	389	420	453	490	529
6	422	456	492	531	574
7	434	468	506	546	590
8	442	477	515	556	601
9	440	475	513	554	599
10	437	472	509	550	594
11	421	454	491	530	572
12	405	437	472	510	551
13	384	415	448	484	523
14	368	397	429	463	500
15	350	378	409	441	477
16		364	393	424	458
17			377	407	440
18				391	422
19					405
20					
F = sum of discounted values	5323	6112	6749	7316	7833

In summary, substantial information is required to estimate the value of F:

- The threat to sustainability posed by resource degradation must be identified and defined (including information on the pace and incidence of the problem).
- Resource degradation must be measured in qualitative and quantitative terms (e.g., t/ha/yr of soil lost to erosion).
- Causality between resource degradation and agricultural system productivity must be established. Specifically, the trajectories over time of output value must be estimated in the presence versus in the absence of resource degradation processes.
- The cost associated with degradation must be estimated for each year by means of the change in productivity with vs. without degradation.
- "F" can then be calculated as shown in Table 2.

Note again, however, that the approach used in example underestimates the true longer-term economic costs of erosion when salvage values or user costs (related to the permanent reduction in the value of the land asset after the period of analysis expires) and non-economic costs (e.g., existence or option values) are important.

Off-site economic costs (X) and effects of agriculture on the external environment (E)

It is well known that farmers will usually underinvest in land-conserving technologies when the costs of land degradation -- and the benefits from investments in land-conserving practices -- accrue off-farm and affect "someone else". In Indonesia, for example, the major cost associated with soil erosion in the uplands is the siltation of irrigation infrastructure in the lowlands (UACP 1987). Similarly, in the USA, the cost associated with the effect of soil erosion on downstream water quality is estimated to be *double* the on-site cost of reduced productivity (Colacicco, Osborn and Alt 1989).

In many developing countries, where safe use of pesticides is not necessarily a high priority, contamination of water supplies is a particularly important problem (McCracken and Conway 1987). Finally, common property resources are particularly susceptible to degradation when community enforcement of well-defined use rights is lacking (Jodha 1991). The costs associated with these external effects are usually difficult to estimate. However, without some sense of external economic costs, total productivity computations and sustainability assessments are incomplete.

Given widespread concern about the state of the planet, it is important to at least attempt to estimate the environmental costs associated with expanded agricultural production. Current and alternative practices can be compared with regard to their (past or expected future) effects on:

- rates of deforestation,
- changes in water quality,
- changes in environmental pollution,
- changes in biodiversity, and
- carbon dioxide (and other greenhouse gases) capture or release.

Many of these impacts are exceedingly difficult to measure and value in monetary terms, not least because most environmental assets or services are not marketed. Environmental valuation typically hinges on estimates of a willingness to pay (for environmental services) or a willingness to accept compensation (for environmental costs). The danger, of course, is what may called an "asymmetry of valuation", where important environmental costs associated with agricultural development are ignored simply because they are difficult to estimate (Pearce 1993). Clearly, this asymmetry can lead to a significant bias in estimates of total productivity, and to mistaken judgments on agricultural sustainability.

Estimating total productivity -- a reprise

When the difficulties of estimation and valuation are overcome, estimates of X and E can be combined with the information on F and C in a comprehensive analysis of total productivity. This analysis is composed of the following steps:

1. Obtain information on value of output (Y), near-term costs (C), longer-term on-site costs (F) and external and environmental costs (X, E) for each time period of analysis, for each technology being considered. The hypothetical data set used in this paper is shown in Appendix Tables 1 and 2.
2. For each technology, calculate the present discounted value of output for each of a sequence of discounting base years.
3. For each technology, calculate the present discounted value of total costs for each of a sequence of discounting base years.
4. For each discounting base year, and for each technology, divide the present value of output by the present value of costs to obtain a total productivity ratio.
5. Assess the trend of the total productivity ratios -- a declining trend indicates a non-sustainable system.

An example of results using this analysis (drawing on the data set shown in Appendix Tables 1 and 2) is provided in Table 3. Note that total productivity for T1 goes down swiftly, whereas total productivity for T2 declines very slowly.

Table 3. Comparisons of present value of output and present value of total costs, and corresponding total productivity ratios, for different discounting base years. Data taken from Appendix Tables 1 and 2.

	T1			T2		
Base year	Present value of output ($/ha)	Present value of total costs ($/ha)	Total productivity ratio	Present value of output ($/ha)	Present value of total costs ($/ha	Total productivity ratio
1	25153	11744	2.14	29958	11226	2.66
2	24464	11862	2.06	29958	11244	2.66
3	23932	11985	1.99	29958	11262	2.66
4	23475	12114	1.93	29958	11280	2.65
5	23074	12247	1.88	29958	11298	2.65

Data sources and data consistency -- a caution

It should be clear that data requirements for quantitative analysis of total productivity are formidable indeed. If, for example, an analysis covering a time period of 20 years is desired, then data for *40 years* is needed -- because of the need to assess the value of output and the value of costs in terms of a sequence of discounting base years. In practice, this may lead to "hybrid" data sets, partly composed of historical data and partly composed of projections or forecasts. It is important to keep these "hybrids" as consistent as possible, using production functions or other kinds of quantitative models.

Indicators of the effect of the external environment on agriculture

Some indicators can serve to trace out environmental trends, external to agriculture, that are likely to impinge in important ways on the sustainability of national or global agricultural systems. These indicators provide the broad context or perspective in which more detailed indicators, or more specific agricultural development activities, can be understood. The development of "sustainable" agricultural practices at the agroecosystem level, undertaken in ignorance of broader global trends, has been compared by some observers to rearranging deck chairs on the *Titanic*. It should be clear, however, that IARC scientists should be *users*, not *developers*, of these indicators. Examples of broad trends in the external environment that are relevant to agriculture include:

- global climate change, with corresponding implications for crop and varietal distribution and adaptation associated with temperature change, or with changes in rainfall levels and intensities;
- local pollution from urban and industrial activity, e.g., ozone or sulfur dioxode;
- the availability and prices of external inputs, including energy used in fertilizers and pesticides, farm machinery, and transport and marketing of agricultural products and inputs; and
- rates of expansion in demand for agricultural products associated with population growth and income growth and distribution.

Predictors of farmer adoption/adaptation

When declining total productivity is an issue, and when this problem can be traced to resource degradation, solutions commonly are sought through technical change (including changes in agricultural production techniques as well as in land management strategies). Technical change may come about through policy adjustments that create incentives for farmers to adopt land-conserving practices; through farmers' own adaptations to changing circumstances; or through use of new inputs or practices developed in cooperation with formal research and extension structures. Indicators used to predict the likelihood of farm-level technical change are generally not "indicators of sustainability". Nonetheless, indicators that help forecast whether farmers will adopt resource-conserving practices can be immensely helpful in honing arguments to policymakers as well as in setting priorities within research institutions.

Approaches to developing sustainability indicators

The conceptual framework developed in this paper for assessing sustainability trends emphasizes the notion of total productivity. It is of some interest to review the extent to which other approaches to developing sustainability indicators are consistent with this framework. In this section, six alternative approaches are discussed. Then, a number of possible approaches for the development of proxy indicators are advanced.

Past approaches

Total factor productivity

Total factor productivity (TFP) is defined as the sum of the value of all outputs from a production system divided by the sum of the value of all inputs (Lynam and Herdt 1988). Estimates of TFP have long been used at the level of the macroeconomy to identify the role of technological change in economic growth: when the contributions of increased levels of inputs are accounted for, the residual is attributed to technical change. Index numbers have been developed that allow estimates of trends associated with changes over time in TFP (Capalbo and Antle 1988). Trends in TFP can be used to track changes in system performance and (implicitly) resource quality when prices and technology are held constant. Whitaker and Lalitha (1993) used this method to assess the sustainability of well-defined cropping patterns in India, using long-term trial data. Ehui and Spencer (1990), using a more advanced version of the technique, included as a cost of production the value of soil nutrients lost through land degradation.

TFP is obviously closely linked to the notion of total productivity used in this paper. Typically, however, TFP estimates feature near-term and (occasionally) longer-term on-site economic costs and benefits (Y, C, F). Off-site economic costs and benefits (X) and environmental impacts (E) usually are not included.

Gross domestic product from agriculture, adjusted for the depreciation of natural resource capital

National income accounts normally contain estimates of a country's gross domestic agricultural product. When per capita agricultural GDP is growing in real terms, many observers feel reassured about the performance of agriculture. However, much of this growth can be merely temporary, achieved at the expense of degraded natural resource capital. When this "capital depreciation" is taken into account, the ensuing adjusted agricultural GDP estimates are more realistic.

This method was originally developed to account for the reduced value of forest or mineral reserves in national income estimates (Repetto and Gillis 1988). Recently, however, it has been applied to the agricultural sectors in two countries, the Philippines and Costa Rica (TSC WRI 1992). The approach typically:

- relies heavily on secondary data,
- is used at the level of the agricultural sector and, as a consequence, says little about the contributions of alternative technologies to sustainability goals,

- says little about the difference between on-site and off-site effects (at the level of the nation, these differences become impossible to differentiate),
- requires that agricultural resource stocks be valued in monetary terms, and
- tends to ignore environmental effects of expanded agricultural production, apart from depletion of natural resource capital.

Moreover, comparisons of benefits and costs in this approach feature their *difference*, not their *ratio* as in the TFP and TP approaches. This makes it difficult to develop index numbers for assessing trends over time, with the consequence that changes in input and product prices may be mistaken for changes in factor productivity and land quality.

Present value of the economic returns to alternative techniques, adjusted for environmental costs

Farm-level enterprise or whole-farm budgets are commonly used to assess the profitability to farmers of alternative production practices, enterprises, or enterprise mixes. When a suitably wide range of environmental benefits and costs is included in the analysis, "environmentally-adjusted" economic or social profitability can be estimated. Finally, when time paths for land quality change and effects on productivity are projected for a number of discrete technical alternatives, net present values can be estimated and comparisons can be made among the alternatives.

Faeth et al.(1991) report the results of such an analysis for the United States. They show that many cropping systems and production practices appear profitable on the surface but produce negative social value when allowance is made for (future) depreciation of soil resources and adjustments are made for the value of subsidies (economically, a mere transfer from one social group to another). In this case, given the sensitivity of farmer selection of technology to prevailing agricultural sector policies, the analysis was primarily aimed at policymakers.

This approach is relatively powerful but relies heavily on modeling future time paths for land quality and system productivity under different technology scenarios. Moreover, it explicitly links agricultural system output (Y) with near-term and longer-term costs associated with resource degradation (C, F) for well-defined technologies, and conceptually can include information on off-site costs (X). Unlike the TP approach, this one emphasizes net present values associated with discrete alternatives. Although future time paths for land quality and system productivity are generated, trend assessment as such is usually not carried out because (as in the previous approach) comparisons of benefits and costs feature their *difference*, not their *ratio*, again making it difficult to develop index numbers.

Present value of alternative land uses, adjusted for environmental degradation

This approach is similar to the previous one, except that it specifically focuses on alternative land uses and land use strategies (e.g., ecotourism versus agroforestry versus extensive livestock husbandry). As such, it is highly data intensive and, to a certain degree, speculative. Some studies of this kind have been developed for game reserves in Africa. As in the previous approach, projected time paths for economic and environmental costs and returns must be estimated for each alternative.

Technical measures of agricultural resource quality

Direct, technical measures of agricultural resource quality are the variables most commonly thought of as "indicators of sustainability". In the USAID-funded Sustainable Agriculture and Natural Resource Management Collaborative Support Program (SANREM CRSP), for example, the following are used as "sustainability markers" (University of Georgia, nd):

- *soil properties* (organic matter content, C, N, P, and S, cation and anion exchange capacities, base saturation, pH, water-holding capacity, infiltration rate, structural stability, mechanical strength);
- *biotic activity* (soil microbial respiration, weed and insect populations, crop disease incidence and severity, crop growth rates and yields);
- *hydrologic measures* (quantity of water runoff, depth of water table, changes in surface water storage); and
- *water quality measures* (sediment and nutrient loads, sequential *measure* of aquatic invertebrate community structure).

A similar list was formulated at a South Asian regional workshop on "measuring sustainability" held in Kathmandu (Harrington, Hobbs and Cassaday 1993)

As noted in an earlier section, technical measures of agricultural resource quality may be seen as tertiary indicators because of their influence on the components of TP, especially longer-term on-site economic costs associated with agricultural production (F). The word "tertiary" does not imply that these indicators are unimportant. It should be obvious that F and, as a consequence, TP cannot be estimated without a good understanding of the physical and biological processes that underlie resource degradation. Such an understanding requires that relevant technical measures be assessed in a time series. Moreover, an understanding of the *incidence* and *pace* of degradation, fundamental to setting priorities and assessing impacts of research on agricultural sustainability, also relies heavily on such technical measures.

Having said that, it should be noted that technical measures of agricultural resource quality are just one part of the information needed to assess total productivity. Clearly, to be most useful, technical measures of agricultural resource quality should:

- emphasize that relatively small set of variables to which F and TP are most sensitive,
- be measured in a time series,
- feature cause and effect links between measured resource quality changes and long-term resource productivity changes, and
- be relatively simple and inexpensive to implement.

It may be useful to repeat here an observation made earlier:

The usefulness of tertiary indicators (such as physical measures of resource degradation) hinges on their ability to faithfully track important components of total productivity. Similarly, the usefulness of combinations of secondary indicators hinges on their ability to unambiguously distinguish whether TP is increasing or decreasing.

Modeling land use trends using remote sensing and other secondary data

Although included as a measure of agricultural resource quality and system performance, the modeling of land use trends can go well beyond this. In essence, modeling can serve to explore the consequences (over space and over time) of changes in land use that are well understood at the plot or farm level. For example, if the following hold:

- a shift in weed species is known to be associated with land degradation (e.g., reduced moisture-holding capacity);
- this shift is known to be highly correlated with a decline in system performance of a particular magnitude;
- this change in weed species can be detected through remote sensing (rather improbable, actually); and
- remote sensing data are available in a time series,

then it may be possible to arrive at relatively precise calculations of trends in system performance and land quality for large areas -- at least with respect to this particular resource degradation process. A more obvious example might be the use of remote sensing time series data to track processes (and consequences) of on-going deforestation. Among others, the SANREM CRSP consortium aims to use remote sensing in its research sites for the purposes described above (University of Georgia nd), as does IFPRI for its work in the Central American hillsides consortium (IFPRI 1993).

Clearly, however, spatial and temporal extrapolation of sustainability indicators should not be confounded with the development itself of those indicators. These models are no substitute for information concerning TP and its components.

Indicators that emphasize environmental quality

The indicators described above (centered on the notion of total productivity) are based solidly on the agricultural production system. Resource degradation problems, their causes, possible solutions and the various effects these have on system performance are featured as primary, secondary or tertiary indicators. They take account of external environmental degradation (not necessarily caused by agriculture) as a factor that may influence output and/ or input use and management practices (to compensate for environmental change). The following measures take a more holistic view of the environment (Table 2).

The pressure-state-response model

In recent work on environmental indicators, several research groups have cooperated in developing a methodology based on the model of "pressure-state-response" (Adriaanse, 1993; IIE,1993; Winograd, 1993; USAID-WRI,1993). This model has much in common with the "problem-cause-solution" model described earlier in the section on categories of sustainability indicators. In this model, there are four groups of indicators.

1. *Pressures*. The first group of indicators deals with causes of environmental problems and is related to human activities that generate pressures on the environment (e.g., rates of population growth and increases in population pressure on resources).
2. *State*: The second group refers to the quality of the environment as a result of human actions, and is related to the state of the agricultural resources and the environment. One subset of this second group might comprise indicators of biodiversity and how it is affected by agriculture.[1]
3. *Responses*: The third group refers to the measures taken by society to improve the state of agriculture and the environment (e.g., policy decisions and responses, especially as they affect the decisions of rural producers and consumers).
4. *Progress*: Finally, indicators should also be employed to forecast and anticipate unsustainable development processes. Therefore, a fourth group of indicators is needed to describe progress made towards sustainability objectives. Arguably, this fourth set of indicators can be forged through analysis and forecasting of trends for categories one through three.

This set of indicators can be useful in diagnosing the current situation in relation to well-defined thresholds, and in designing policies based on objectives that will reorient actions and responses for the implementation of sustainable development. In this way, we will be able to examine the results of interventions and decide which policies should be created, reinforced or eliminated.

A need for short cuts: some approaches to developing proxy indicators

Estimation of total productivity and its components is clearly data intensive and costly. Despite their complexity, none of the approaches described above take into account *all* of the factors that go into TP trend assessments. The development of proxy indicators -- readily observed variables (possibly qualitative) that are correlated with TP or its

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[1] Indicators of biodiversity might involve:
a. monitoring populations of key wild species (this requires research into species as indicators, and cross disciplinary work to develop monitoring systems);
b. monitoring areas of natural vegetation, and the maintenance of habitat in agricultural areas (an example could be the maintenance of hedgerows in European agriculture);
c. monitoring of landraces and wild crop species relatives (research needs could include the estimation of minimum viable population sizes for *in situ* conservation, or the ecological identification and monitoring of areas for germplasm conservation); or
d. economic evaluation of the use of biodiversity (this can be viewed as the economic value of extraction of natural production, or the future value of germplasm for crop improvement).

components -- would make it possible for farmers and extension workers as well as researchers to participate in assessing sustainability trends. Proxy indicators may be developed for secondary and tertiary indicators. An incomplete listing of possible approaches to developing proxy indicators follows.

Yield trends

Crop yield trends may be useful as proxy indicators under some conditions. Certainly, a declining trend in yields (with no corresponding reduction in the use of inputs and no substantial allocation of enterprises to land quality classes) typically is seen as cause for alarm. In this case, any possibility of increasing off-site or environmental costs only reinforces the conclusion that the system is unsustainable. In other words, when Y decreases but C, F, X and E are either stable or increasing, TP will decline. Yield trend information is less useful when yields are rising but researchers suspect that changes in C, F, X or E are important. In this case, additional information must be brought to bear.

Data on yield trends are usually more likely to be available than other kinds of information. Not infrequently, yield data are the only secondary data available in a time series!

Readily observable results of resource degradation

In an earlier section, the importance of technical measures of changes in resource quality was noted. These technical measures are important for understanding the processes underlying resource degradation, and as an input for estimating F. It was noted, however, that many technical measures are complex and costly to implement, which makes it all the more difficult to develop time-series estimates.

At times, however, it may be possible to identify readily-observable resource quality variables. Obvious examples include the presence of rather marked effects of erosion (gullies, rills, siltation), or signs left by water-induced land degradation (e.g., salt deposits, signs left by waterlogging). Similarly, variables may be identified that are proxies for relatively complex land quality measurements, e.g., indicator weed and indigenous plant species that are particularly susceptible to (or tolerant of) well-defined changes in soil health. Threshold levels may be established at which these weeds or plants begin to emerge or predominate. It then becomes possible to make rapid surveys of villages or study areas and, by means of these indicators, arrive at a rough sense of the state and trends of resource quality and system performance. Note that these proxies are most useful when:

- the link between the proxy (e.g., indicator species) and the underlying variable (e.g., soil health) is well established,
- the effect of the underlying variable (e.g., soil health) is linked to changes in one or more components of total productivity, usually F,
- information on other components of TP is available.

Farmers' adaptations that mask degradation

Resource degradation does not always lead directly to a commensurate decline in system performance. Farming systems usually have some flexibility, allowing farmers to introduce adaptations that buffer the effects of degradation. Jodha (1989) notes, for example, that farmers in Nepal replace cattle with goats as fodder becomes scarce, and that in many areas farmers replace maize with sorghum as soil moisture-holding capacity declines. Similar examples may be found in the Cerrados area of Brazil, where *Panicum* grass gives way to *Brachiaria* as soil fertility deteriorates.

Information on farmers' use of adaptations can serve as proxy indicators. As in the previous case, cause and effect links need to be established between processes of degradation, the thresholds used by farmers for introducing selected adaptations, and implications for system performance (total productivity). In particular, researchers must be able to demonstrate that farmers' adaptations result from declining resource quality and not other factors, such as changes in market conditions.

Community-level assessment of causes of resource degradation

Resource degradation and declining total productivity are difficult to measure. However, when well-defined causal factors are highly correlated with these processes, it may be easier to track the *causes* than the *effects*, particularly when participatory methods can be used. For example, community-level assessment might be used to estimate:

- increases in rates of in-migration (affecting population pressure on resources and soil erosion);
- changes in crop residue management or rates of organic matter application to farm fields (affecting soil fertility);
- changes in livestock populations and farm yard manure production, per unit of cultivated land (affecting soil fertility) (Harrington et al.1990);
- changes in farm household income and wealth levels (affecting farmers' ability to invest in specific resource-conserving techniques, or to postpone consumption) (Anderson and Thampapillai 1990);
- changes in the per capita availability of common property resources, or changes in the way these are managed within the community (affecting assets available to the very poor and therefore pressures on marginal resources) (Jodha 1991);
- changes in the local implementation of water pricing policies (affecting rates of groundwater depletion); or
- changes towards less diverse cropping systems (affecting buildup of pests, diseases, or weeds).

For this approach to be feasible, a reliable link must be forged between the causal factor and the degradation process (not always easy), and identification of the causal factor itself must be amenable to assessment through participatory methods at the community level (see Lightfoot et al.1992 or Mishra et al.1992 for a discussion of these methods).

Farmer adoption of resource-conserving practices

At times, information on farmer adoption of resource-conserving practices may be used to infer changes in the pace and incidence of resource degradation and changes in TP. For example, when maize and sorghum stover in hillside systems in Central America is no longer burned, but rather is left as a mulch cover on the soil surface, consistent and dramatic reductions are observed in rates of soil erosion (Tripp et al.1993, Bravo Espinoza et al.1993, van Nieuwkoop 1993). Moreover, when farmer adoption of land-conserving practices can be detected through remote sensing, these indicators can be used over relatively large areas at a minimal cost. Of course, a link between technology adoption, longer-term economic costs (F) and total productivity must be established. Once this is in place, however, monitoring farmer adoption can be used to estimate the pace and incidence of degradation, and progress made towards reversing it.

Caution is needed, however, to avoid the use of circular arguments. Sometimes, certain techniques are defined *a priori* as being "sustainable", without being analyzed for effects on total productivity or its components. To the extent that these techniques are adopted, agricultural systems are *said* to become more sustainable. For example, it may be claimed that a particular system is more sustainable when the use of external inputs is reduced, because conventional wisdom asserts that reduced input use fosters sustainability. Circular arguments of this kind should be avoided.

Farmer participatory resource mapping

It has been shown that farmer groups are capable of constructing maps of their local community that display considerable power and insight (Chambers 1992, Lightfoot et al.1989). Maps of this kind can be made to focus on the agricultural resource base, with map symbols corresponding to land quality categories described in local terms. Then, longtime village residents can be asked to draw a series of maps, each one showing standard land quality categories as they were at specified times in the past. This provides a time series whereby trends in resource quality can be approximated. In addition, the performance characteristics of the different land quality categories can be ascertained[2], and implications for overall trends in agricultural system performance can be inferred.

Results of participatory resource mapping should be calibrated with technical measures of land quality and total productivity. In particular, caution should be used to minimize memory bias. Note that resource mapping can be used to cover relatively large areas reasonably quickly when remote sensing data are unavailable, or when secondary data in general are either unavailable or unreliable (Gill 1992).

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[2] Farmers' terms for land categories often refer fairly explicitly to land productivity under different circumstances, e.g., "holds water a long time and is good for traditional rice" (Fujisaka 1991).

Farmer participatory appraisal using cohort analysis

Different groups of farmers within an ecoregion often have different lengths of experience with a production technique or a land management strategy. When this is the case, perceptions from more experienced farmers (and observations taken from their fields) can be useful in forecasting changes that other farmers will likely face sooner or later. In the Nepal terai, for example, it was found that farmers having only recent experience with intensive rice-wheat systems were enthusiastic about improvements in system performance associated with the introduction of modern inputs. Farmers with longer experience, however, were more concerned with stagnating system productivity despite ever-higher levels of those inputs (Harrington et al.1990). Differences of this kind can serve as indicators when calibrated with measures of TP and resource quality. Note that care must be taken with the approach because early innovators do not have the advantage of their neighbors' accumulated knowledge. Later adopters may manage early steps in the time path better as a result.

Towards a research agenda for the development of sustainability indicators

The notion of total productivity is helpful in operationalizing the concept of sustainability because it links agricultural resource quality, off-site externalities, and environmental effects with the performance and productivity of agricultural systems. Moreover, it helps research managers and policymakers to set priorities and assess impacts because it allows them to define and, to a certain extent choose, the nature and incidence of costs associated with meeting increased demands for agricultural products. Technology development and policy change can influence, to a certain degree, the relative importance of environmental, external, and longer-term economic costs in agricultural development.

It should be recognized, of course, that total productivity is not a perfect indicator of sustainability. Estimates of past TP trends may shed little light on future sustainability if resource degradation accelerates (increasing economic and environmental costs) while productivity growth stagnates (slowing growth in the value of output). Moreover, TP does not *explicitly* take account of the concept of irreversibility, although this should *implicitly* enter in the costs assigned to different kinds of resource degradation or environmental impacts. Nonetheless, TP serves as a useful conceptual framework in linking most important concepts and -- equally important -- pointing out where additional research is needed.

Research on sustainability indicators that uses the notion of total productivity should emphasize a number of themes, including the following:

1. Development, adaptation and use of methods for measuring and valuing the off-site economic and environmental costs associated with different agricultural practices. Considerable progress has been made in the development of methods for valuing environmental assets (Winpenny 1991, Pearce 1993, Munasinghe 1993), but these are

not commonly employed in comparisons of agricultural technologies. Environmental measurement and valuation tools generally are not well known in agricultural research institutions.

2. Development, adaptation and use of methods for assessing the long-term effects of resource degradation on the productivity of agricultural systems, particularly the time paths associated with degradation-productivity links. A number of alternative approaches may be explored, including long-term trials, farmer monitoring, modeling, participatory assessment, use of remote-sensing data in a time-series, substitution of cross-section for time-series information, etc.. While most of these approaches are not new in themselves, they have not typically been used to generate information useful for estimating total productivity.
3. Development, adaptation and use of methods for assessing the spatial incidence of resource degradation problems, including information on the pace, causes and possible solutions for these problems. GIS must be more vigorously used as an instrument for organizing and using information relevant to total productivity and its components.
4. Development of ways to link estimates of TP and its components with the broad developmental issues with which we are all concerned -- poverty, population growth, income and employment generation, food security, and quality of life.
5. Development of ways to firmly link proxy indicators (including but not restricted to the proxy indicators discussed above) with specific components of total productivity. This will allow wider participation in sustainability assessments, in the context of a sensible conceptual framework. In this way, proxy indicators can help operationalize the concept of sustainability -- in the context of a total productivity approach.

Adriaanse A.,1993. "Environmental Policy Performance Indicators, General of Environment of the Dutch Ministry of Housing, Physical Planning and Environment (VROM)". The Hague, Netherlands.

Anderson, J. and J. Thampapillai, 1990. *Soil Conservation in Developing Countries: Project and Policy Intervention.* Policy and Research Series. Washington, DC: World Bank.

Batie, S., 1989. "Sustainable Development: Challenges to the Profession of Agricultural Economics". Presidential Address, AAEA Summer Meeting 1989, Baton Rouge, Louisiana, July 30 - August 2, 1989.

Bravo Espinosa, M., J.L. Jimenez V. and Martien van Nieuwkoop, 1993. "Avances de la Investigacion en Sistemas de Labranza de Conservacion en la Region Mixteca Oaxaquena, Mexico". Unpublished draft.

Capalbo, S. and J. Antle (eds.), 1988. *Agricultural Productivity: Measurement and Explanation.* Washington, D.C.: Resources for the Future. 404 pages.

Chambers, R. 1992. "Methods for Analysis by Farmers: The Professional Challenge." 11 September 1992. Presented at the 12th Annual Farming Systems Symposium, Michigan State University, 13-18 September, 1992.

CIMMYT, 1989. *Toward the 21st Century: Strategic Issues and Operational Strategies of CIMMYT.* Mexico, DF: International Maize and Wheat Improvement Center.

Colacicco, D., T. Osborn and K. Alt, 1989. "Economic damage from soil erosion". *Journal of Soil and Water Conservation.* January-February, 1989.

Conway, G., 1986. *Agroecosystem Analysis for Research and Development.* Bangkok: Winrock International.

Crosson, P., 1992. "Sustainable Food and Fiber Production". Presented at the annual meeting of the American Association for the Advancement of Science, Chicago, February 9, 1992.

Crosson, P. and J. Anderson, 1993. “Incorporation of Natural Resource and Environmental Issues in the Research Agenda of NARSs”. A Report to ISNAR. Unpublished draft.

Ehui, S. and D. Spencer, 1990. "Indices for Measuring the Sustainability and Economic Viability of Farming Systems". Resource and Management Program Research Monograph No. 3. Ibadan: IITA.

Faeth, P., R. Repetto, K. Kross, Q. Dai and G. Helmers, 1991. *Paying the Farm Bill: US Agricultural Policy and the Transition to Sustainable Agriculture.* Washington, DC: World Resources Institute. 70 pages.

Gill, G., 1993. "O.K., The Data's Lousy, But Its All We've Got (Being a Critique of Conventional Methods)". International Institute for Environment and Development. Gatekeeper Series No. 38.

Harrington, L., 1993. "Sustainable Agriculture for Uplands in Asia: Direct vs. Preventive Contributions of New Technology". Invited paper for the CGPRT Centre regional seminar "Upland Agriculture in Asia". Bogor, Indonesia, April 6-8 1993.

Harrington, L., P. Hobbs, T. Pokhrel, B. Sharma, S. Fujisaka, and C. Lightfoot, 1990. "The Rice-Wheat pattern in the Nepal Terai: Issues in the Identification and Definition of Sustainability Problems". *Journal for Farming Systems Research-Extension.* 1(2):1-27.

Harrington, L., P. Hobbs and K. Cassaday (eds.), 1993. *Methods of Measuring Sustainability Through Farmer Monitoring: Application to the Rice-Wheat Cropping Pattern in South Asia.* Proceedings of a Workshop, 6-9 May 1992, Kathmandu, Nepal. Mexico City: CIMMYT.

IFPRI, 1993. "Policy Research for Sustainable Intensification of the Central America Hillsides". A Proposal to the Inter-American Development Bank (IDB). May, 1993.

IIE (Instituto de Investigaciones Economicas), 1993. "Principales Problemas que Afectan el Desarrollo Sostenible en America Latina y el Caribe con Enfasis en los Sectores Agricola y de Recursos Naturales". Consultoria para el Proyecto IICA/GTZ, Documento Borrador, IIE-Universidad de Costa Rica, San Jose, Costa Rica.

Jodha, N. S., 1991. "Rural Common Property Resources: A Growing Crisis". International Institute for Environment and Development. Gatekeeper Series No. SA24.

Jodha, N. S., 1989. "Mountain Agriculture: Search for Sustainability". Presented at the International FSR/E Symposium, Fayetteville, Arkansas, October 9-12 1989.

Lightfoot, C., N. Axinn, P. Singh, A. Bottrall and G. Conway, 1989. *Training Resource Book for Agroecosystem Mapping.* Process documentation of an experiential learning exercise in agroecosystem mapping held at Rajendra Agricultural University, Pusa, Samastipur, Bihar, India, March 1989. IRRI and Ford Foundation.

Lightfoot, C., Dalsgaard, P., Bimbao, M., and Fermin, F. 1992. Farmer Participatory Procedures for Managing and Monitoring Sustainable Farming Systems. Unpublished draft.

Lurie, T., 1991. "Saving the Forests: India's Experiment in Cooperation". *The Ford Foundation Letter*. Spring/Summer 1991. Vol. 22, No. 1, pp. 1-5, 12-13.

Lynam, J. and R. Herdt, 1988. "Sense and Sensibility: Sustainability as an Objective in International Agricultural Research" CIP-Rockefeller Conference on Farmers and Food Systems. Lima: CIP.

McCracken, J., and G. Conway, 1987. "Pesticide Hazards in the Third World: New Evidence from the Philippines". International Institute for Environment and Development. Gatekeeper Series No. SA1.

Mishra, P.R., Bottrall, A.F., and John, K.C. 1992. "Beyond FSR/E: Designing Sustainable Farming Systems in a Fragile Upland Environment in Eastern India." Presented at the Asian Farming Systems Symposium, Colombo, Sri Lanka, 2-5 November 1992.

Munasinghe, M. (ed.), 1993. *Environmental Economics and Natural Resource Management in Developing Countries*. Washington, DC: World Bank. 307 pages.

Pearce, D., 1993. "Valuing the Environment: Past Practice, Future Prospect". Prepared for the First Annual International Conference on Environmentally Sustainable Development, World Bank, Washington DC, September 30 - October 1, 1993.

Poleman, T., 1989. "Hunger or Plenty? The Food/ Population Prospect Two Centuries after Malthus". Cornell Agricultural Economics Staff Paper 89-30. Cornell University.

Repetto, R. and M. Gillis (ed.), 1988. *Public Policies and the Misuse of Forest Resources*. A World Resources Institute Book. Cambridge University Press, 432 pages.

Robey, B., S.O. Rutstein and L. Morris, 1993. "The Fertility Decline in Developing Countries". Scientific American. December, 1993, pp. 60-67.

Tripp, R., D. Buckles, M. van Nieuwkoop and L. Harrington, 1993. "Land Classification, Land Economics and Technical Change: Awkward Issues in Farmer Adoption of Land-Conserving Technologies". Presented at the "Seminario para la Definicion de una Metodologia de Evaluacion de Tierras para un Agricultural Sostenible en Mexico", El Batan, Mexico, August, 1993.

TSC and WRI, 1992. *Accounts Overdue: Natural Resources Depreciation in Costa Rica*. Washington, D.C.: Tropical Science Center and World Resources Institute.

UACP, 1987. Farming Systems Research: Upland Agriculture and Conservation Research Highlights, 1985-86. Ministry of Agriculture, Agency for Agricultural Research and Development. Indonesia.

University of Georgia, (nd). "A Landscape Approach to Sustainability in the Tropics". The Global Plan for the SANREM CRSP Submitted by a Consortium Led by the University of Georgia.

USAID and WRI, 1993. *Green Guidance for Latin America and the Caribbean.* Bureau for Latin America and the Caribbean, United States Agency for International Development and the Center for International Development and Environment, World Resources Institute, Washington, D.C..

van Nieuwkoop, M., 1993. "Sintesis de los Estudios de Diagnostico Realizados Dentro del Proyecto 'El Sistema de Labranza de Conservacion in Maiz de Temporal' durante el Ciclo PV-92." CIMMYT Economics Program, Mimeo.

Whitaker, M. and S. Lalitha. 1993. "Quantifying the Relative Productivity and Sustainability of Alternative Cropping Systems." ICRISAT, India. April 1993.

Winograd, M. 1993. *Environmental Indicators for Latin America and the Caribbean: Toward Land Use Sustainability.* Ecological Systems Analysis Group in collaboration with Project IICA/GTZ, Organization of American States and World Resources Institute, Washington, DC (in press).

Winpenny, J., 1991. *Values for the Environment: A Guide to Economic Appraisal.* London: HMSO. 277 pages.

Appendix Table 1. Hypothetical yield, benefit and cost data set for T1

Year	Yield T1 (kg/ha)	Gross Returns ($/ha)	On-site near-term costs ($/ha)	External costs ($/ha)	Environ-mental costs ($/ha)	Total costs ($/ha)
1	1400	3500	1000	100	200	1300
2	1312	3280	1000	105	206	1311
3	1262	3155	1000	110	212	1322
4	1222	3055	1000	116	219	1334
5	1187	2968	1000	122	225	1347
6	1152	2880	1000	128	232	1359
7	1127	2818	1000	134	239	1373
8	1102	2755	1000	141	246	1387
9	1082	2705	1000	148	253	1401
10	1062	2655	1000	155	261	1416
11	1052	2630	1000	163	269	1432
12	1042	2605	1000	171	277	1448
13	1038	2595	1000	180	285	1465
14	1030	2575	1000	189	294	1482
15	1024	2560	1000	198	303	1501
16	1014	2534	1000	208	312	1519
17	1004	2509	1000	218	321	1539
18	994	2484	1000	229	331	1560
19	984	2459	1000	241	340	1581
20	974	2435	1000	253	351	1603
21	964	2410	1000	265	361	1627
22	954	2386	1000	279	372	1651
23	945	2362	1000	293	383	1676
24	935	2339	1000	307	395	1702
25	926	2315	1000	323	407	1729
26	917	2292	1000	339	419	1757
27	908	2269	1000	356	431	1787
28	899	2246	1000	373	444	1818
29	890	2224	1000	392	458	1850
30	881	2202	1000	412	471	1883

Appendix Table 2. Hypothetical yield, benefit and cost data set for T2

Year	Yield T2 (kg/ha)	Gross returns ($/ha)	On-site costs ($/ha)	External costs ($/ha)	Environ-mental costs ($/ha)	Total costs ($/ha)
1	1400	3500	1000	100	200	1300
2	1400	3500	1000	101	201	1302
3	1400	3500	1000	102	202	1304
4	1400	3500	1000	103	203	1306
5	1400	3500	1000	104	204	1308
6	1400	3500	1000	105	205	1310
7	1400	3500	1000	106	206	1312
8	1400	3500	1000	107	207	1314
9	1400	3500	1000	108	208	1316
10	1400	3500	1000	109	209	1319
11	1400	3500	1000	110	210	1321
12	1400	3500	1000	112	211	1323
13	1400	3500	1000	113	212	1325
14	1400	3500	1000	114	213	1327
15	1400	3500	1000	115	214	1329
16	1400	3500	1000	116	216	1332
17	1400	3500	1000	117	217	1334
18	1400	3500	1000	118	218	1336
19	1400	3500	1000	120	219	1338
20	1400	3500	1000	121	220	1341
21	1400	3500	1000	122	221	1343
22	1400	3500	1000	123	222	1345
23	1400	3500	1000	124	223	1348
24	1400	3500	1000	126	224	1350
25	1400	3500	1000	127	225	1352
26	1400	3500	1000	128	227	1355
27	1400	3500	1000	130	228	1357
28	1400	3500	1000	131	229	1360
29	1400	3500	1000	132	230	1362
30	1400	3500	1000	133	231	1365

Appendix Table 3. Changes in yields, output value and total costs between T2 and T1.

Year	Yield T1 (kg/ha)	Yield T2 (kg/ha)	Yield change T2-T1 (kg/ha)	Change in output value ($/ha)	Total costs T1 ($/ha)	Total costs T2 ($/ha)	Change in total costs T2-T1 ($/ha)
1	1400	1400	0	0	1300	1300	0
2	1312	1400	88	220	1311	1302	-9
3	1262	1400	138	345	1322	1304	-18
4	1222	1400	178	445	1334	1306	-28
5	1187	1400	213	533	1347	1308	-39
6	1152	1400	248	620	1359	1310	-49
7	1127	1400	273	683	1373	1312	-61
8	1102	1400	298	745	1387	1314	-72
9	1082	1400	318	795	1401	1316	-85
10	1062	1400	338	845	1416	1319	-98
11	1052	1400	348	870	1432	1321	-111
12	1042	1400	358	895	1448	1323	-125
13	1038	1400	362	905	1465	1325	-140
14	1030	1400	370	925	1482	1327	-155
15	1024	1400	376	940	1501	1329	-171
16	1014	1400	386	966	1519	1332	-188
17	1004	1400	396	991	1539	1334	-205
18	994	1400	406	1016	1560	1336	-224
19	984	1400	416	1041	1581	1338	-243
20	974	1400	426	1065	1603	1341	-263
21	964	1400	436	1090	1627	1343	-284
22	954	1400	446	1114	1651	1345	-305
23	945	1400	455	1138	1676	1348	-328
24	935	1400	465	1161	1702	1350	-352
25	926	1400	474	1185	1729	1352	-377
26	917	1400	483	1208	1757	1355	-403
27	908	1400	492	1231	1787	1357	-430
28	899	1400	501	1254	1818	1360	-458
29	890	1400	510	1276	1850	1362	-487
30	881	1400	519	1298	1883	1365	-518