

Valuing Nutrients in Soil and Water

Concepts and Techniques with Examples from IWMI Studies in the Developing World

Pay Drechsel, Mark Giordano and Lucy Gyiele



Research Reports

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Research Report 82

**Valuing Nutrients in Soil and Water:
Concepts and Techniques with Examples
from IWMI Studies in the Developing World**

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Summary

The value of soil nutrients in plant growth and agricultural output is closely related to water availability. Likewise, agricultural water productivity is in large part determined by nutrient supplies. Despite the importance of nutrient-water interactions, they are often ignored in analysis. For example, assessments of the benefits of irrigation often fail to consider the costs of increased nutrient export through greater crop harvest while the value of nutrient import is often neglected in discussions of wastewater agriculture. It is only through the combined and balanced consideration of nutrients and water that their true value can be measured and accurate assessments of the relative benefits and costs of various agricultural land and water management options can be assessed. However, to conduct such an analysis it is essential to have methods for valuing soil nutrients. The primary goal of this report is to provide descriptions of some of those methods and some examples of their application.

After discussing the interrelationships between soil nutrients and water and reviewing methods for determining nutrient balances, this report

describes an array of available methods for soil nutrient valuation (the Replacement Cost Approach, the Productivity Change Approach, Willingness-to-Pay, Hedonic Pricing and Total Factor Productivity) and provides a discussion of four nutrient valuation studies, which together cover a range of scales, perspectives, and geographic contexts. The case studies, based on previous work from the International Board for Soil Research and Management (IBSRAM) and the International Water Management Institute (IWMI), include a comparison of the costs of nutrient mining in two Ghanaian farming systems, a valuation of nutrients in wastewater irrigation in Mexico, a continental assessment of nutrient depletion costs in sub-Saharan Africa, and an examination of possible approaches to valuing soil organic matter and its various functions—an often ignored area in literature. The report concludes with a synthesis of the advantages and limitations of the two analytical approaches most commonly used in developing countries, considerations for choosing between them and their usefulness for future research.

Valuing Nutrients in Soil and Water: Concepts and Techniques with Examples from IWMI Studies in the Developing World

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Introduction

Soil fertility is one of the key factors in determining agricultural output, and soil fertility depletion is seen as the most important process in the land degradation equation and a primary constraint to improving food security in developing countries. In the African context, for example, soil nutrient depletion is the main biophysical factor limiting increases in per capita food production for the majority of small farms (Sanchez et al. 1997), and even in the relatively dry Sahel region, it is often the supply of nutrients, not water, which limits farm productivity (Penning de Vries and Djiteye 1982; Breman 1998). Soil nutrients are also a primary, though often ignored, factor determining the costs and benefits of agricultural water management interventions and water productivity. For example, while irrigation typically increases crop yield, it also increases nutrient exports through harvest removal and leaching. Conversely, wastewater irrigation as commonly practiced in many developing countries may have negative health impacts but can also provide valuable crop nutrients.

Despite the obvious importance of understanding soil nutrient value in agricultural land and water management, there has been little focus in the literature on methods for its economic assessment. As a result, the true value

of nutrients and nutrient change remains unclear, making the provision of practical and cost-effective nutrient management solutions to farmers and governments more difficult, and complicating the targeting of research for resource conservation and development. Recognizing this problem, the Soil, Water, and Nutrient Management (SWNM) Programme of the Consultative Group on International Agricultural Research (CGIAR) and the former International Board for Soil Research and Management (IBSRAM) took the initiative to develop a framework for the economic assessment of nutrient depletion (Drechsel and Gyiele 1999). IBSRAM's later merger with the International Water Management Institute (IWMI) both highlighted the need to jointly consider nutrients and water in research and development agendas and created the opportunity and impetus to thoroughly revise and update the original IBSRAM work. This report is one result of that opportunity.

The report begins with an overview of the physical and economic interconnection between soil nutrient and agricultural water availability. It then describes concepts and techniques for deriving and interpreting the basic physical data—the nutrient balance—needed in many nutrient valuation studies before turning to the

primary subject: methods for the economic valuation of soil nutrients. A range of available valuation methods is described, including the more commonly applied Replacement Cost and Productivity Change Approaches (RCA and PCA) as well as the less frequently used Willingness-to-Pay, Hedonic Pricing and Total Factor Productivity methods. The practical application of some valuation techniques are then illustrated

through a description of four case studies, drawn directly from IBSRAM/IWMI research, which together cover a range of scales, perspectives, and geographic contexts. The paper concludes with a discussion of the relative merits of the various valuation approaches discussed, offers considerations for choosing between the most common approaches, and provides suggestions for future research and analysis.

Linkages between Soil Nutrients and Agricultural Water Use

The linkages between soil nutrients and agricultural water use are many but might be best conceptualized by considering their potential for positive and negative reinforcement. On the positive side, water can increase the ability of plants to use soil nutrients and, vice versa, nutrients can increase the ability of plants to convert water into crop output. For example, water is a prerequisite for soil-supplied nutrient uptake by plants, and soil water content is the single most important factor controlling nutrient uptake rates as well as other chemical and biological processes such as mineralization. Likewise, water can only be used by plants if nutrient availability is sufficient. Work in Africa's Sahel region highlights this point. There it has been shown that often only 10 to 15 percent of rainwater is used for plant growth. The rest is "lost" through runoff, evaporation and drainage, largely because crops cannot use it due to lack of nutrients for sufficient (root) growth (Penning de Vries and Djiteye 1982).

On the negative side, nutrient and water application can destabilize the soil nutrient balance and have long-term negative impacts on

crop growth and harvest. Over-fertilization can limit the ability of water to contribute to crop growth by causing salinization and damage to soil structure. Likewise, irrigation can cause nutrient depletion through leaching. Further, while irrigation can increase yields in part by making soil nutrients plant-available in the short-term, it can indirectly contribute to soil fertility decline in the long term through the increased harvest removals made possible by higher production. These nutrient losses can only be compensated for by increases in nutrient inputs.

However, the interaction between soil nutrients and water is not only a biophysical one. It is also economic and has obvious implications for farm economics and sustainability, analysis of alternative agricultural management options and investments, water productivity and decision-making on water allocation. Despite their interrelationship, research projects and agricultural management interventions in which nutrient and water balances are jointly considered are rare. This may partly be due to the fact that tools for valuing soil nutrients—the focus of the remainder of this paper—receive relatively little attention.

Measuring Soil Nutrients and Nutrient Change

In order to value soil nutrients, it is essential to be able to measure either the nutrients themselves or their change over time. The classical approach for monitoring soil nutrient change, as applied to management intervention, is the analysis and comparison of soil fertility parameters between different soil treatments, preferably over several seasons or years. However, experiments that can measure such parameters are costly, and the selection of analytical techniques that measure changes in the most relevant soil nutrient stocks or reserves can be difficult (cf. Greenland 1994; Pieri 1992, 1995). Alternatively, soil can be considered as a “black box” from which nutrient inflows (e.g., precipitation, irrigation, fertilizer, and manure) and outflows (e.g., erosion, harvest, leaching, and burning) are compared. Simply subtracting the nutrient outputs from the nutrient inputs allows the calculation of a nutrient balance. A negative nutrient balance shows a net export from the system while a positive balance indicates net nutrient import. Thus the nutrient balance can be considered both as a land-quality indicator describing soil fertility change under a given natural or managed regime as well as a simple entry point for the economic assessment of soil nutrient change.

The nutrient balance approach was first used in Africa, but is increasingly being applied elsewhere (Craswell et al. 2004). A milestone in the application of the technique was the quantification of nutrient depletion by land-use class at national and sub-continental scales in sub-Saharan Africa (Stoorvogel and Smaling 1990). The resulting report, the first of its kind, described the balances of the three major nutrients—nitrogen (N), phosphorous (P) and potassium (K). The study gave birth to a range of further studies, focusing primarily on farm-level estimates of nutrient flows and budgets. Various authors have since used nutrient balance

calculations in decision-support models to monitor the effects of changing land-use practices. Among these models, NUTMON (box 1) is widely known and has proven to be an adaptable instrument for nutrient monitoring (Smaling and Fresco 1993; Vlaming et al. 2001).

Nutrient balance models such as NUTMON are also valuable when using data obtained from a site or set of sites to extrapolate or “scale-up” to larger areas (Stoorvogel and Smaling 1998; Brand and Pfund 1998). However, there are limitations inherent to any such aggregation (Syers 1996; Scoones and Toulmin 1998). Two primary issues are the representativeness of sample site(s) and the applicability of data collected at one scale (geographic or temporal) in representing processes, which may occur at broader scales. As a simple example of the representation problem, one field may have a net nutrient loss (e.g., an eroded upper slope) while a nearby field (e.g., lower slope) has a gain (see also box 2). Unless both areas are given some form of proportional representation in samples, extrapolation will bias results. As an example of the potential for scaling-up problems, measurements taken at the plot level may ignore interactions which occur at larger farming system scales such as livestock induced nutrient movement between grazing zones and crop land (box 2). Similarly, measurements taken on a seasonal or annual basis may ignore longer term processes impacting nutrient balances such as those related to crop marketing and fallows.

Efforts to measure nutrient balances are helped by an understanding of the various processes and their relative magnitudes, through which nutrient change occurs in particular farming systems or regions. Figure 1 illustrates the relative importance of various nutrient-depleting processes as measured in sub-Saharan Africa (SSA). While it is commonly believed that the largest source of nutrient loss is erosion, the

Box 1. NUTMON.

NUTMON (<http://www.nutmon.org/>) is an integrated, multi-disciplinary model which targets various actors involved in the process of managing natural resources in general and soil nutrients in particular. Using the NUTMON methodology, farmers and researchers can jointly analyse nutrient flows and balances to improve soil fertility management. NUTMON software can be used to analyze nutrient balances at the farm, regional, national, and supra-national levels and can be useful in understanding the effects of current and alternative land use options on productivity, farm finances and sustainability. The model uses a combination of primary data, transfer functions and assumptions to generate the required information.

The NUTMON Toolbox version 2.0 goes significantly beyond earlier versions presented by Smaling and Fresco (1993) and considers the major nutrient inflows and outflows (erosion, leaching, harvest, fertilization, atmospheric deposition, etc.) in addition to interactions with livestock and human activities such as household waste recycling. Nutrient inputs through wastewater, for example, can be added to those entering the system via precipitation.

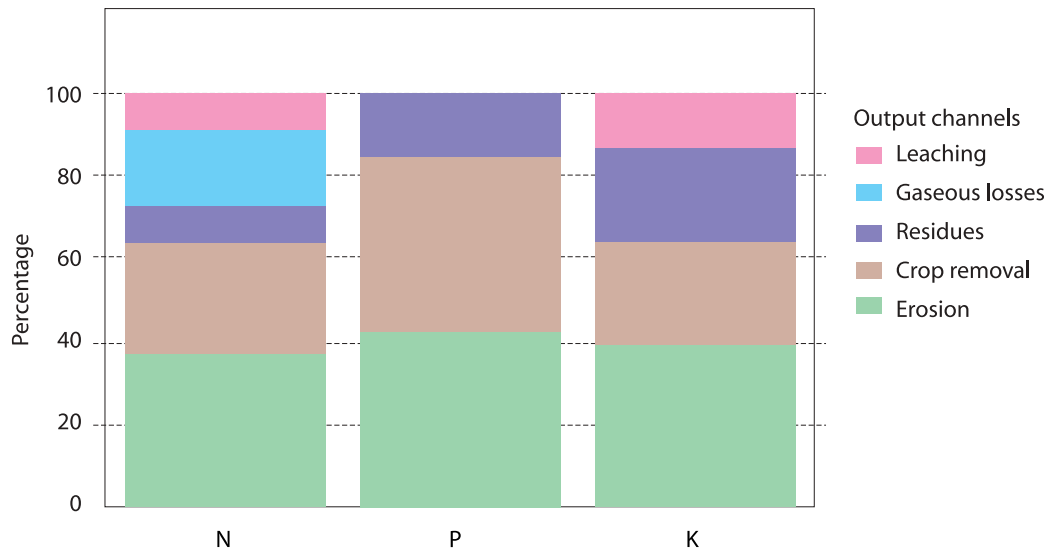
NUTMON is also a useful tool to supplement water-biased yield gap studies. Estimates of the amount of water needed to reach “optimal” yields often overlook the impact of additional water on nutrient depletion. Using NUTMON, the translation of yield increase to nutrient export can easily be seen as can the impacts of leaching. The utility of NUTMON has been further improved through its use in participatory research and as a simple device to encourage debate and dialogue among farmers and scientists (Defoer et al. 1998).

Box 2. Spatial variability in nutrient balances.

Variability across Fields: Spatial variability is a common pillar of indigenous nutrient conservation in East and West Africa. Farmers tend to plant nutrient demanding crops on more fertile patches such as ash piles and termite mounds, where organic inputs have been applied, or near homesteads where crops are better protected against thieves and animals, and where transportation distances are shortest. In these areas, the most valuable (cash) crops are typically produced (Nwafor 1979; Prudencio 1993; Quansah et al. 2001), and nutrient balances tend to be close to positive (Smaling and Braun 1996) in contrast to other farmed land. Developing an accurate picture of farm-scale nutrient balances clearly requires an understanding of the variation in balances at the field scale.

Cross Scale Processes: In a case study from Burkina Faso, the flows of nitrogen (N) and phosphorous (P) for both single fields and a village territory were assessed (Krogh 1997). The results suggested that while N and P are lost from fields, balances within the boundaries of the village territory or “village production system” were only marginally negative, indicating that cultivation was more sustainable than had been thought by other researchers. Similar results were found in a study from Kenya (Vlaming et al. 1997). In both cases, subsistence farmers were able to compensate for on-farm nutrient losses from the removal of harvested products through the input of manure derived from grazing off-farm on communal pastures. In these examples, the processes of relevance occurred at the scale of the village territory and would be missed by smaller, field-scale measurements.

FIGURE 1.
Composition of N, P and K outputs on rain-fed soils of sub-Saharan Africa.



Source: Data from Stoorvogel and Smaling (1990).

Note: The figure summarizes all output data provided by Stoorvogel and Smaling (1990) under various FAO land/water classifications for rain-fed land in SSA.

figure shows that loss through harvest and crop residue removal can be in fact of a similar magnitude. The consideration of crop and crop-residue removal in nutrient balances may be especially important where land pressure does not permit long fallow periods, for example, in the

East African Highlands (Drechsel et al. 2001a). The point is that making an effort to understand the processes at work at the location and scale of interest will increase the likelihood that scarce resources, and then management interventions, can be profitably targeted.

Economic Valuation of Nutrients and Nutrient Change

This chapter outlines the main economic techniques which have been (or could be) used to value soil nutrients and nutrient change. It first discusses two relatively simple methods, the Productivity Change Approach (PCA) and the Replacement Cost Approach (RCA). Of all methods, these two have been the most commonly applied in the economic evaluation of soil services, especially as related to developing

countries (cf. Grohs 1994; Enters 2000; Bojö 1996). While these techniques are relatively well known, this chapter adds information on areas where the literature remains thin, including possible adjustments to the RCA for nutrient availability and fertilizer efficiency. The chapter then describes some of the possible alternatives to these approaches including Hedonic Pricing, Contingent Valuation and Total Factor Productivity.

Despite the number of possible approaches, applied nutrient valuation studies have been relatively limited, especially in developing countries, and those which do exist are usually focused on erosion—the most visible nutrient depleting process. One factor in explaining the overall low number of studies is the fact that the costs of soil degradation as well as the benefits of soil conservation are inherently difficult to quantify. This is true in part because of the potentially long time-scales involved, but also because of the substantial variation in values between locations. For example, the value of a unit of nutrients (e.g., 1 kg of nitrogen) may differ considerably depending on its local biochemical availability to plants and its impact on plant production; the financial returns of that production at a given point in time; and the remaining nutrient stocks in the soil. While there are no valuation techniques that can overcome these problems, it has been suggested (cf. De Graaff 1996, modified) that the consideration of the following issues and questions will at least help guide the analyst in choosing a workable approach:

- The objective(s) and the user(s): Who needs the assessment and why? Which method fits best into the current decision-making process of the user(s) and their institution(s)? Which methods produce results that relate to the way of thinking of the user(s)?
- Evaluation criteria: Is the set of evaluation criteria (e.g., yield and nutrient balance) derived from the study objectives complete? Can the method produce results that are credible and relevant for these criteria?
- Method sensitivity: Can the evaluation method produce results that are objective, consistent and allow for a clear-cut comparison between management alternatives?

- Cost-effectiveness: What (amount of) data does the method require? Are these data assessable and at what cost? How many nutrient in- and output processes should be considered? Do the analytical costs match the value of the information?
- Scope: Given budget, time, human resource and data availability constraints, what is the appropriate scope of analysis and level detail? Should a simple or a more sophisticated method be applied? What margin of error is tolerable?

The Replacement Cost Approach (RCA): Valuing Input Costs

In developing countries, and perhaps more generally, the most common methodology for the economic assessment of soil nutrients specifically, as opposed to soil in general, is the RCA. The approach's popularity most likely stems from the fact that it is relatively simple to apply when nutrient loss data are available (Boj6 1996; Predo et al. 1997; Drechsel and Gyiele 1999). In essence, the RCA measures the costs that are or might be incurred to replace damaged or lost soil assets, such as nutrients (Grohs 1994), but could also be used to value nutrients gained through processes such as wastewater irrigation (for example see below "Valuing Nutrients from Wastewater Irrigation in Mexico: Contrasting Perspectives and Divergent Results").

The RCA is primarily used to assign monetary values to depleted soil nutrients. The value of the nutrients is typically calculated as the cost of purchasing a quantity of chemical fertilizer with a nutrient content equivalent to the quantity lost. Organic or local fertilizers, such as rock phosphate, are less often considered in replacement cost calculations, but could—

depending on farmers' actual practices—be more appropriate. RCA applications often only consider the actual cost of physical fertilizers, though additional labor and other costs of fertilizer application could and should be incorporated. Depending on the objective of the study, nutrients gained or lost through individual or multiple processes (e.g., only erosion and/or leaching and/or harvest) can be assessed using the RCA. Models which calculate net nutrient balances such as NUTMON (see box 1) are well suited to supplying the required physical data.

A key advantage in using the RCA is that market prices are usually available for at least some common nutrients, making assessments simple once the nutrient database is obtained. However, in applying input prices, caution must be used as the appropriate price to apply depends on the purpose of the analysis (see box 3). Local market prices might be appropriate to determine financial implications for farmers, while a world market price might be used to calculate societal impact at the national or international level. However, the impact of market conditions and policy distortions on price also needs to be carefully assessed and considered before drawing conclusions from any calculations. Further, special care should be used in determining

which nutrients are valued for “replacement”. Decisions to consider industrial fertilizers and fertilizer prices, information about which is generally easy to obtain, are not necessarily relevant when organic fertilizers are more abundant and cheaper, or new land is still available at no or low cost. In this context, other approaches are necessary (for example see below “The Costs of Nutrient Depletion in Kumasi, Ghana: An Example at the Farm Scale”).

As with any valuation method, the RCA suffers from some inherent limitations which should be considered on a case by case basis. For example, on the one hand, not all fertilizer applied is used by plants—a certain amount will be lost again—so the quantity needed for full replacement will be higher than that suggested in RCA calculations (see box 4 for possible solutions). On the other hand, soil nutrients may not be the (only) limiting factor in production, and so their loss may have no real economic value or a value less than the full replacement costs. Similarly, a significant portion of lost nutrients might themselves not have been plant-available (see box 4), and so there is no justification for putting a cost on their replacement. An especially important drawback of the RCA as normally applied is that it only places value on nutrients that can be easily replaced. It does not, for

Box 3. Economic versus financial analysis.

Economic analysis differs from financial analysis in three primary ways. First, economic analysis considers “social” costs and benefits whereas financial analysis considers costs and benefits from the perspective of specific individuals or groups. Distortions induced by regulations, subsidies, overvalued currencies and market imperfections all give rise to differences in economic and financial costs and reduce the applicability of market prices for valuing inputs and outputs for economic analysis. For example, with respect to soil nutrient analysis, tariffs and subsidies can cause considerable differences between domestic and international fertilizer and crop prices. Second, when discounting is involved in analysis, the appropriate “social” and “private” rates can differ, with social rates typically lower reflecting a longer term perspective on resource value (see box 6). Third, externalities or off-site costs and benefits are typically ignored in financial analysis while they are an integral part of economic analysis (Enters 1998; Barbier 1998).

Box 4. Adjustments for nutrient availability.

Standard RCA calculations value all nutrients lost from a site even though the entire quantity may not have been of relevance for plant production. To compensate for this problem, adjustments can be made for actual nutrient availability (Bishop and Allen 1989). Such adjustments are particularly important for assessments of eroded soil materials. For example, Bishop and Allen (1989) assumed that only 4 percent of total nitrogen in eroded soil material would have been available in any given year. Even with an assumption of 10 percent, the RCA would overestimate erosion costs by a factor of 10. Failure to address this issue contributes to the often observed differences between RCA and PCA assessments (see for example Bojö 1996).

example, consider the cost of replacing damage to soil structure that might also accompany nutrient loss and which would not be addressed through fertilizer application (Enters 1998). Another significant limitation of the RCA is that it does not assess the costs of avoiding damage to soil fertility. Rather, it assesses the costs that were or might be incurred if a damaged asset is restored.¹ Despite these problems, the relative ease of use of the procedure and the possibility of incorporating adjustments for fertilizer efficiency and nutrient availability as suggested in table 1 still make the technique a potentially valuable tool.

The Productivity Change Approach: Valuing Production Change

The Productivity Change Approach (PCA) has been used extensively in both developed and developing countries to estimate the economic costs of various forms of natural resource degradation and is probably the most common method for assessing the economic value of soil in general (as opposed to nutrients specifically in the RCA). The main advantage of the approach is that it is logical, straightforward to apply (as long as relevant data such as crop yield changes

over time are available) and relatively easy to comprehend even for non-specialists. In addition, the PCA can easily be used to measure actual change or, when coupled with yield simulations, to assess likely impacts of possible interventions. Still, most analyses to date have used the PCA only to assess the effects of soil erosion and not other nutrient-depletion processes (Enters 1998). This is in large part because the approach becomes more difficult to implement when specific factors, such as soil nutrient change, are of interest rather than overall changes in land services affecting crop productivity.

In contrast to the RCA, the PCA does not focus on the actual costs of nutrients. Rather, the PCA is used to place a value on the services soils provide in terms of, typically, agricultural output. The PCA assumes that the value of productivity change is equal to the difference in crop yields with and without that change, multiplied by the unit price of the crop which is or might be grown, potentially adjusted to reflect any differences in the costs of production (Barbier 1998). In other words, the PCA assumes that nutrient value is equal to the change in revenue or profit caused by nutrient change. The actual application of the PCA involves a two-step procedure. First, the physical effects of nutrient change on crop yield are estimated. Second, the

¹Other shortcomings of the RCA are presented in Enters (2000).

TABLE 1.
Replacement Cost Approach: Challenges and solutions.

Challenges	Solution
Does not consider whether the valued nutrients were, or would become, the de facto limiting factor for crop production. It could also be other nutrients, such as micro-nutrients, or missing pest control or water deficiency.	The common focus on NPK is in fact only an approximation, but allows comparisons between different studies. Crop foliar analysis and fertilizer trials could verify which nutrients are actually limiting and of value.
Does not consider low fertilizer efficiency, i.e., a part of the fertilizer is immediately lost again. This implies that higher replenishment rates are needed than those calculated as net loss, thus the replacement costs increase.	Nutrient-specific adjustment factors are suggested, especially for nitrogen (N). For N, a leaching loss below the root zone of 50% can be considered a reasonable average, which implies an adjustment factor of 2 for the nitrogen costs in the RCA. P and K are not or less affected.
Does not consider that a significant part of the nutrients (lost through erosion) might have never been plant-available (see box 4).	Correction factor of 0.1 (i.e., 10%) for nutrients lost through erosion. This factor is also necessary to narrow the common gap to the PCA.
Does often not consider that farmers use other nutrient sources than (expensive) industrial fertilizer.	If the nutrient content of any alternative input (manure, compost) is known, its corresponding replacement costs can be calculated.
Does not consider full costs of fertilizer purchase (e.g., transportation costs) and of fertilizer application (e.g., labor).	These costs could easily be assessed and added to the fertilizer-based replacement costs or in the larger frame of a cost-benefit analysis (CBA).
Does not consider changes in the fertilizer retail price due to large-scale demand, e.g., if nutrient replenishment receives policy support.	For larger scale assessment (not farm, but region or national) corresponding discounts could be analyzed and considered.
Does not account for the impact of externalities, such as the increase in atmospheric carbon due to additional consumption of energy for fertilizer production.	Depending on the user of the analysis (e.g., international community), this could be an important cost factor in a social CBA.
Does not consider likely side-effects of fertilizer applications on, for instance, micro-nutrient availability, soil salinity or soil acidity, which can effect in further soil amelioration costs (e.g., due to the necessity of liming or extra drainage).	Based on actual soil conditions (acidity, salinity, micro-nutrients status) soil scientists can judge if such a situation is likely or not.

value of the resulting change in production, i.e., how the yield change translates to a change in income, is calculated. Thus in a soil nutrient study, the PCA takes the change in income from agricultural production caused by changes in nutrient contents as a proxy for the value of the nutrients. If such an analysis targets future change, it is necessary to consider discounting techniques to account for the impact of time on valuations (box 5).

To relate the change in land productivity to a change in nutrient supply, a key requirement is detailed information on the physical relationship between nutrient change, soil change and crop yields. While seemingly straightforward, the ease of making such calculations should not be taken for granted. Yields can fluctuate for many reasons including climatic variability and the

presence of pests. Long-term experiments to verify the impact of nutrient change are scarce, and results remain strongly affected by site-specific variables such as rainfall and inherent soil fertility, making assumptions necessary (Lal 1995). That said, there are a number of methods by which yield can be associated with nutrient change and used in PCA calculations. These methods range from regression functions to the comparison of actual yields on depleted soils with those on "conserved" soils (cf. Bishop and Allen 1989; Lal 1995; Boj  1996). In practice, many PCA studies have focused on water-induced erosion. In that context, Boj  (1996) suggested a number of techniques that could be used to estimate the relationship between yield reduction on the one hand and soil and nutrient loss on the other, including:

Box 5. The role of time and the need for "discounting".

While it is relatively simple to compare physical nutrient changes across time, comparing the economic value of that change is not so straightforward, since a "dollar today is not equal to a dollar tomorrow." This is because (i) of time preference or the fact that many people prefer to obtain benefits (or avoid costs) in the present as opposed to the future, implying that a unit of benefit today is "worth" more than the same unit of benefit in the future; and (ii) the opportunity cost of capital which reflects the scarcity value of capital (savings) and returns to alternative investments. To compare costs and benefits that occur across time, it is necessary to use the concept of discounting. The process of discounting can be used to convert the future value of costs or benefits to a present value by dividing by an appropriate "discount" rate. The rate used is often assumed to be either a market interest rate or the cost of funds to the decision-making agent. The economic rationale for discounting and its implications for environmental management in developing countries have been discussed extensively in literature (Markandya and Pearce 1998; Enters 2000; Pearce et al. 1990; Winter-Nelson 1996; Rabl 1996; Pearce and Turner 1990; Hanley and Spash 1993).

The discussion is animated since conventional discounting procedures, especially as related to the choice of an appropriate discount rate, are often alleged to discriminate against future generations and resource conservation through the use of inappropriately high interest rates. Two alternative approaches have been suggested. One is to adopt a lower, "social" discount rate which reflects the divergence in private and social costs and benefits. The other is to impose a sustainability criterion on activities with environmental impacts (Pearce and Turner 1990). Kotschi et al. (1991), for example, argued for an ecological discount rate of zero for natural resources and their benefits, since natural resource values do not decrease with time. With a discount rate of zero, the future value of a given environmental service is equal to the present value, increasing the calculated worth of conservation over what would otherwise be the case. However, others have argued that there is no unique relationship between high discount rates and environmental deterioration and so a lowered discount rate could be counterproductive (Pearce and Turner 1990).

- (i) Expert judgment
- (ii) General or site estimated soil (nutrient) change—yield functions
- (iii) Soil depth change—yield models
- (iv) Plant-growth models

The basic principle behind any method is that some set of processes causing changes in soil nutrients have an overall impact on crop yields. This relates to a key advantage of the PCA. The approach does not focus on certain (types of) nutrients or consider actual or potential nutrient availability. What matters is yield as a function of all soil “services”—physical, biological and chemical. Once yield change is estimated, the commodity’s price is then applied to calculate the economic value of the gained or lost services. As with the RCA, the appropriate price to use depends on the purpose of the analysis and can significantly steer the assessment.

While the PCA has many advantages, it also suffers from a number of inherent problems such as the difficulty in linking yield with nutrient loss as described earlier (Nye and Greenland 1960; Lindgren 1988; Theng 1991; Prasad and Goswami 1992; Enters 1992). Further, estimates must ensure that technological progress and changes in farming practices, and their effects on yields, are isolated in analysis from nutrient change. This is difficult, since farmers can be expected to adapt their farming systems in the face of soil fertility decline and other changes. The approach also assumes that soil nutrients are only of value when they can be used to produce marketed goods for which prices exist or can be approximated. Finally, the possible existence of irreversibility—that it may be impossible to return soil productivity to its pre-degradation state—suggests that a higher cost should be given to nutrient depletion than simply

what is associated with yield decline over some given time period so as to account for the permanent reduction in the (soil) capital stock (Sanders et al. 1995; Simpson et al. 1996).²

Willingness to Pay: Inference when Prices are not Available

The fundamental basis behind the two valuation methods just described is that nutrient inputs (RCA) or agricultural outputs (PCA) are, or can be, priced in the market. However, even when explicit markets or prices do not exist, soil nutrients still have value. The problem is developing a way to discover that value. The Willingness-to-Pay (WTP) approach is one methodology that attempts to value soil nutrients by discovering their implicit value to farmers or others. WTP studies often use the Contingent Valuation Method (CVM), a technique used to assess the valuation of goods or services which are not traded and, therefore, have no explicit price. The approach is referred to as “contingent”, because participants are asked about their valuations of goods, such as plant nutrients, contingent on some hypothetical scenario. Comprehensive discussions of contingent valuation methods with regard to natural resources in general are given in Mitchell and Carson (1989), Pearce and Turner (1990), and Hanley and Spash (1993).

The standard approach in using CVM is a questionnaire-based survey of target populations (Mitchell and Carson 1989). The interviewer suggests a price for a “service” (e.g., nutrient-rich wastewater for irrigation instead of a nutrient-poor water source) and the respondent indicates whether he/she would be “Willing-to-Pay” in general for the service as well as if the suggested amount is acceptable. An iterative

²Further limitations of the PCA are discussed by Enters (2000).

procedure follows until the interviewer discovers the highest value the respondent places on the service.³ The CVM is considered to be most appropriate when respondents are familiar with the resource to be valued and when the hypothetical market is “realistic.” When respondents are unfamiliar with the resource, they may also be allowed to consult with colleagues or household members to determine answers (Alberini and Cooper 2000). A simplified version of the method is “contingent ranking”, a matrix ranking exercise suitable for participatory on-farm appraisals, which uses scores to estimate the willingness to pay for a number of goods and services (Hanley and Spash 1993). Related to the WTP approach is the Willingness-to-Accept (WTA) approach. The WTA approach measures the price that individuals would demand to compensate their foregoing a particular good or service. A key advantage of the WTP approach is that it allows, indeed requires, the participation of those who would use the resources in question. A key disadvantage is that the amount people say a resource is worth and the amount they would actually pay for that resource may be divergent.

Hedonic Pricing: Placing a Value on Resource Characteristics

The hedonic pricing method is used to place values on amenities associated with particular goods and is probably most frequently used in the valuation of housing attributes.⁴ The method is based on the idea that people value the characteristics of goods or the services they

provide rather than the goods themselves. Hedonic pricing is one method of placing values on each characteristic, such as soil nutrients, of a particular asset, such as land. The standard technique for applying the methodology is to use regression analysis on the sale or rental prices of land with different properties/qualities (Pearce and Turner 1990). In the case of soil nutrients, the basic assumption is that higher-quality soils and investments in soil conservation translate into higher land values, i.e., higher future benefits to a producer (Barbier 1998). In the developing-country context, the hedonic pricing approach has seen little if any use in valuing soil nutrients, perhaps because land markets, and the institutional arrangements (such as property rights) that foster the development of markets and meaningful prices, are often poorly developed, especially for farms (Grohs 1994; Nunan et al. 2000). The utility of hedonic pricing is probably further reduced in cases where traditional rules, rather than strict market economics, steer land allocation, and where there is still sufficient land for shifting cultivation. Despite these problems, the selected use of the technique in developing countries could provide valuable insights and contrasts to the traditional RCA and PCA studies.

Total Factor Productivity: A Way to Consider Nutrient Stocks

While Total Factor Productivity (TFP) is not a commonly used technique in the economic valuation of soil nutrients or soil nutrient change, it is described here to show its potential utility in overcoming a major conceptual shortcoming of

³The starting price is increased to see if the respondent would still be willing to pay at the higher price, and so on, until the respondent declares that he/she is not willing to pay the extra increment on the bid. It is important to note that a poorly designed or implemented survey can easily influence and bias responses, leading to results that bear little resemblance to the relevant population's “true” valuation. Resolving these difficulties involves careful design and pre-testing of the questionnaire, competent survey administration and the execution of econometric tests to help identify sources of bias, as well as the analysis of the respondent's actual ability to pay.

⁴For example, in wealthier countries, hedonic pricing is frequently used in such tasks as estimating the impact of park land on the prices of nearby homes. The rationale for using the approach is that many aspects of the environment have no directly established market price (e.g., there is no market for “park land services” just as there is no direct market for “soil productivity services”).

the RCA and, to a lesser extent, the PCA: the failure to consider the role of nutrient stocks in influencing the value of soil nutrient change. As mentioned above, the impact of changes in soil nutrients are site dependent and influenced by base conditions. For example, the loss of a given quantity of nutrients in rich soils may have a negligible impact on crop production while the same change in poor soils may soon lead to complete crop failure. Correction for this variation requires further soil analysis or more sophisticated concepts such as TFP. TFP is typically defined as the value of all outputs divided by the value of all inputs. Using knowledge of the levels of each input, the contribution of individual inputs to overall productivity can then be estimated using various forms of regression analysis.

While the TFP concept and measurement techniques are widely used for marketed goods with marketed inputs, they are applied less often for goods without market prices. Ehui and Spencer (1993) suggested extension of the concept to include the unpriced contribution of natural resource stocks and flows to TFP analysis. Combining PCA and RCA, nutrient inflow and outflows are valued. In determining the cost share for resource stocks, the opportunity cost for each soil nutrient is approximated with its replacement costs, e.g., market prices for chemical fertilizer. Resource flows are considered as the temporal or spatial difference between nutrient levels. Expanding the concept, Intertemporal Total Factor Productivity (ITFP) is defined in terms of the productive capacity of a (soil nutrient) system over time. It

is the rate of change of an index of outputs divided by an index of inputs, which can include both conventional inputs and outputs and the unpriced contribution of natural resource stock and flows. ITFP can be a meaningful measure of sustainability as it addresses the question of change in the productivity of a system between two or more periods. A system is sustainable if the associated ITFP index does not decrease. Simpson et al. (1996) illustrate the importance of this TFP extension in the case of Machakos, Kenya, in their response to Tiffen et al. (1994). To internalize externalities, a modification called Total Social Factor Productivity (TSFP) was proposed (Herdt and Lynam 1992).

Empirical Examples

With some understanding of the available techniques for valuing soil nutrients, we now turn to illustrations of previous work by IBSRAM/IWMI in nutrient valuation studies. The first study, from Ghana, assesses the private costs, i.e., costs as they are experienced by farmers, of soil nutrient depletion in two different farming systems. Focussing on wastewater irrigation in Mexico, the second study demonstrates the divergence of perspectives between local farmers and regional communities. The third study highlights the continental costs of nutrient depletion in SSA.⁵ The final study, more a discussion of issues than a particular case, examines options for the valuation of Soil Organic Matter and soil carbon—important but little studied topics within the realm of nutrient valuation.

⁵Case studies employed variations of the RCA and RCA/hedonic pricing. The final case discusses the RCA along with the PCA. For examples of applications of other techniques in developing country contexts readers are referred to Grohs (1994), Pagiola (1996), Gebremedhin et al. (1999), Shiferaw and Holden (2001), and Kumar (2004).

Valuing Nutrient Depletion in two different Farming Systems in Ghana

IWMI used the RCA to analyse the costs of soil nutrient depletion in farming systems along an urban–rural gradient in and around Kumasi, Ghana in West Africa’s tuber belt (IWMI 2002). At one end of the gradient, in an urban agricultural system, vegetables are grown on scarce open spaces with access to irrigation water, and soil fertility decline can only practically be countered through regular fertilizer applications, as possibilities for shifting location do not exist. At the other end of the gradient—a “traditional” maize–cassava system—there is no significant land shortage, giving peri-urban and rural farmers the flexibility to shift production to alternative fields as crop yields decline. The goal of the study was to estimate the costs of soil nutrient depletion from the farmers’ (private) perspective. The study demonstrates, among other things, that the results are significantly influenced by the specific farming conditions, options available to farmers to maintain production levels, and input and output prices, especially the cost of fertilizer.

The costs of nutrient depletion in mixed-vegetable farming systems

In the Gynease suburb of Kumasi, land availability is severely constrained and farmers respond to soil fertility decline by applying

fertilizers. In these farming systems, vegetables are grown continuously in the same beds resulting in 3 cabbage and at least 8–9 spring onion or lettuce harvests per year. Nutrient losses are high due to frequent harvests, removal of crop residues, and leaching on often sandy soils.

To compensate for nutrient losses, farmers apply substantial amounts of organic fertilizer—mainly locally available poultry manure—at a rate of 20–50 t/ha for cabbage and 50–100 t/ha for lettuce and spring onions. For cabbage, inorganic fertilizers are also applied. Irrigation water provides additional nitrogen when extracted downstream from the city. Irrigation is done with watering cans, mostly in the dry season and during dry spells in the rainy season. Annual application rates are high and range from 640 to 1,600 l/m², with an average of about 1,000 l/m². Table 2 summarises nutrient application rates in the study site.

To analyse the costs of nutrient depletion, the RCA was used based on local nutrient input prices. To conduct the assessment, a simplified version of the standard NUTMON model (box 1) was applied which considered only major nutrient in- and outflows including crop harvest, plant residues, manure, fertilizer, irrigation water, and precipitation. Leaching and losses through erosion were estimated through soil analyses

TABLE 2. Annual nutrient application (kg/ha) rates for vegetable (cabbage/lettuce/spring onion) production in and around Kumasi Ghana.

Soil nutrient	Annual nutrient application rate by source (kg/ha)			
	NPK fertilizer (only used on cabbage)	Manure	Irrigation water	
			Upstream of Kumasi	Downstream of Kumasi
N	75–180	770–1,650	10	50
P ₂ O ₅	75–180	420–900	7	11
K ₂ O	75–180	350–750	50	80

comparing fields with and without erosion and fertilization, and compared with empirical data. The local price of poultry manure was used to calculate replacement costs as it is the fertilizer actually used by farmers. The analysis showed that, despite significant N and K losses of 180 kg of N and 50 kg of K₂O, the annual costs of nutrient depletion totalled only about US\$45/ha, consisting of US\$10/ha for the manure and US\$35/ha for handling and application. As average farm sizes are about 0.1–0.2 ha, annual costs per farm are about US\$5–9. If the inexpensive poultry manure were not available in Kumasi, the use of mineral fertilizer would have increased the replacement costs four times, assuming constant costs for handling and application.

The costs of nutrient depletion in traditional maize–cassava systems

The costs of nutrient depletion were also assessed using a hybrid of the RCA and hedonic pricing methods for a “traditional” rain-fed farming system located in the Atwima district of peri-urban Kumasi. In this system, nutrient losses occur mainly through the removal of harvested cassava and maize and their residues. NUTMON analysis showed that nutrient losses were mainly centered on N (58 kg/ha) as the other nutrients are largely replenished through fallow burning. In general, farmers do not attempt to compensate for N losses by fertilizer applications. Instead, they utilise new N pools by opening “new” plots (shifting cultivation) allocated by local chiefs. In fact, they may never return to their old fields. In conducting the analysis, depletion or replacement costs were assessed by calculating the costs of acquiring and preparing a new location for cropping. Although this represents a departure from the conventional RCA, moving to a new location is, in essence, the farmers’ method of nutrient replacement. In addition to movement

costs, a one-time rental payment, which is sometimes requested by local chiefs, was included in the cost calculations. As farmers actually shift production, this hybrid RCA/hedonic pricing approach appeared most applicable to their point of view.

In the study area, different tenure arrangements are common, including share-cropping and land rental. The annual rent for a new plot ranges from about US\$10–50/ha, paid for the whole term in advance, with lower rates often indicating a higher risk of eviction for land development (Nunan et al. 2000). A correlation between land rental prices and soil quality could not be confirmed, although Nunan et al. (2000) have mentioned such an influence. In addition to land acquisition costs, farmers also incur land-clearing costs in the order of US\$40/ha. Maize productivity decline and increasing weeding costs are generally severe enough to induce farmers to shift production after 2 years. Thus, the financial cost of nutrient depletion per hectare can be calculated as follows:

$$(2 \text{ years} \times \text{US\$}30 [\text{average land rent}] + 1 \times \text{US\$}40 [\text{land clearing}]) / 2 \text{ years} = \text{US\$}50/\text{year}.$$

If N could be replenished annually by applying fertilizers it would be possible to crop on the same field for at least 4 years. The amount of inorganic fertilizer needed would cost US\$116 over this period. Thus the calculation is:

$$(4 \text{ years} \times \text{US\$}30 [\text{average land rent}] + 1 \times \text{US\$}40 [\text{land clearing}] + \text{US\$}116 [\text{fertilizer}]) / 4 \text{ years} = \text{US\$}69/\text{year}.$$

As other cost factors do not differ much, the example shows what farmers already knew—that fertilizer application is less profitable than shifting cultivation. However, the situation might look different if the farmers were able to obtain poultry manure at the same low cost at which it

TABLE 3.
Costs of soil nutrient depletion in two contrasting farming systems, Kumasi, Ghana.

Estimated costs	Urban mixed-vegetable system		Peri-urban maize–cassava system	
	(0.1 ha farm)	(US\$)	(0.7 ha farm)	(US\$)
Annual costs (actual)	Nutrient replacement	1.0 ^a	Land rent	21
	Manure handling/application	3.5	Land clearing	14
	Total	4.5	Total	35
Annual costs (per ha)	Nutrient replacement	10	Land rent	30
	Manure handling/application	35	Land clearing	20
	Total	45	Total	50
Net annual income (actual farm size)		400–800		200–450
Cost of actual nutrient depletion as a % of net income	About 1%	--	About 10%	--

Note: ^a US\$14 on average for inorganic industrial fertilizer if poultry manure is not available.

is now available to the urban vegetable farmers, who not only have lower transport costs but also a higher general profit margin for investments.⁶

Comparing the two systems

Table 3 provides a comparison of the costs of soil nutrient depletion in the two systems. On a per hectare basis, farmers in both locations are faced with similar annual costs for nutrient decline (around US\$50). However, the exact techniques used in the two calculations to arrive at this figure were varied so as to reflect the actual practices used by farmers to counter crop-yield decline. This approach—following what farmers actually do—avoids what Barbier (1998) called an estimation that “can only be an accurate reflection of on-site costs by chance.” Where land availability is constrained (the first case), the costs of nutrients and their replenishment with manure are most relevant. Where farmers can easily find new land or open “new” nutrient pools (the second case), land

acquisition and preparation are the relevant and determining variables affecting cost calculations.

The results also highlight the fact that cost assessments can be highly dependent on factors not related to soils and nutrients. Large-scale poultry production in Kumasi provides a ready supply of inexpensive nutrients. Without this local poultry production, the costs of soil nutrient depletion to the farmers would be significantly higher. It is also interesting to note that labor costs make up a significant share of total replacement costs. This aspect is frequently omitted in RCA studies and explains much of the cost underestimation of which some studies have been accused (Enters 1998). In fact, in urban Kumasi, labor costs (actual or opportunity costs) are higher than in rural Ghana, and most farmers use their own labor (especially for manual watering). This keeps the urban plots smaller (0.1–0.2 ha) than the average 0.7 ha of those in the maize–cassava system.

⁶Quansah et al. (1998) explain that farmers not only shift between fields because of the declining effect of ash fertilization, but also to avoid increasing weeding costs under longer cultivation. In this example, extra weeding costs over 4 years were largely balanced by the costs of the second land clearing in the 2-year system.

Box 6. Diverse impacts of wastewater use.

The composition of municipal wastewater must be taken into account to calculate its true value, be it positive or negative. Besides the problem of pathogens and chemical pollutants, the total nutrient content in wastewater must also be considered—if it exceeds crop needs or if certain nutrients are over-represented, soil nutritional imbalances can occur. These imbalances can affect the availability and uptake of under-represented nutrients. For example, if wastewater irrigation exceeds the recommended nitrogen dosage for optimal yields, it may stimulate vegetative growth, but delay ripening and maturity, cause micro-nutrient deficiencies and, in extreme circumstances, crop failure. Likewise, a predominance of domestic wastewater may affect the yield of salt-sensitive crops in addition to soil structure and groundwater quality. Some effects might not be obvious immediately, but may represent hidden or long-term costs for the environment, farmers and society. In short, the economic impact of wastewater use is much more complex than discussed in this chapter. A variety of valuation techniques can be used to quantify the different socioeconomic, health, and environmental impacts of wastewater use (Hussain et al. 2002).

Valuing Nutrients from Wastewater Irrigation in Mexico: Contrasting Perspectives and Divergent Results

While most research on the valuation of soil nutrients has concentrated on the costs of nutrient depletion, Scott et al.'s (2000) study of Guanajuato, Mexico focused on nutrient enrichment or gains. Wastewater is usually considered as a negative externality, but it can also have positive aspects if its nutrients, when applied through irrigation, reduce the need to apply inorganic or other fertilizers (box 6). As in the previous example from Ghana, the RCA was used in the study. However, while the Ghana case assessed the costs of lost nutrients, the Mexican study calculated the benefits of additional nutrient supply. In carrying out the analysis, the amounts of N and P delivered to fields through untreated wastewater irrigation under current practices were first estimated and compared with a scenario using less nutrient-rich treated wastewater (table 4). Table 5 shows how nutrient costs were then calculated based on

prices provided by local commercial fertilizer suppliers (see the next case study for additional details on how such calculations are made).

Combining this and other information, the costs of replacing the reduced amounts of N and P in the water incurred by the construction of a wastewater treatment plant were calculated. These costs include the fertilizer itself as well as the labor needed to apply it. Based on survey data, the researchers concluded that the foregone annual value of the reduced nutrient delivery was approximately US\$900/ha. However, this value constitutes an overestimate as the nutrient requirements for alfalfa, the principal crop grown, are greatly exceeded when untreated wastewater is applied (table 4). A more realistic estimate excludes the value of the difference between crop nutrient demand and nutrient supply from the untreated wastewater. Making this

TABLE 4.

Simulated total nitrogen (N) and phosphorus (P) deliveries (kg/ha) from actual measurement of both untreated and treated wastewater, Guanajuato, Mexico.

Study site	Untreated (kg/ha)		Treated (kg/ha)		Change through treatment (%)	
	N	P	N	P	N	P
San Jose de Cervera	455	76	36	7	-92.2	-90.6
Santa Catarina	1,597	258	285	42	-82.2	-83.5
Comparison with alfalfa requirements	88	115	88	115	--	--

adjustment, the annual value of the "lost" nutrients is reduced to around US\$135/ha.

Multiplying the crop-useful share of the total water treatment capacity of the plant with the value of nutrients lost to farmers, the operating plant "costs" farmers some US\$18,900 per year in forgone nutrients. The result demonstrates that any economic impact assessment must be comprehensive enough to capture unintended side effects and unexpected benefits or costs. In addition, it illustrates the importance of the point of reference. From the farmer's perspective, the construction of the treatment plant has a negative

impact in that it reduces the provision of free nutrients—a positive externality—and results in additional costs if soil fertility is to be maintained. From the perspective of the plant's intended beneficiaries—local and regional communities who expect a cleaner environment, safe drinking water and improved sanitary and health conditions—this is irrelevant (assuming they are not also farmers). It is thus left to a social cost-benefit analysis to determine, from a social aspect, whether the plant should be constructed and, if so, how the costs and benefits of operating the plant should be distributed.

TABLE 5.

Unit costs of nitrogen (N) and phosphorus (P) fertilizers in Mexico, 1999.

Source of nutrients		
N source	N content (%)	Cost (US\$/kg)
Urea	46.0	0.40
Ammonium nitrate	33.5	0.52
Ammonium sulphate	20.5	0.37
Average	--	0.43
P source		
	P content (%)	
Triple superphosphate	46.0	0.51
Single superphosphate	18.0	0.56
Di-ammonium phosphate (DAP)	46.0	0.63
Mono-ammonium phosphate (MAP)	52.0	0.57
Average	--	0.57
Application cost (combined N+P) in US\$ /ha	--	31.58

Nutrient Depletion and GDP in sub-Saharan Africa

On-site impacts of nutrient depletion can be considered at various scales. The previous two cases focused predominantly on the field scale or farming system scale, taking the farm household as the decision-making unit. Such analyses are useful to improve the understanding of the economic impact of soil nutrient change and serve as a valuable input for decision making on interventions in the agricultural sector. However, they do not provide insights into the magnitude of the problem at regional, national, or continental scales. The importance of broad-scale assessments should not be underestimated as they provide valuable insights to policymakers at national and international levels. In particular, they can be a useful instrument for identifying “hot spots” or priority areas for soil-conservation interventions and areas with a high potential risk of food insecurity in addition to raising problem awareness.

With this in mind, IBSRAM conducted a continental-scale assessment of the costs of soil nutrient depletion in sub-Saharan Africa (Drechsel et al. 2001a). The research goal was to inform policymakers of the “hidden” costs of soil-nutrient mining so as to highlight the potential impact and benefit of soil-conservation investments. The study thus targeted the social costs of nutrient depletion as opposed to the private costs emphasized in the previous studies.

The undertaking of a continental scale analysis requires an approach that can be applied across a large number of states and diverse environmental and socioeconomic conditions. The approach has to be relatively undemanding with respect to data requirements, use data which can be compared and aggregated across countries, and produce

outputs that are understandable by and acceptable to policymakers. To meet these prerequisites, the RCA was employed using nutrient balance predictions (N, P, and K deficits) for the year 2000 provided by Stoorvogel and Smaling (1990) and data obtained through a fertilizer retail price survey in 15 African countries.

To value nutrients via fertilizer prices requires either a translation of the lost nutrients into marketed fertilizer types or an expression of fertilizers in nutrient units. Since the types of fertilizers (and nutrient compositions) available vary among countries, calculations were based on the costs of nutrient units rather than the costs of specific marketed fertilizers. This simplified the comparison with the already estimated nutrient losses. The calculation can target each nutrient or just one taking advantage of the more or less fixed price ratio between the main nutrients. The study followed the second approach which required the analysis of the cost or price ratio between the main macro-nutrients (i.e., N, P and K). Based on world market prices for products and applying knowledge of product content, macro-unit prices were calculated (table 6) along with standardized nutrient ratios. Based on these price ratios, average nutrient costs in K_2O equivalents⁷ were determined. The results for Nigeria are shown in table 7. The last column in the table provides the average cost per K_2O unit (US\$0.45/kg). Multiplied by the price ratio of the raw materials for nitrogen and phosphorous per K_2O unit (table 6), the nutrient costs could then also be calculated for N (US\$0.52/kg) and P_2O_5 (US\$1.49/kg).

The procedure was repeated for the 14 other sub-Saharan African countries included in the

⁷Any other nutrient could also be used. As K was the “cheapest” nutrient, its use as denominator allowed price ratios between the three nutrients larger than 1 (table 6).

TABLE 6.
World market prices of fertilizer raw materials.

Costs	Fertilizer raw material		
	Ammonia (NH ₃)	H ₃ PO ₄ salts	KCl
Raw material (US\$/t)	140.0 ^a	276.8	94.7
Nutrient in raw material	N	P ₂ O ₅ ^b	K ₂ O ^b
Nutrient (%) in raw material	ca. 77	ca. 53	ca. 60
Nutrient (US\$/t)	182 ^a	522	158
Nutrient (US\$/kg)	0.182	0.522	0.158
Price ratio/K ₂ O unit	1.15	3.3	1.0

^aSource: FERTECON (<http://www.fertecon.com>) data for June 1998.

^bCalculation example: 1t of ammonia costs US\$140, about 77 percent is N. Thus, 1t pure N would cost US\$182.

^cBy standard convention, the oxidized forms of P and K are used (P₂O₅, K₂O).

survey. Average unit prices and their standard deviations were then multiplied by the corresponding quantities of depleted nutrients. A correction factor of 5 percent was used for nutrients lost through erosion (i.e., only 5 percent of the nutrients were valued), as only a small percentage of these is actually plant-available. This was discussed by Drechsel and Gyiele (1999) and suggested by Bishop and Allen (1989) (see also box 5).

The average nutrient costs for all countries were:

- N: 0.50 ± 0.10 US\$/kg
- P₂O₅: 1.22 ± 0.20 US\$/kg
- K₂O: 0.43 ± 0.06 US\$/kg

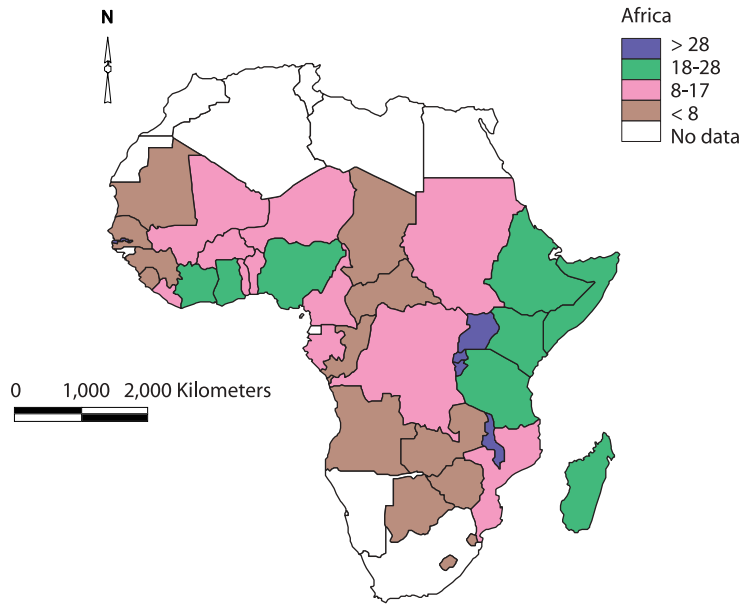
These figures were used as estimates of nutrient costs for countries not covered in the survey after taking into account variations in fertilizer type and transport distance (seaport versus land-locked countries).

The results of the analysis indicate that soil nutrient depletion is a significant on-site cost for

TABLE 7.
Costs per unit of nutrient in K₂O price equivalents in Nigeria.

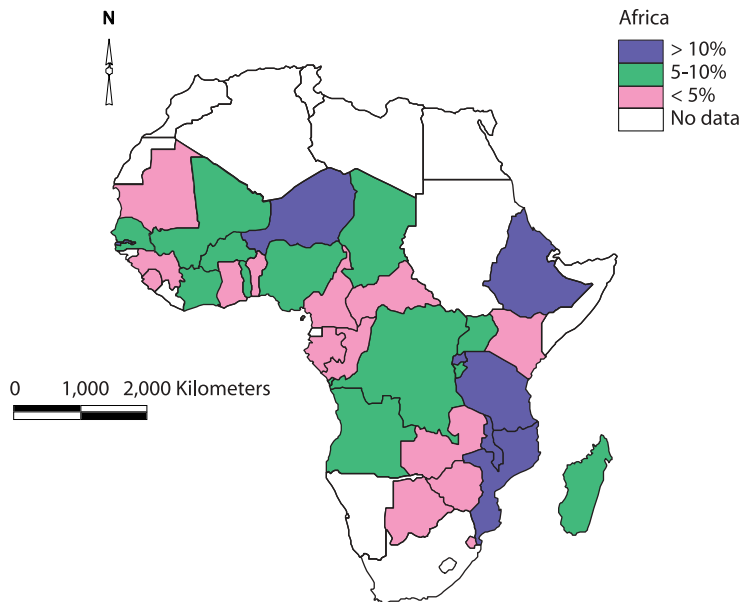
Fertilizer product	N	P ₂ O ₅ K ₂ O	K ₂ O equivalents	All three nutrients	Price survey US\$/100 kg	Cost /K ₂ O eq (US\$)
15:15:15	17.3	49.5	15.0	81.9	31.0	0.38
20:10:10	23.0	33.0	10.0	66.0	28.9	0.44
20:10:10+10Ca	23.0	33.0	10.0	66.0	27.4	0.42
25:10:10	28.8	33.0	10.0	71.8	31.7	0.44
Urea (46%N)	53.0	0.0	0.0	53.0	30.1	0.57
Single super phosphate (18% P ₂ O ₅)	0.0	59.4	0.0	59.4	28.1	0.47
Mean						0.45

FIGURE 2.1.
Costs of nutrient depletion in US\$/ha total arable land including fallow but excluding pasture in sub-Saharan Africa.



Note: Only countries covered by the survey of Stoorvogel and Smaling (1990) and with information available on their GDP in 2000 are considered.

FIGURE 2.2.
Costs of nutrient depletion as a percentage of the agricultural gross domestic product (GDP) in sub-Saharan Africa.



Note: Only countries covered by the survey of Stoorvogel and Smaling (1990) and with information available on their GDP in 2000 are considered.

the agricultural sector in Africa. For SSA as a whole, nutrient depletion accounts for about 7 percent of the agricultural gross domestic product (GDP) of both crop and livestock production. This amounts to an annual cost of approximately US\$32 per farm household, or about US\$20 for each hectare of arable land (currently cultivated and fallow land). In some African nations, particularly those in the East African Highlands (Burundi, Malawi, Rwanda and Uganda) nutrient depletion per hectare is especially severe, even after adjusting for nutrients lost through erosion (figure 2.1). The primary reason for this is the high land-use intensity and resultant higher nutrient exports through continuous crop removal

due to the low percentage of arable land under fallow (Drechsel et al. 2001b). In terms of share of the overall agricultural economy, nutrient depletion claims the largest proportion in Mozambique, Niger, Rwanda, Ethiopia and Tanzania (figure 2.2). In general, the estimates from the study can be considered conservative, since they include only the fertilizer cost of nutrients already lost and not the additional fertilizers required because of limited fertilizer efficiency after replacement. Neither do the estimates consider labor costs, which as the previous examples have shown, can significantly affect the results of the calculations, especially if low-cost organic fertilizers are used.

Considerations for the Economic Valuation of Soil Organic Matter

The emphasis in this report has been on soil nutrients per se, but an important and related issue is soil carbon (C) or soil organic matter (SOM). SOM is complex and consists of living and dead plant and animal residues of different age, activity and resistance. SOM contributes to soil structure, soil water-holding capacity, soil nutrient content and nutrient exchange capacity and thus soil fertility and agricultural yields in general. Physical science literature on the importance of SOM is extensive. However, there have been few attempts in the economic literature to value it.

SOM losses have long been recognized as a significant aspect of soil degradation in tropical environments where shifting cultivation via slash-and-burn is practiced (Nye and Greenland 1960, 1964; Van Noordwijk et al. 1997; Diels et al. 2002). As with soil nutrient depletion, SOM depletion can be described as the balance between SOM input (or, better, development) and SOM losses. In contrast to the assessment of N,

P, and K balances, direct measurements or estimations of carbon inputs and outputs are more difficult (Detwiler 1985). To obtain a quantifiable proxy for SOM losses, it is possible to analyze soil carbon, which makes up the majority of SOM, over time or between different treatments, for example, with and without erosion or fire (box 7). In many agricultural systems, most losses of SOM and soil carbon occur during the first 5 years of cultivation (figure 3), and the remainder largely over the following 2 decades (Detwiler 1985).

Even after measuring SOM or soil carbon loss or gain, another key challenge is determining an appropriate price to apply (box 8) in its valuation. Kumar (2004) used the RCA. He analysed the loss of carbon through erosion and used the market price of farmyard manure to estimate the price of carbon. As carbon is one of the most frequent elements in the topsoil, its valuation more than doubled the replacement costs based only on N + P + K.

Box 7. Modeling carbon dynamics.

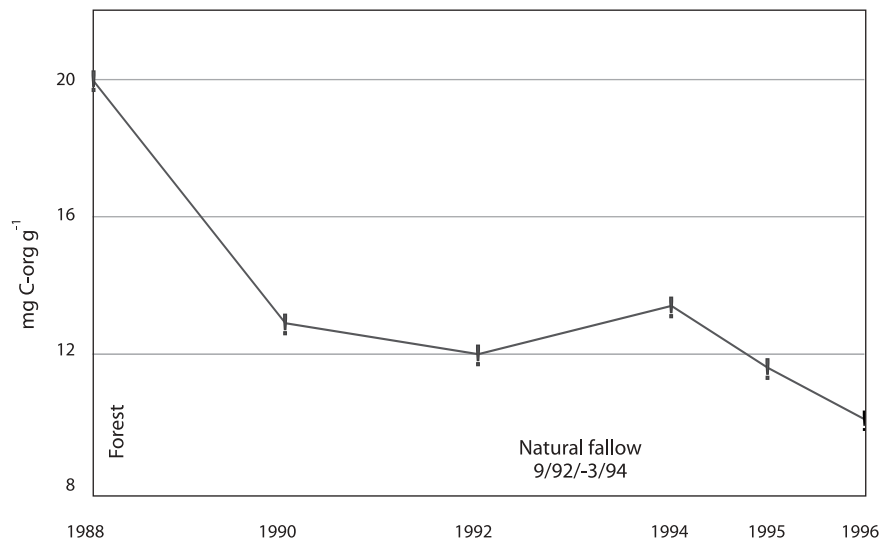
Other than the approach of Pieri (1992) for a site-specific organic matter balance, most carbon models focus on larger (regional) scales and the carbon dynamic. The “Century” model is one well known method originally designed to study SOM dynamics over periods of up to several thousands of years. The model can simulate soil C, N, P, and S dynamics under different litter and organic matter fractions. This and other carbon-related models are described by Paustian et al. (1997), Eikelboom and Janssen (1994), Noij et al. (1993), Chertov and Komarov (1997) and Diels et al. (2002).

In a variation on the RCA, Izac (1997) illustrated how various functions of SOM could be substituted by differing man-made inputs (figure 4). Individual SOM services could then be valued by using the market price of similar goods or by approximating the value of the next best alternative/substitute good with or without a market price or from farmers’ willingness to pay for a corresponding service. In this Substitute Goods Approach, the value of SOM could be considered equivalent to the sum of the costs of the various substitutes. Diels et al. (2002) demystified the quantitative effects of SOM changes on the important water and nutrient storage services under

savannah conditions, thus providing the base for the valuation of corresponding substitutes.

One possible method for avoiding the pricing problem for SOM and soil carbon is the use of the PCA, as it values the provision of soil services in general rather than physical quantities. However, trials with and without SOM change would still be needed to determine the relationship between yield and SOM to separate the impact of lost soil depth, loss of nutrients not associated with SOM, and other factors. The various difficulties described here may explain why the economic valuation of soil organic matter remained the exception despite the general concerns about its depletion.

FIGURE 3. Decline of soil organic carbon (mg C-org g⁻¹) during cultivation (IBSRAM, unpublished data from Côte d’Ivoire).



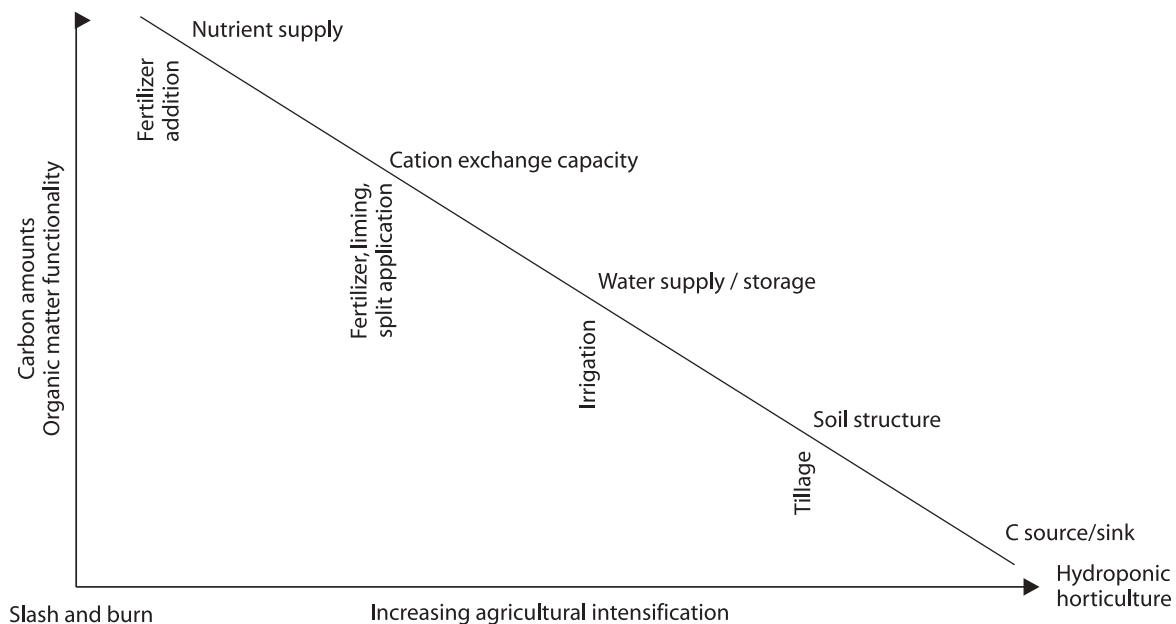
Box 8. Market and shadow prices of organic carbon.

Determining values to apply to SOM and soil carbon services is not straightforward as the following examples show:

- In Northern Europe, gardeners have used nutrient-poor and acidic peat over many years for soil structure amelioration and water retention. In Germany and Switzerland, they paid about US\$240–330 per metric ton of carbon.
- At an international expert meeting on global warming (FAS 1996), participants recommended a shadow price for soil carbon in the order of US\$10 to 20 (ranging from US\$5 to 40) per metric ton of carbon emitted to reflect a broad range of potential environmental damages caused by the loss of SOM. This magnitude is consistent with the marginal damage estimates reported in the IPCC review of literature on global impacts of climate change (Pearce et al. 1996).
- With regard to C sequestration through agroforestry in African smallholdings, Woomer et al. (1998) estimated input costs (rock phosphate, tree seedlings and labor) of US\$87 per ton of carbon. Significantly lower costs (<US\$10) are possible via tropical tree plantations (Dixon et al. 1993). Actual examples for credits for emissions abatement through carbon sequestration often range between US\$1 and 38 per ton of carbon, though most commonly they are in the range of US\$2 to 5 (Dumanski et al. 1999; Pretty and Ball 2001). One condition for the success of soil carbon trading is the ability to measure or estimate the amount of carbon actually sequestered through land management.

FIGURE 4

Options to substitute principle functions of soil organic matter (Drechsel and Gyiele [1999] reproduced and modified from Izac [1997] with permission from Elsevier Science).



Discussion and Conclusions

Soil nutrients are clearly critical in determining plant growth and agricultural output. However, the actual value of those nutrients is often dependent on water availability. Likewise, the role of agricultural water in supporting crop growth is in large part determined by the availability of nutrient supplies. Despite the importance of nutrient-water interactions, they are often ignored in actual analysis. For example, while the benefits of irrigation in increasing yield are often recognized and measured, the simultaneous costs of increased nutrient exports from the topsoil through harvest removal are not. Similarly, while the costs of potential health problems from wastewater agriculture are commonly discussed, the (at least partially) offsetting benefits and increased income (or reduced expenditures) from nutrient supplies through the water are many times forgotten. It is only through the combined and balanced consideration of nutrients and water that the true value of nutrients and irrigation can be measured and accurate assessments of the relative benefits and costs of various agricultural land and water management options carried out. However, to conduct such analysis it is essential to have methods for valuing soil nutrients. The primary goal of this paper was to review the main methods available along with a range of case studies demonstrating their use.

Five methodologies were discussed, and the important characteristics of each are summarized in table 8. Of the five, only two have been used substantially in developing country studies—the RCA and the PCA—largely because of difficulties in applying the others in such contexts (cf. Drechsel et al. 2004). These two methodologies are fundamentally different in nature. The RCA attempts to place a value on actual nutrient loss

or gain while the PCA attempts to value the change in production caused by that change.

Naturally two methodologies with such different approaches are likely to assign different economic values to soil nutrients or their change. In general, RCA estimates are considerably higher (often up to ten times) than corresponding estimates based on the PCA (see also descriptions by Grohs [1994], Bojö [1996], Predo et al. [1997], and Clark et al. [1998]). The divergence would be even larger if RCA studies were expanded beyond their typical focus on only the best known and most easily analyzed macronutrients (i.e., N, P and K) to include the economic value of other relevant nutrients (e.g., Mg, S, Ca, Zn, Cu, etc.) and soil services. As an example of the potential impact, the consideration of soil carbon by Kumar (2004) resulted in a doubling of replacement cost estimates as compared to the consideration of only N, P and K.

One reason for the divergence between RCA and PCA estimates is that the RCA typically values the total volume of studied nutrients, including the quantity not of relevance for current crop growth (though this problem could be overcome through relatively simple adjustments, see table 1). In contrast, the PCA only considers the nutrients and soil services directly impacting yield. Put another way, the RCA implicitly focuses on long-term impacts (by valuing change in nutrient stocks, without analysing the size of the stock) while the PCA focuses on shorter time horizons (by focusing on changes in actual crop output).⁸

In deciding between replacement cost and productivity change approaches, it is critical to explicitly consider the questions to be answered and the intended use of any results. For

⁸Grohs (1994) and Barbier (1998) provide additional theoretic explanations for differences in RCA and PCA outcomes.

TABLE 8.
 Characteristics of the approaches for the economic assessment of soil nutrients discussed in this paper.

Method	RCA	PCA	Willingness to pay	Hedonic pricing	TFP
Advantage	Simple to apply if nutrient loss or balance data and fertilizer prices are available, or nutrient content of wastewater	No need to separately consider different nutrients, nutrient fractions, benefits, etc. Particularly appropriate for erosion	Relatively easy to apply and farmer-oriented	Indirectly finds values of soil services not explicitly priced or quantified	Considers contribution of nutrients to output, valuing nutrients within the specific context in which they are used
Valuation concept	Costs of replacing lost or gained nutrients, usually proxied by commercial fertilizer prices	Income loss over some specified time period	Farmers' perception of impact	Contribution of various soil services to land values	Contribution to production
Application	Nutrient depletion or gains	Erosion or soil sedimentation	Soil conservation measures, nutrient depletion, and others	Nutrient depletion, soil degradation in general	Nutrient depletion, soil fertility decline
Facilitation of interaction (participatory on-farm research)	Marginal and typically only if farmers are familiar with fertilization	Yes, especially in cases with obvious land degradation and yield decline	Yes	No	No
Monetary values used	Market price of direct soil nutrient substitutes (e.g., chemical fertilizer)	Price of harvested crops	Artificial prices; contingent ranking; scores	Differences in land purchase or rental prices	Typically market prices
Special data needed	Nutrient loss data, better net nutrient balance	Erosion loss; yield-soil loss function	None	Land (rental) prices	Inputs to production, net nutrient balance
Shortcomings (examples)	Not all nutrients lost or gained are used by plants; does not consider context of overall soil fertility	Typically difficult to obtain site-specific nutrient change-yield functions	Many sources of bias possible	Not feasible in areas without meaningful land markets; mathematically demanding	Mathematically demanding
Data demand	High	High	Low	High	High

analyses of nutrients specifically, as opposed to broader soil services, the RCA has an obvious advantage in that it is tied directly to the nutrients themselves. When the focus is on soil fertility change or soil degradation (or improvement) in general, for example through erosion which not only affects nutrients but soil broader soil services, the PCA becomes increasingly attractive as it implicitly considers all biological, chemical and physical soil properties affecting soil productivity.

Another consideration in choosing between the two approaches is data requirements and availability. The RCA has the clear advantage that it is simple to apply once net nutrient losses or gains are known (e.g., via NUTMON) since market prices for key nutrients are usually available, as the examples from Mexico and SSA show. However, this advantage can also skew results. The ability to incorporate easily-available commercial fertilizer prices may encourage analysts to ignore more cost effective, but more difficult to quantify, options actually available to farmers such as manure application or shifting cultivation. Again, this problem can be addressed, for example, as was done in the case study from Ghana.

The data demands of the PCA can also be partially overcome by farmers themselves. Involving farmers in participatory research also has the decided advantage that it at least helps to ensure that critical socioeconomic components are not ignored and that results are farmer relevant.

Whatever method is used, the outcome must be compared with a "control" so as to put the

results in context. Here it is important to be realistic when using results to inform decision making on agricultural practices and soil conservation. There is neither a no-erosion scenario on sloping lands (Barbier 1998), nor is there crop production without alteration or exploitation of soil fertility including soil nutrients. In the same vein, it is essentially pointless to make comparisons between farming and no-farming options. The issues are essentially one soil fertility management practice versus another. Soil fertility decline has a cost and so does soil conservation. All decision makers in soil conservation must thus consider both, as farmers already do.

Clearly the use of economic methods for assessing soil nutrients and soil nutrient change in developing countries is filled with many challenges. To address them, research aimed at finding better ways to apply theoretically valid methods in the context of smallholder agriculture, where rural land and other markets tend to function poorly, would be especially useful. In particular, research which applied alternative methods to the RCA and PCA would help us better understand the true value of soil nutrients from different perspectives. However, as Tisdell (1995) stated in IBSRAM's first "Issues in Sustainable Land Management," economics will never give cut-and-dry answers, but merely provide a set of tools to be used in analysis. Ultimately it will always be up to analysts to make compromises between the precision of biophysical assessment, economic rigor, and data requirements in choosing methods that best meet the objectives of the study at hand.

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