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Methods for the economic assessment of the on- and off-site impacts of soil erosion

Thomas Enters

IBSRAM
International Board for Soil Research and Management
SWNM
The Soil, Water, and Nutrient Management Programme

The SWNM is a system-wide programme of the CGIAR that brings together four complementary research consortia on nutrient depletion, inefficient water use in dry areas, acid soils, and water erosion of soils. The programme is convened by IBSRAM and the International Centre for Tropical Agriculture (CIAT), and each consortium engages national agricultural research and extension systems, non-government organizations, advanced research organizations, and international agricultural research centres. The key to success of the SWNM is the adoption of a new research paradigm on sustainable land management. The main elements are farmer participation, a landscape perspective, an interdisciplinary research approach, institutional strengthening, development of appropriate policy, and sharing of research methodology. The consortia develop and share innovative tools for the assessment of sustainability and impact, using information technology such as geographic information systems and decision support systems. The outputs of the SWNM go beyond the improved and appropriate technologies for sustainable land management by delivering new research tools and indicators, enhanced institutional capacity, and scientifically sound and relevant information to help decision-makers tackle some of the most intractable land degradation problems.

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Preface

Soil erosion, the physical movement of soil particles from one location in the landscape to another, has attracted the attention of concerned soil scientists and conservationists for more than a century. A multitude of studies on indigenous and modern soil-conservation practices indicates that the proper management of soils can reduce soil erosion substantially and decrease its on- and off-site impacts that appear to threaten economic growth and the survival of people in some locations. Yet, while the negative consequences of soil erosion and degradation are widely recognized, and the number of soil-conservation projects and programmes is mushrooming, adoption rates of improved land-management practices are very disappointing. One is tempted to ask why so little has been achieved since soil and land degradation continue to make headlines.

The processes of soil erosion and degradation are physical, and may be accelerated considerably by economic activities. Their impacts are social and can be assessed in financial or economic terms, as can be the costs and benefits of other activities and their attendant effects. Thus, soil conservation competes with other activities, projects or programmes for scarce resources. It will not receive the attention that it may deserve, as long as conservationists rely on emotional appeals. Instead strong arguments for soil conservation need to be built on thorough economic assessments of the on- and off-site impacts of soil erosion, in order to understand what happens at various hierarchical landscape levels and to provide the necessary input to environmental decision making.

The number of detailed and credible economic assessments of soil erosion is still limited. In addition, there is considerable evidence that methodologies used were ‘captured’ by those groups responsible for their application. Cost-benefit analysis and other methodologies have been used to serve the ends of those charged with using them, comparisons of studies are rarely possible, and the objectivity of valuation studies, in general, has been called into question.

I am not claiming that this review addresses all the problematic and contentious issues that have been raised in the past by agronomists, soil scientists, ecologists, economists and philosophers alike. I have directed my attention at practical issues that research needs to address in order to make cost-benefit analysis an appropriate methodology for translating physical variables and processes into monetary values. More than anything, the intention of the review was to bring the interested reader and practitioner up to date on the issues surrounding economic assessments of soil erosion, to point out gaps of knowledge, and to stimulate a constructive discussion that will move forward our collective attempts of coming to grips with the cost of continuing soil erosion and degradation. Above all, it was my objective to provide food for thought and if you do not agree with everything I say I have achieved this objective.

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As with most reviews, this is as much a reflection of other people's ideas and work as it is of my own. Accepting that no piece of work is produced in a vacuum, there is a long list of people who have helped in various ways in the completion of the review. Of those who have offered particular assistance and inspiration are Frits Penning de Vries, Rebecca Clark and Rohan Nelson. Other people who have helped in one way or another include: Bruce Aylward, Ed Barbier, Joshua Bishop, Jan Bojö, Sampurno Bruijnzeel, Kees Burger, Steven de Jong, Adam Dickinson, Malcolm Douglas, Anantha Duraiappah, Derek Eaton, Simeon Ehui, Anders Ekbom, Sverre Grepperud, Renan Goetz, Jon Hellin, David Higgitt, Paul Huszar, Peter Jipp, John Kerr, Peter Lindert, Ingrid Mulder, Jan Nibbering, Stephen Northcliff, Stefano Pagiola, Michael Richards, Jonathan Rigg, Sara Scherr, Eric Smaling, Douglas Southgate, Michael Stocking, Keith Syers, Clem Tisdell, Cathryn Turton, Floris van der Pol, D.E. Walling, and Jim Winpenny. Some of the people in this long list sent me copies of papers and reports, directed me to unheard-of web sites, provided additional names and e-mail addresses, or made perceptive and productive comments on early drafts of the review. I am indebted to all of them.

I would also like to thank Eric Craswell and Robin Leslie of IBSRAM. The former encouraged me to take on the task of reviewing the economic issues of soil erosion. The latter edited the final version and made it readable. However, I claim full responsibility for any errors or omissions or anomalous statements.

Foreword

Impact analysis and evaluation are essential to the effective management of agricultural research. At the end of one project cycle, analysis of potential impact is a key input to priority setting and research strategy formulation. As research projects end, impact analysis and evaluation become a critically important part of determining the return on investment. Many investors in research, including donor agencies, development banks and governments, now insist on impact analysis as a prerequisite for further investment.

The degradation of land and water resources is a complex problem that does not lend itself to simple cost benefit analysis. While the bare hills and sediment-rich streams are obvious signs of soil erosion to most observers in the tropics, our scientific knowledge of its environmental, social, and economic impacts is dispersed and superficial. Yet soundly based information on the impact of soil erosion is required not only for research managers, but also for policy-makers who allocate development resources and make the laws that ultimately guide land management.

Research on global tools and methodologies is a central activity of the system-wide programme on soil, water, and nutrient management (SWNM) that IBSRAM co-convenes with CIAT under the Consultative Group for International Agricultural Research (CGIAR). As part of the SWNM programme, IBSRAM commissioned Thomas Enters to write a review of methods for the assessment of the impact of soil erosion. The publication of this report and of the proceedings of the associated workshop on “Assessing the causes and impacts of soil erosion at multiple scales,” held in Bogor, marks an important step in the harmonization of methods for impact assessment under the SWNM programme. The work would not have been possible without the generous support of the UK Department for International Development. IBSRAM acknowledges this support and the inputs from many colleagues in centres from inside and outside the CGIAR. Further publications on impact assessment in the SWNM field are planned.

We hope that the publications will encourage not only debate, but also data collection and analysis that contributes to the knowledge base.

Eric T. Craswell
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Methods for the economic assessment of the on- and off-site impacts of soil erosion*

Introduction

Soil erosion, a natural process that can be accelerated dramatically by human activities, is viewed as the most widespread form of soil and land degradation. It is believed widely to be a major threat to sustainable crop production, if not the long-term viability of agriculture in general. The major causes of soil degradation are deforestation and removal of natural vegetation (43%), overgrazing (29%), improper agricultural practices (24%), and over-exploitation of natural vegetation (4%) (Oldeman *et al.*, 1991).

Soil does not contribute to 'well-being' directly (Barrett, 1997). From an agricultural perspective it is valued as an essential input in crop production. The proper use of soil has been linked to the rise of ancient civilizations and the flourishing of agricultural economies. The hypothesis is that the development of some civilizations stagnated and some of their economies collapsed with an increase in soil abuse and topsoil erosion (Carter and Dale, 1955; Hudson, 1985).

Soil erosion is particularly problematic in tropical countries because of high rainfall intensities and generally less fertile soils. It is also a threat to those developing countries where agricultural production is crucial to development and the majority of the rural population base livelihood strategies on the primary sector. Unfortunately, many of such rural residents have been pushed to the margins of agricultural production, i.e. shallower and poorer soils, and the sloping land and forest frontiers of the uplands. In these situations agriculture can be the main cause of soil erosion and watershed deterioration, though the impacts of other activities such as road construction or logging operations should not be downplayed. Cultivating upland soils often leads to a reduction in natural soil fertility and crop productivity, undermining future income generation (Alfsen *et al.*, 1996) and economic growth (Alfsen *et al.*, 1997). Soil erosion and the depletion of soil resources have thus important economic implications for countries whose economies depend heavily on the agricultural sector (Barbier and Bishop, 1995).

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The impacts of erosion are potentially far reaching, not only for upland producers. Farming practices can also inflict off-site costs on lowland economies through the processes of erosion and sedimentation and changes in hydrological patterns. Ultimately, the continuous depletion and exploitation of soil resources may threaten prospects for sustainable economic growth. Hence, the magnitude of immediate and future costs of erosion is an issue that not only individual farm households should be interested in. Policy-makers require answers to questions related to the cost and benefit structure of erosion as well as its remedial measure, soil conservation, in order to prioritize problems and to design incentive structures that make mitigative measures more attractive. An important task is thus to assess the actual extent and impact of soil degradation and to evaluate the economic significance of soil erosion. This is only possible if appropriate assessment frameworks and tools are available, which allow for the identification, quantification, and valuation of the impacts of erosion.

Financial and economic analyses have been applied for at least two decades for evaluating the cost of erosion, soil degradation or land degradation in developing countries, as well as the benefits of soil conservation, though the number of detailed and credible valuation studies is still limited. Numerous measures have been developed to estimate the magnitude of the cost involved. The diversity in methodological approaches and underlying assumptions, the tendency by some analysts to ignore complications, as well as the focus on on-site costs and financial aspects, make it very difficult to compare valuation results and to assess their usefulness for decision making.

Objectives and structure of the report

To further its economics research within the soil, water, and nutrient management (SWNM) programme and to provide the means for integrating economics within the framework for evaluating sustainable land management (FESLM), IBSRAM intends to develop an assessment framework for evaluating the impacts of soil erosion. Preliminary work, based on financial cost-benefit analysis and on-site impacts has provided insights into the complexities of valuation studies while providing useful results first (Renaud, 1997). The primary objectives of this review are:

- to provide an overview of research methods on on- and off-site impacts of soil erosion and soil conservation;
- to provide an overview of different valuation approaches to soil erosion and soil conservation; and
- to assess the practical value of different approaches.

These objectives will assist the development of a comprehensive but user friendly assessment framework.

The structure of the report basically follows the objectives outlined above. The report consists of 12 chapters including the introduction and bibliography. The first part of the review concentrates on on-site issues whilst the second discusses the off-site implications. The concluding section summarizes the most important issues.

Each section describes the physical aspects and relationships of environmental and economic systems outlining the potential on- and off-site effects of soil erosion. This is followed by reviews of economic approaches drawing on theoretical and empirical work.

Economists involved in empirical work have questioned recently the usefulness of complex models because of data availability limitations in many developing countries. They have suggested and adopted a more straightforward cost-benefit approach for evaluating costs and benefits. The review will therefore focus on cost-benefit analysis and discuss issues involved in its application.

As the breadth of issues dealt with in the review indicates, natural resource economics requires a multidisciplinary approach. It posits an in-depth understanding of the effects of erosion on physical and chemical soil properties, the relationship between erosion and crop yields, farmer decision making and agriculture, geomorphology and the hydrological responses to land cover changes, as well as economic systems such as labour markets and credit availability. It cannot be within the scope of this report to provide detailed information on all of these issues. Wherever necessary the reader is guided towards additional literature. Also, as other reviewers have indicated, issues are very location-specific (Magrath and Arens, 1989; Pagiola, 1993; Clark, 1996; Pender and Kerr, 1996; Grepperud, 1997a). What is of utmost importance in one study may be of only minor relevance in another. In fact, what may be counted as a negative externality in one scenario may turn out to have positive impacts in a different scenario, at a different scale or time. No attempt is made to cover all the differences between studies. The main focus of the report is on valuation methodologies.

Approaches to measuring the physical process of soil erosion

Soil erosion is a complex phenomenon influenced by natural and socioeconomic factors. The economic impacts of soil erosion are felt at two levels. The immediate on-site effect is declining crop yields if inputs are not adjusted to maintain soil productivity. When the soil leaves the boundary of the field it can cause negative (or positive) externalities with associated off-site costs (or benefits). The externalities are addressed in the second part of the review (see section 9). Here I will focus on the soil-erosion process, its measurement, and its on-site impacts.

Until the early 1980s, quantitative determinations of the extent and impact of erosion by water (as opposed to wind) have been rather sketchy. Data required to quantify the causative parameters of erosion processes were scarce (El-Swaify and Dangler, 1982). Over the last fifteen years, knowledge gaps have been filled and our understanding of erosion has increased, though there is still much confusion over the relationships between soil erosion and soil degradation. This confusion is evident in many of today's analyses of the costs of erosion. Most economists do not distinguish between soil erosion and soil degradation in their analyses. The result of this confusion is that nutrient depletion is usually disregarded in crop yield forecasts and that the costs that can be attributed to the impacts of soil erosion are overestimated.

Box 1. Erosion, depletion, and degradation.

Soil erosion is a physical process and refers to the wearing away of the land surface by water and/or wind as well as to the reduction in soil productivity due to physical loss of topsoil, reduction in rooting depth, removal of plant nutrients, and loss of water. Soil erosion events are quick processes.

Nutrient depletion means net loss or decline of soil fertility due to crop removal or removal of nutrients by water passing through the soil profile. The soil depletion process is less drastic than soil-erosion events and can be remedied through cultural practices and by adding appropriate soil amendments.

Soil degradation is a broader term for declining soil quality encompassing the deterioration in physical, chemical, and biological attributes of the soil. Soil degradation is a long-term process. Both erosion and nutrient depletion are part of soil degradation.

Land degradation is the reduction of the capacity of the land – together with factors such as climate, topography, soils, hydrology, and vegetation – to produce goods and services. It is more than just a physical or environmental process. Ultimately it is a social problem with economic costs attached as it consumes the product of labour and capital inputs into production.

Adapted from Blaikie and Brookfield (1987); Lal (1990); and Eaton (1996).

In many developing countries, soil nutrient mining is a very serious problem (Sanders *et al.*, 1995). Recent research on soil nutrient balances highlights that beside erosion, soil fertility is also reduced by the removal of harvested crop parts and residues, leaching and volatilization/denitrification losses

(Smaling and Fresco, 1993; Stoorvogel *et al.*, 1993; Smaling *et al.*, 1996; Roder *et al.*, 1997; Syers, 1997). Nutrient depletion cannot be seen, which explains why it has received less attention in the past although it is a very important contributor to soil degradation and should be part of any thorough economic valuation (van der Pol, 1992). Lindert (1997, p. 1), however, contends that "there are no clear signs that erosion has been a key source, or an accelerating source, of soil degradation in Indonesia over this half-century". He reports similar results for China (1996, p. 17-18):

> "Over a recent half-century, China's soil quality slipped in some respects, but not overall. Interestingly, the negative trends for some regions and time-periods do not fit popular fears. The topsoil trends for some regions and time-periods do not fit popular fears. The topsoil trends are probably not worse in the erosion-prone parts of China than elsewhere, and probably not worse since the 1950s than earlier. Weighing the mixture of trends in different soil characteristics suggests that the average quality of China's cultivated soils rose modestly from the 1950s to the 1980s."

Within many economic analyses, there is a tendency to attribute soil-fertility decline only to soil erosion. Erosion is treated as the sole contributing factor to soil degradation and yield declines, as the impacts of nutrient depletion on crop yields are underestimated or completely neglected. However, it is also clear that soil erosion can be, particularly on steeper slopes, a major component of on-site costs (Gachene *et al.*, 1997). Its magnitude needs to be measured, which is particularly important if damages are assessed according to the replacement cost approach (see 6.1).

Erosion is a two phase process consisting of the detachment of soil particles and their transport by erosive agents such as water or wind from a particular site (Osuji, 1989). It can be categorized as (i) natural (or geologic) erosion that occurs independent from human activity and (ii) accelerated (or anthropogenic) erosion that is caused by human disturbances. The distinction between the two types of erosion is important because natural erosion rates may serve to establish benchmark soil loss tolerance rates.

The concept of tolerable soil loss is concerned with limiting erosion to levels at which no irreversible degradation or productivity losses occur (Phillips, 1989). But natural erosion as a conservation goal has received criticism for its lack of realism because as Phillips (1989, p. 221) argued, "accelerated erosion is virtually inevitable whenever vegetation is periodically removed and soil surfaces disturbed." In the context of assessing the costs of erosion, the difference between the two is important particularly if even the low levels of natural erosion are viewed as costs.

The most common methods to survey erosion rates are based on:

- aerial photographs;
- experimental plot studies;
- calculations based on sediment measurements and estimated sediment delivery ratios; and
- empirical mathematical models.

Aerial photos cannot be used to express erosion rates in meaningful terms for a quantitative assessment (Grohs, 1994). Numerous problems arise when cost estimates are based on results derived from small plots (Stocking, 1996). In general one can expect overestimates in erosion rates. On the other hand, Purwanto and Bruijnzeel (1996) warn that artificially bounded plots tend to underestimate runoff and sediment yield from backsloping bench terraces.

As briefly discussed above, erosion processes are site-specific and transferring data from one geographical area to another is not advisable. However, experimentally derived data are indispensable for verifying estimates of soil loss derived by simulation models. The third method bases average erosion rates on sediment loads of rivers multiplied by a sediment delivery ratio (SDR). It is used rarely because of the difficulties involved in measuring sediment loads and in specifying sediment delivery ratios (Grohs, 1994; Clark, 1996).

Empirical-mathematical models express erosion losses in terms of t ha^{-1}, provide data for any size of geographical area, and can be reasonably accurate if models are validated. Wischmeier and Smith (1978) developed a soil-erosion equation, the Universal Soil Loss Equation (USLE). Following Seckler (1987) the USLE may be written:

$$E = f(C, S, T, L)$$

where E is the average annual erosion expressed in t $ha^{-1}\,y^{-1}$, C is the climatic factor (rainfall erosivity), S is the soil factor (erodibility), T is the topography factor comprised of slope gradient and slope length, and L is the land utilization factor that expresses the plant cover in relation to bare soil. While the application of the USLE in environments for which it was originally not designed is problematic (Harper, 1986; Stocking, 1987; Bishop and Allen, 1989) an analysis of the four physical parameters shows the following:

- erosivity and erodibility are not changeable by intervention;
- slope topography can be modified by changing gradients (e.g. terrace construction) and slope length (e.g. alley cropping), thereby influencing runoff; and
- the land utilization factor can be influenced by vegetation management or mulching, effectively reducing splash erosion and increasing water infiltration rates.

None of the four methods for measuring or predicting soil-erosion rates is ideal. The first does not provide quantified information. Results from experimental plot studies have numerous limitations (see Stocking, 1996) but are necessary for calibrating and validating models. Difficulties in calculating sediment delivery ratios make the third method an unlikely candidate. Empirical mathematical models have been applied in recent studies (Table 1) and have the potential to predict more reliable erosion rates if they are validated prior to use. Their drawback is that they are very data demanding, although some such as SLEMSA (Soil Loss Estimation Model for Southern Africa) require less data.

Table 1. Methods used to quantify soil erosion in recent studies.

Author, year, and location	Quantification of soil erosion	Comments
Wiggins and Palma, 1980 El Salvador	Estimates based on slope and presence or absence of topsoil	Other parameters can remain constant in the particular study
Attaviroj, 1986 Thailand	Average values for sloping lands and USLE for off-site costs	Estimates taken from other studies
Cruz *et al*., 1988 Philippines	Estimates based on rainfall polygons, slope categories, soil types, and land use	Estimates stem from a separate report
Bishop and Allen, 1989 Mali	USLE	Reject MUSLE
Magrath and Arens, 1989 Java, Indonesia	Estimates based on erosion studies conducted under comparable conditions	
Ehui et al., 1990 Western Nigeria	SCIAF in combination with experimental results	SCUAF uses simplified version of USLE
Pagiola, 1993 Kenya	USLE	USLE overestimates soil loss because it neglects deposition
Grohs, 1994 Zimbabwe	SLEMSA	Rejects USLE for Zimbabwe
Bishop, 1995 Mali and Malawi	USLE	USLE ignores soil deposition
Barbier, B., 1996 Central American Hillsides	Proposes the use of MUSLE	More accurate for small watersheds
Eaton, 1996 Malawi	Relies on data of earlier studies from other countries	

Note: SCUAF (Soil Changes Under Agroforestry).
MUSLE (Modified Universal Soil Loss Equation).

Some general conclusions can be drawn from the table, although the application of a particular method depends on numerous aspects such as resource availability, purpose of the study and data availability, amongst others. It appears that over the last fifteen years most analysts have resorted to using empirical models. Ehui *et al.* (1990) and Nelson *et al.* (1996b) have used simulation models that do not require erosion estimates as inputs. If off-site costs are of no interest and on-site costs are calculated based on crop productivity changes caused by soil erosion, then the separate estimation of soil erosion rates is not necessary. The replacement cost approach on the other hand requires not only the calculation of erosion rates but also the nutrient contents of the eroded material.

The USLE is often viewed as a compromise because analysts are thrown into a situation of limited data availability or the only data that are provided are of a suspect nature as they may have been collected for a very different purpose, such as to produce a picture of crisis (Thompson and Warburton, 1985; Seckler, 1987; Enters, 1994; and Stocking, 1995).

There are at least two other erosion simulation models available. The RUSLE (Revised Universal Soil Loss Equation) is scientifically superior to the USLE. The main difference is that RUSLE targets conservation tillage systems, especially no till but has not been used in any of the studies (Renard *et al.*, 1994). The WEPP (Water Erosion Prediction Model) has been developed to incorporate more complex technology. Because it is process-based, the WEPP can deal with erosion and sedimentation problems from a holistic field setting, considers deposition, ephemeral gully erosion, sediment yield, and spatial and temporal variations (Renard *et al.*, 1994). The WEPP is even more data demanding than other models and will, at least in the medium term, not be applicable to developing country situations.

Quantifying the impact of erosion on soil properties and crop yields

The effects of erosion on productivity have been researched for decades and are generally well documented, although not necessarily in the form of quantified data suitable for economic analysis. Erosion reduces actual and potential productivity by decreasing soil depth and plant available water capacity, removing valuable nutrients (the bases of the replacement cost approach) and altering soil physical properties (Littleboy *et al.,* 1996). The on-site impacts of erosion on productivity are exceptionally complex, being both soil- and plant-specific (Stocking, 1996). Clark (1996) lists fourteen different impacts of erosion that affect soil properties and use of soil as an input in agricultural production in different ways.

Figures for soil degradation and productivity decline quoted in the literature are sometimes extrapolated from limited data sets and may exaggerate the problem. Most analysts consider "moved soil" as "lost soil", even though much of it may be deposited on other agricultural land (Enters, 1992; Lutz *et al.*, 1994; Whitmore *et al.,* 1994; Stocking, 1996), may be trapped by indigenous technologies such as soil-harvesting structures (Humbert-Droz, 1996; Zhang *et al.*, 1997) or trapped and redistributed to fields as an inexpensive source of fertilizer (Chandrakanth and Romm, 1990). Quine *et al.* (1992), for example, concluded in their study in China that only 20% of the eroded material originated from the cultivated land and ascribed the low net loss to traditional soil-conservation strategies. A number of analysts have noted that the USLE as well as the RUSLE do not account for soil depositions (Table 1). The simulation models do not represent fundamental hydrological and erosion processes and their results are inaccurate. Physical soil loss is only a rough proxy for soil-fertility decline (Bishop, 1995) and it is difficult to attribute crop yields to differences in past erosion (Olson *et al.,* 1994). In fact, as Pagiola (1994) notes, even high erosion rates may affect crop yields only marginally on deep soils with favourable subsoil characteristics.

It is difficult to quantify the relationship between erosion and soil productivity accurately using time series data, because technological advances (e.g. irrigation, fertilization and improved crop varieties) have masked the cumulative effects of erosion on production (Littleboy *et al.*, 1996). Magrath and Arens (1989, p. 24) note the problem of comparing "estimated" with "actual" yield:

> ''These predicted yield declines can only be compared with actual yield trends on Java with considerable caution. Over the last 15 years yields of major dryland crops have consistently risen despite ongoing erosion. However, these yield increases have only been possible through the continued intensification of farming practices."

The focus of soil scientists on measuring soil erosion dictated the work of economists to some extent for many years. It has led at times to erroneous assumptions particularly when erosion rates under existing cropping practices were compared with hypothetical practices that eliminated erosion completely. However, as Barbier (1996, p. 7) stresses, "even if it was feasible to reduce erosion to negligible levels, this can only be accomplished by the farmer investing in conservation measures, which is not a costless exercise". Soil erosion can take many years to impact crop productivity. Littleboy *et al.* (1996) reported that the decline in sorghum yields due to erosion was minimal for the first 25 years of simulation for Alfisols in India. In addition, the independent variables of soil erosion measure soil movement, not changes in critical soil properties (Sanders *et al.*, 1995). There is rarely a one-to-one relationship between the amount of soil lost and the effects on yields. While the displacement of soil is irreversible, the effects of erosion on productive capacity depend on the depth and quality of soil remaining and not on soil lost (Scherr and Yadav, 1996). In addition, in semiarid regions reductions in moisture-retention capacity due to erosion are often a more significant contributor to yield declines than the loss of soil *per se* (Lindgren, 1988; Pagiola, 1994; Pender and Kerr, 1996). Hence, it is not sufficient to rely on erosion estimates but their effects on crop yields need to be understood and quantified in order to compare soil-eroding with soil-conserving agricultural practices and to assess soil erosion and degradation.

Olson *et al.* (1994) recently evaluated different methods to determine soil-erosion-productivity relationships. The methods included:

- topsoil removal and addition;
- paired comparisons between eroded phases of soils within a field on a similar landscape position;
- analyzing yield data for a soil series from many plots in numerous fields with variable management and on different landscape positions;
- factor analysis and geostatistics; and
- simulations models.

They conclude that “each method has inherent strengths, weaknesses, and biases that can result in the measured soil productivity response attributed to erosion being potentially confounded with other variables, such as landscape position, soil formation, or management” (p. 589).

Little long-term, systematic, and empirical research on the relation between erosion and crop productivity has been conducted in the developing world. The paucity of data is lamented by almost all analysts. This is not to say that no time series data on relevant parameters have been collected. However, to my knowledge they have not been examined to establish the relationship that is crucial for the economic analysis. Therefore recent studies have applied various methods, from informal expert judgment studies to complex plant growth simulation models, to estimate yield declines for different erosion scenarios (Table 2).

Table 2. Methods used to quantify the erosion-yield relationship in recent studies.

Author, year, and location	Method	Comments
Wiggins and Palma, 1980 El Salvador	Estimates based on experimental data from the US	2% yield decline for each cm of topsoil lost
Attaviroj, 1986 Thailand	Estimates based on regression analysis	Assumes no positive impact of soil-conservation measures
Cruz *et al.*, 1988 Philippines	None	Use replacement costs approach
Bishop and Allen, 1989 Mali	Inferred erosion yield decline function	Exponentially declining function with annual productivity losses from 2 to 10%

Table 2. cont'd.

Author, year, and location	Method	Comments
Magrath and Arens, 1989 Java, Indonesia	Estimates based on results of three earlier studies	Annual lproductivity losses range from 0 to 12%
Ehui et al., 1990 Western Nigeria	Regression analysis relating maize yield to cumulative soil loss	IITA model developed by Lal (1981; cited in Ehui *et al*., 1990)
Pagiola, 1993 Kenya	Linear regression	Based on artificial desurfacing studies
Grohs, 1994 Zimbabwe	Plant growth simulation models EPIC and CERES; inferred erosion yield decline function	Models produce different results, but reveal similar trends; annual productivity losses from 0.3 to 1%
Bishop, 1995 Mali and Malawi	Regression analysis relating yields to cumulative soil loss	IITA model developed by Lal (1981, cited in Bishop, 1995)
Barbier, B., 1996 Central American Hillsides	Proposes the use of EPIC	Not available
Eaton, 1996 Malawi	Combines existing data with adapted data from Ehui *et al*., 1990	Calculates the "economic productive life of the soil"
Nelson *et al*., 1996a Philippines	APSIM	Simulates the effects of erosion on the daily stocks of soil water and nitrogen available for plant uptake

Note: EPIC (Erosion Productivity Impact Calculator).
CERES.
APSIM (Agricultural Production Systems Simulator).

Models have found more widespread acceptance only recently. Nelson *et al.* (1996a) distinguish four different type of models:

- statistical or empirical models or inferred soil loss yield decline functions (Bojö, 1996);
- productivity index models;
- component process models; and
- cropping systems models or soil plant models (Bojö, 1996).

Statistical or empirical models such as SCUAF or the models used by Ehui *et al*. (1990), Bishop and Allen (1989), Pagiola (1993) and Grohs (1994) (Table 2) compare erosion and crop yields through techniques such as multiple linear regression. A simple model is the Productivity Index (PI) model, which assumes that erosion alters crucial soil properties with subsequent productivity effects (Littleboy *et al*., 1996). Component process models describe the transformation of mass and energy involved in specific processes of a plant/soil system. Examples include CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) and CERES, a processed-based crop model (Nelson *et al.*, 1996a). CERES simulates the impact of reduced soil rooting depth on yields, assuming all other factors to be constant (Bojö, 1996). It does not simulate the impacts of erosion but can be used for this purpose. Also, it does not consider changes in chemical soil properties and thus consistently estimates lower relative yield declines per cm of soil moved than EPIC (Erosion Productivity Impact Calculator) (Grohs, 1994). Cropping systems models or plant/soil models simulate the interaction between changing weather patterns, management, and soil conditions. Examples of such models with the capacity to simulate the impacts of erosion on crop productivity include EPIC, SCAR (Soil Conservation in Agricultural Regions), PERFECT and APSIM (Nelson *et al.*, 1996a). Models, such as EPIC, are also useful for analyzing technology choices (Sanders *et al.*, 1995).

Computer simulation of cropping systems is essential to determine the long-term effects of soil erosion on crop yields, particularly in situations where short-term measurements may not provide sufficient insights. They provide a means of integrating experimental data and extrapolating them across a range of environments and management strategies (Nelson *et al.*, 1996a). The recent combination of EPIC and ArcView (EPIC-View) enables the user to view and analyze data spatially. Models provide a powerful tool for the future. However, as Clark (1996, p. 17) reminds us, "the results of model-simulations are only as representative as the input data used". Hence, the choice of an appropriate method should not be guided by the availability of software and hardware but rather should be "dictated by constraints in data, analytical capacity and time" (Bojö, 1996, p. 170).

Even relatively simple models have to be validated. Bishop and Allen (1989) considered the use of the model developed by Lal for Nigerian conditions, in their Mali study, to be questionable. Pagiola (1993) rejected the use of EPIC in his study in Kenya because detailed soil information was not available, a feature that is probably common for most upland environments in the tropics. If there are no data available to parameterize models then their use should be ruled out.

Evaluating costs and benefits

Over the years numerous static and dynamic models of farmers' decision making with respect to land-use practices and crop choice have been developed. For example, Barrett (1989, 1997) and Goetz (1997) have developed models for assessing the optimal control of soil erosion to determine how macroeconomic and sectoral policies influence soil conservation. Grepperud (1997b) studied the effects of revenue uncertainty on soil conservation using a dynamic economic model. Complex bioeconomic models have been used to integrate biophysical parameters of the natural with the economic environment faced by agricultural producers and to simulate the likely response of farmers to different pressures under different assumptions (Barbier, B., 1996). Such models are useful for determining the impacts of incentives or disincentives on soil degradation. They can also be designed for calculating the costs and benefits of soil erosion. Yet, their complexity restricts their user friendliness. In addition, as Grepperud (1997a, p. 18) concludes they "focus on decision-makers who are fully informed about complex soil-plant processes and how cultivation practices and input use influence them".

In response to such restrictions and the recognition that farmers can usually choose only from a small number of options due to limited information — a limitation that researchers face too — a simple bioeconomic model based on cost-benefit analysis has been used in more recent studies.

Cost-benefit analysis (CBA) provides a logical framework for the systematic collection and presentation of information from the perspective of the trade-offs in decision making. It is a common tool for project appraisals and is designed to assist decision-makers in choosing alternative courses of action and allocating scarce resources (Sugden and Williams, 1978; Hufschmidt *et al.*, 1983). The choice is usually between two or more alternative courses of action. In the context of soil erosion and conservation, or generally natural resource conservation, many people think about large projects when they refer to the term "project". This is not necessarily so because the term refers to any investment activity in which financial resources are expended to create capital assets that produce benefits over an extended period of time (Gittinger, 1982). Broadly defined, a project "is a way of using resources; a decision between undertaking and not undertaking a project is a choice between alternative ways of using resources" (Sugden and Williams, 1978). Following these definitions it becomes clear that any activity for which resources are spent in anticipation of future returns, i.e. agricultural practices by individual farm households, is a project. In terms of alternative courses of actions, CBA enables the analyst to compare the cost and benefit structure of soil-eroding with soil-conserving practices to assess the cost of soil erosion.

The great advantage of CBA, when pursued with integrity, is that some implicit judgements are made explicit and subject to analysis. As such, CBA is a decision-aiding framework and a good quality CBA is but one element of an overall assessment. The CBA lends itself to developing into an interactive, participatory process whereby those people affected by decisions assist in the definition of options and their likely impacts (see Nelson *et al.*, 1996b). At the same time, they provide valuable information on inputs and outputs.

Before embarking on the application of CBA, decisions have to be made on a number of issues of which, for the purpose of the discussion here, the actual valuation techniques for erosion-related impacts are of the greatest significance. They determine what one actually needs to measure.

Alternative valuation techniques at the microlevel

Three valuation techniques[1] are commonly used to assess the costs of soil erosion as well as the cost and benefits of soil conservation:

- hedonic pricing (property valuation);
- replacement costs; and
- change of productivity.

Hedonic pricing and property valuation use land prices to estimate the economic value of soil erosion. Sale prices and/or rental charges of land experiencing different levels of erosion are assessed using regression analysis (Clark, 1996). The basic assumption is that investments in soil conservation will translate into higher land values, i.e. a future benefit to a farm household (Barbier, 1996). Since land markets are poorly developed in most upland areas and institutional arrangements are often not sufficient to ensure property rights, hedonic pricing is of only limited practical value (Grohs, 1994).

The replacement cost approach

The replacement cost approach calculates the costs that would have been incurred in order to replace a damaged asset (Grohs, 1994), usually the annual marginal costs of fertilizer applications to compensate for the loss of soil nutrients due to erosion. The replacement cost approach is appealing but misleading because:

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[1] Scherr and Yadav (1996, p. 4) mention four approaches, i.e. the costs of replacing lost nutrients, the value of lost yield, the value of increased inputs to maintain yields, and the cost of rehabilitating the plot to its former condition. The second and the third approach constitute comparisons between soil-eroding and soil-conserving practices and are thus comparable to the change of productivity approach. The fourth approach refers to the “unattainable standard” criticized by Fox and Dickson (1988) and Barbier (1996). Another alternative approach is contingent valuation (Clark, 1996) and the estimation of the soil’s value as a resource (Clark *et al*., 1996).

- the link between the loss of nutrients and loss of production is not established (Norse and Saigal, 1992);
- soil erosion does not only affect the nutrient status of the soil but also its organic- matter content and its physical structure;
- soil nutrients may not be the most limiting factor in crop production (Bojö, 1996);
- fertilizer applications are not necessarily the most cost effective option available to farmers for maintaining yields; in extreme cases, i.e. on deep and fertile soils, farmers may not even experience any yield decline (Stocking, 1996). Fertilizer applications would be irrational;
- it is only a proxy for actual productivity loss;
- artificial fertilizers supply nutrients in plant available form, whereas erosion also removes fixed elements (Clark, 1996); and
- a rational response would be to apply fertilizer only as long as the compensatory input produces revenue and not all that is lost (Fox and Dickson, 1988).

The replacement cost approach can estimate costs that are significantly greater than those obtained using the change of productivity approach (Predo *et al.*, 1997), although it does not account for soil physical changes (Grohs, 1994). This is particularly the case on better soils. It take changes of the capital stock into account and addresses thus the issue of potential production.

Most studies rely on the cost of inorganic fertilizer (Table 3), not on the actual cost of replacing the nutrients, which would also include the cost of transporting the fertilizer to the field as well as its application. Both activities are time consuming, particularly in upland environments where farmers' fields may be at a considerable distance from their village (Enters, 1992). Kim and Dixon (1984, cited in Clark, 1996) value the costs of physically returning the soil where it came from by trucks. Norse and Saigal (1992) suggest expressing the nutrient loss in terms of potential loss of production and comparing it with the cost of soil conservation. This comes very close to the change of productivity approach, when the impacts of eroding practices are compared with soil-conservation practices.

Table 3. Methods used to evaluate the costs of soil erosion.

Author, year, and location	Method	Comments
Wiggins and Palma, 1980 El Salvador	Change of productivity	Compared with soil-conservation practices
Attaviroj, 1986 Thailand	Change in area under cultivation	On-site benefits not calculated
Cruz *et al*., 1988 Philippines	Replacement cost	What actually constitutes an economic cost is unclear

Table 3. cont'd.

Author, year, and location	Method	Comments
Bishop and Allen, 1989 Mali	Change of productivity Replacement costs approach in Appendix B	Costs and impact of conservation not accounted for costs of Costs of fertilizer application not accounted for Adjust for plant availability of nutrients
Magrath and Arens, 1989 Java, Indonesia	Change of productivity	Costs and impact of conservation not accounted for
Ehui et al., 1990 Western Nigeria	Change of productivity	comparison of cost and impact estimates for five different land-use systems
Norse and Saigal, 1989 Zimbabwe	Replacement costs; based on earlier work by Stocking (1986)	Include a nutrient budget perspective
Pagiola, 1993 Kenya	Change in productivity	Uses crop budgets to compare cropping with and without terraces
Grohs, 1994 Zimbabwe	Change of productivity	Costs and impact of conservation not accounted for
Bishop, 1995 Mali and Malawi	Change in productivity	Costs and impact of conservation not accounted for
Barbier, B., 1996 Central American Hillsides	Proposes change of productivity	Costs and impact of conservation not accounted for
Eaton, 1996 Malawi	Change of productivity adapted data from Ehui *et al*., 1990	Calculates the present value of incremental net returns (PVINR) for alternative cropping systems
Nelson *et al*., 1996b Philippines	Change of productivity	Compare costs and impacts of three alternative systems

In summary, the replacement cost approach is simple to apply when nutrient loss data are available (Bojö, 1996; Predo *et al.*, 1997). However, as Richards (1997) notes, the use of fertilizers to replace eroded soil nutrients is clearly an imperfect proxy. It assumes that it is possible to produce crops without soil erosion, an underlying assumption for which the change in productivity approach is criticized too (Barbier, 1996). In addition, the replacement costs approach is probably more difficult to comprehend by farmers — in particular subsistence farmers — because they do not experience the cost of fertilizers and its replacement directly themselves. This deficiency thus hampers active participation of farmers in the analysis.

The change of productivity approach

In recent years, the change of productivity approach has been used by the majority of analysts (Table 3). Following the approach, the erosion damage equals the value of the lost crop production valued in market prices (Grohs, 1994). As a physical measurement it relies on crop yields with and without soil erosion. Crop yields are then multiplied by the unit price of the crops.

The change in productivity approach is logical and is straightforward to apply. The use of the latest simulation models allows for making yield forecasts under a variety of conditions. However, the methodology has some inherent problems too. First, crop production is highly variable and depends, especially in a monsoonal climate, on the reliability of the onset of the rain (this explains partially why farmers do not see the direct connection between erosion and crop yields, or view erosion as an event that washes away seeds and fertilizer but not the soil).

That yield decline is not always ascribable to nutrient depletion caused by erosion has been pointed out by various authors (Nye and Greenland, 1960; Lindgren, 1988; Theng, 1991; Prasad and Goswami, 1992). Weeding has long been recognized as an important determinant of crop yields in the tropics (Moody, 1982; Warner, 1991). In particular, during the early stages of plant growth, weeds seriously compete with agricultural crops. Ashby and Pfeiffer (1956, cited in Chang, 1968) have shown that effective weeding can increase yields by more than 100%. As cultivation continues, weeding pressure increases (Clarke, 1976) and ultimately forces farmers to abandon a field and to shift cultivation to a new area (Moody, 1982). The change from shifting cultivation to permanent agriculture is also resulting in the elimination of many woody, secondary species and their replacement by aggressive, herbaceous, and pantropical weeds (Kellmann, 1980). Shifting cultivators in particular are far less affected by soil erosion *per se* but rather by an increase in labour requirements that correlates with shorter fallow periods. Thus, contributing observed yield declines only to erosion results in cost overestimates.

Second, the technique has to ensure that technological progress over time is isolated from the analysis. The correct measure of yield damage from erosion is the difference between yield applying erosive techniques and yield applying soil-conserving practices. The question of what production in the eroded cases should be measured against is not answered in most studies. Yield declines are compared with hypothetical benchmarks of uneroded soils as if soil-conserving crop production would not have a completely different cost structure. In fact the major cost of conservation is labour input (de Graaff, 1993) and the need to perform certain tasks during a season of low labour availability may be a significant cost factor (see example in Table 4 and discussion in 7.4).

Table 4. Median labour estimates for maize cultivation in the Philippines (adapted from Nelson *et al.*, 1996c).

Operation	Description	Hedgerow intercropping		Traditional farming	
		PD ha^{-1}	PAD ha^{-1}	PD ha^{-1}	PAD ha^{-1}
Hedgerow establishment	Setting out contours, weeding, and ploughing 1 m contour strips, gathering and planting double rows of cuttings	51	9	-	-
Land preparation	Ploughing twice with a mouldboard plough, harrowing and furrowing of planting rows twice	-	22	-	26
Sowing and fertilizing	Hand fertilizing in planting holes	9	-	11	-
Pruning at planting	With machete to 50 cm. Prinings applied evenly to the cropping alleys	10	-	-	-
Thinning	Hand thinned to 1 plant per hill	4	-	5	-
Weeding	One month after planting	14	5	17	6
Pruning during crop	Every 45 days. Prunings applied evenly to the cropping alleys	10	-	-	-
Harvesting	By hand	9	-	10	-
Postharvest clearing	Cutting remaining plants in the fields	11	-	13	-
Total		117	36	56	32

Note: PD = person days.
PAD = person-animal day.

Third, it is unclear what type of benchmark practice soil-eroding practices should be compared with. Especially the question of which benefits to include has not been answered. If we follow Eaton (1996), the present value of incremental net returns (PVINR) would measure differences in long-term crop yields against differences in labour input. If the alternative to a till system is a no till system, this procedure does not cause any problem, because we are not dealing with a product change. However, an agroforestry or contour cropping system uses part of the original cropping area and produces new crops. As Norse and Saigal (1992) argue, returns derived from the new crops should not be included in a national soil-erosion assessment. From a farm household's point of view, however, such returns need to be considered. Excluding them from a CBA would be irrational.

Fourth, if all cost and benefits are considered then in a macrocatchment or national level assessment, the question arises where to draw the line for the on-site analysis. For example, if the dissemination of soil-conserving practices is coupled with intensified extension then should the costs of extension be included?

Fifth, the possible existence of irreversibility means that a higher cost should be charged against erosion than just the estimated relation between yield decline and erosion to include the possibility of irreversible damage (Sanders *et al*., 1995) and the reduction of capital stock (see 6.1)

Cost-benefit analysis of on-farm impacts

A CBA of alternative agricultural practices with and without, or reduced, erosion is futile as long as it does not consider a farm household's circumstances and the different input requirements. Farming systems are highly heterogeneous. Amongst others, they differ in the degree of mechanization, cash or subsistence crop orientation, the area under perennial crops, and the involvement in livestock rearing. Furthermore, there are differences in social, ethnic, and household characteristics as well as in accessibility and marketing opportunities. All these factors influence what a household can do and perceives to be in its interest, in other words, what is appropriate to analyze within the framework of the CBA.

Most studies analyzed for this review focus on parameters of the natural system. As has been shown, without the knowledge of soil and crop interactions, it is not possible to assess the on-site costs of soil erosion. However, the in-depth knowledge of the natural system is not sufficient to evaluate costs and benefits properly. The basic CBA also requires economic data whose collection can be just as time consuming and arduous.

The basic methodology of economic analysis comprises two steps, which can be further subdivided into seven steps (Box 2):

- identify and measure the environmental effects; and then,
- translate them into monetary terms in the formal analysis.

Within the scope of this review it is not possible to discuss all aspects of conducting a CBA. Instead the following discussion will focus on four critical issues. They are:

- the evaluation criteria;
- the discount rate;
- the time horizon; and
- the value of labour.

Box 2. The main steps of cost-benefit analysis

1. Defining the alternatives
2. Identifying environmental effects (cost and benefits)
3. Selecting key externalities
4. Quantification in physical terms of the environmental effects
5. Valuing of the environmental effects
6. Weighing of the costs and benefits
   a. between different income groups
   b. in time (discounting)
7. Sensitivity analysis

Adapted from Angelsen and Sumaila, 1995.

Choosing the appropriate evaluation criterion

For comparing costs and benefits of alternative actions or investments, four appraisal and evaluation criteria are commonly used. They include: internal rate of return (IRR), benefit-cost ratio (BCR), net present value (NPV) and net benefit-investment ratio (Gittinger, 1982; Bojö, 1986b). The essential element that the four measures have in common is that they allow costs and benefits to occur in streams spread over time (Bojö, 1986b). The time aspect is crucial when soil-conserving practices are compared with exploitative practices. In terms of crop productivity, practices become more distinguishable only in the future. In other words, yields are expected to differ more significantly in the future than at present or after a period of only two to five years. The production of perennial crops has similar characteristics. A gestation period of four to five years means that costs occur while no benefits can be reaped. Thus not only may absolute costs and benefits differ but they may also occur at different times. A comparison is only possible by bringing the stream of values together and discounting needs to be applied to properly evaluate the investments (Betters, 1988).

The appropriateness of the four evaluation criteria for choosing among alternatives has been discussed in detail by Gittinger (1982) and Price and Nair (1984). All four criteria assist decision making as to how far one option is “better” than others. Yet, their results are sometimes misleading (Trivedi, 1986; Price and Nair, 1984). The NPV is considered to be the best all-round selection criteria (Wasberg, 1989) and also the most straightforward (Gittinger, 1982), although Hueting (1991) contends that the NPV formula is meaningless for environmental measures when long-term effects are involved.

Hueting's criticism reminds us that the application of CBA is not undisputed in environmental economics. Unfortunately it has several disadvantages, which it has in common with many other evaluation methods. It has received considerable criticism in the literature for various reasons (Enters, 1992). Most critiques have been refuted by economists as irrelevant because they are rather directed at traditional economics and not CBA *per se*. Critics and advocates of CBA are still debating valuation as a decision-making aid. Its objectivity (Tacconi, 1995) and value-neutrality (Söderbaum, 1994) are questioned.

This is not the place to provide an in-depth analysis of the points raised by economists, ecologists and philosophers over the last ten years. It should be suffice to say that CBA is not a means to an end, but a coherent method for organizing and presenting information expressed in monetary values, which allows for direct comparison among alternative options such as soil- eroding and soil-conserving land-use practices. Expressed in a monetary value it is not only possible to compare alternative land uses but also to aggregate the NPV or the present value of incremental net returns (PVINR) of individual activities. Thus the costs of erosion can be estimated not only for one field but also for a whole farm enterprise, a community or any larger area. The basic technique of calculating the NPV is "to discount costs and benefits occurring in different periods and express them all in a common value at any one point of time" (Squire and Tak, 1975, p. 39). If the NPV is positive, the investment earns a surplus. Deducting the stream of net income earned from the erosive practices from the stream of net income from a soil-conserving practice determines the "incremental" value which in this case is the cost of erosion (Eaton, 1996).

Choosing the "right" discount rate

The real rate of discount is a much debated issue (Enters, 1992; Ekbom, 1992; de Graaff, 1996). The calculation of NPVs requires the determination of an appropriate discount rate, both as a private and/or social rate. A "weak spot" in many cost-benefit studies is the rationale for the choice of discount rate (Bojö, 1986a; Ekbom, 1992). The selected interest rate obviously influences the results of the CBA and needs careful consideration (Hoekstra, 1985). The emphasis in the following discussion is on "appropriate". According to Gittinger (1982, p. 314)

> "for financial analysis, the discount rate or cut-off rate is usually the marginal cost of money to the farm or firm for which the analysis is being done. This often will be the rate at which the enterprise is able to borrow money."

Frequently, borrowing and saving rates do not indicate appropriate discount rates because such facilities are not available to smallfarmers (Hoekstra, 1987; Moll, 1989). Where equity capital is used it is possible to determine the rate of return a farmer normally expects from some existing long-term farm enterprises such as livestock or orchards. However, most smallfarmers use little equity capital (Hoekstra, 1985). Tiffen (1996, p. 168) on the other hand has recently pointed out that “even poor people can find capital for what is really profitable, and the importance of that capital in raising the productivity of agriculture as land becomes more scarce”. This emphasizes again the diversity of situations and calls for a very careful analysis in every individual case.

According to Hoekstra (1985) the discount rate differs among farmers and is based on several factors regarding the farmers’ current status, outlook, attitude towards risk and uncertainty and the length of waiting time before consumption. Using this approach, well-fed farmers who are pessimistic about the future because they face sustainability problems on their farms have a lower discount rate than poorly fed farmers with an optimistic outlook regarding future production. As a result, applying the same discount rate to all farmers should be avoided. While acknowledging differences in time preferences and discount rates among farmers is useful, Hoekstra (1985) ultimately does not discuss what exactly constitutes an appropriate rate. Furthermore, it is also not necessarily the question whether farmers are willing to forego present consumption but rather whether they are able to do so. For resource-poor households in many upland environments this question should be answered negatively.

Schreier (1989) suggests that smallfarmers base their investment decision on their marginal time preference rate (MTPR). He acknowledges that it is a problem to discover the appropriate MTPR and suggests that it is usually higher than a government subsidized interest rate. This is reiterated by Barbier (1996, p. 4) who stresses that “private individuals are also presumed to have a high degree of time preference, and thus employ higher discount rates, on average, than society as a whole”. Since the social rate of discount is usually assumed to be in the order of 10%, the private rate of discount would be higher, i.e. at least 15%.

Betters (1988) recommends using a range of discount rates in financial analysis because of the difficulty in specifying appropriate rates. The review of various studies (Table 5) shows that some analysts are following this suggestion. It also highlights that several authors do not provide any kind of rationale for their choice of discount rate. The empirical basis for the rates used is at best weak; in most studies no explanations are provided, a criticism voiced by Bojö (1986b) more than ten years ago. Furthermore, in several studies differences between the private and social rate of discount are not stressed or obvious.

Table 5. Applied discount rates.

Author, year, and location	Rate in %	Rational for choice of particular rate
Wiggins and Palma, 1980 El Salvador	5, 10 and 15	Based on prevailing commercial rates + 2% to compensate for subsidized credits + 2% for unsatisfied demand
Attaviroj, 1986 Thailand	5, 10, 20	Not discussed
Cruz *et al*., 1988 Philippines	n.a.	Only costs for one year calculated
Bishop and Allen, 1989 Mali	10	Not discussed Conservative assumption
Ehui et al., 1990 Western Nigeria	10	Opportunity cost of capital
Pagiola, 1993 Kenya	10	Not discussed
Grohs, 1994 Zimbabwe	0, 10, 15	Not discussed
Bishop, 1995 Mali and Malawi	5, 10, 15	Costs and impact of conservation not accounted for
Eaton, 1996 Malawi	5, 10, 15	Not discussed
Nelson et al., 1996b Philippines	12 and 40	12% is rate of time preference estimated in another study Farmers face 40% interest rates or more
Renaud, 1997 Thailand	0, 10, 15, 26	Average interest rate farmers face when borrowing money in the village

Note: Figures in bold represent the base case.
n.a. = not applicable.

Choice of time horizon

The NPV is not only very sensitive to discount rates but also to time horizons. Here again the analyst is faced with making assumptions. Dixon and Fallon (1989) argue that many poor subsistence farmers may have a time horizon that only goes to the next season because of pressing current needs. This shortsightedness, they continue, explains exploitative patterns of land use and the farmers' unwillingness, incapability or disinterest in investing in resource conservation. Barbier (1987) points out that poor people often have no choice but to opt for immediate economic benefits at the expense of the long-term sustainability of their livelihoods.

While there is no doubt that many upland farmers make decisions to fulfill their short-term needs, it would be wrong to assume that their decision making is generally guided by short-term thinking. In particular under the present bio-physical and socioeconomic conditions as well as externally imposed land-use restrictions, many villagers spend long hours discussing strategies to improve their standard of living and to provide for a better future for their children. Recent studies on the transformation of agriculture in Southeast Asia also show that farmers spend considerable financial resources on their children's education, clearly a long-term investment (Rigg, 1997).

If we accept the villagers' shortsightedness, a CBA of growing perennials becomes meaningless. Using a time horizon of, for example, five years would result predominantly in costs and only negligible benefits.

A minimum criterion should be that the time horizon conforms with the production characteristics of the species under investigation. In addition, the "right" time horizon depends partially on the discount rate applied. The higher the discount rate the lower will be the net present value of soil-conserving practices that predominantly have higher returns in the future. Most analysts of the studies reviewed fail to provide any rationale for their choice of time horizon, which ranges from six to 100 years (Table 6).

Bojö (1986b) stresses that distant future benefits should not be exaggerated, because extending the time horizon from 30 to 40 years, for example, would have only a marginal effect on the net present value, using a discount rate of 10%.

Table 6. Choice of time horizon.

Author, year, and location	Time horizon in years	Reasons given
Wiggins and Palma, 1980 El Salvador	30	Conservation measures last for at least 30 years
Attaviroj, 1986 Thailand	15	On-site benefits not calculated
Cruz *et al*., 1988 Philippines	Estimates only for one year	Not discussed
Bishop and Allen, 1989 Mali	10	Not discussed Conservative assumption
Ehui et al., 1990 Western Nigeria	20	Not discussed
Pagiola, 1993 Kenya	100	Not discussed
Grohs, 1994 Zimbabwe	50	Not discussed
Bishop, 1995 Mali and Malawi	5, 10, 20	Not discussed

Table 6. Choice of time horizon.

Author, year, and location	Time horizon in years	Reasons given
Eaton, 1996 Malawi	10 and 20	Not discussed
Nelson et al., 1996b Philippines	25	Not discussed
Renaud, 1997 Thailand	6	Ex-postproject evaluation of six-year project

Note: Figures in bold represent the base case
n.a. = not applicable

Valuing labour

In their review of six studies that estimated the costs of erosion in Canada, Fox and Dickson (1988, p. 27) conclude:

> "Farmers have been reluctant to adopt conservation tillage, not because of a lack of information, not because of 'perceptions' and not because 'old habits die hard', but because they would lose money, both in the short and in the long run."

They also find (p. 1) that "soil erosion costs farmers dearly" but that soil conservation costs them even more. The reason for this discrepancy is that, as Fox and Dickson (1988) criticize, technologically unattainable standards are used as a basis for measuring erosion costs. Several of the studies reviewed here also operate on the assumption that sustainable crop production is possible without any additional costs, although labour inputs may change considerably with the introduction of a new technology. There is no or only minimal value ascribed to labour, and its greater use may even be counted as a benefit — apparently reducing unemployment or at least seasonal underemployment — as in the study in El Salvador (Wiggins and Palma, 1980).

Investment costs and labour requirements in soil conservation are usually high (De Graaff and Nibbering, 1996). Given the considerable proportion of family labour in both crop production and soil conservation and the fact that assumptions on labour input and wage rates drive the results of any economic assessment, it is absolutely crucial to obtain an accurate value of the opportunity cost of labour (Ellis-Jones and Sims, 1995). Unfortunately the importance of labour inputs and costs (establishment as well as maintenance) are all too often underestimated. This shortcoming of several studies was briefly criticised above. Table 4 provides an overview of the potential differences between two alternative cropping systems.

Identifying the appropriate opportunity cost of labour is not easy. It depends on the nature of the activity to be performed, on the characteristics of the labourer (age, wealth, and gender), the season (growing season or slack season) and the availability of nonfarm and off-farm employment. Most studies are characterized by a strong farming bias even though farm household incomes are increasingly influenced by off-farm employment opportunities. This development severely restricts labour availability at certain times of the year and raises the opportunity cost for labour, particularly of younger farmers who favour nonfarm employment opportunities over agriculture (Parnwell and Taylor, 1996; Rigg, 1997).

Renaud (1997) uses a cost of 50 baht day^{-1} that corresponds with the agricultural salary paid in the region. To Nelson *et al.* (1996b) labour is the most important variable cost in upland farming systems. They report (p. 19) that a "farm laborer would expect to be paid 120 pesos day^{-1} and receive meals valued at 40 pesos". However, none of the interviewed farmers was working for these daily wages, neither could they afford to hire at this cost. As off-farm labour was only very sporadic the authors used beside 160 a rate of 35 pesos day^{-1}. The second estimate not only decreased the absolute cumulative net present value of all three alternatives, but also made the soil-conserving land-use practices more attractive than the other two alternatives.

How to value labour is an issue as much debated as the choice of discount rate and time horizon. While it has been suggested that under certain circumstances the opportunity cost of labour can be zero (Stocking and Abel, 1993), it is doubtful whether zero return to labour is acceptable even under conditions of high unemployment. What is clear is that labour costs vary enormously according to circumstances that need considerable attention in extrapolating results.

Scaling up from field to national levels

CBA of the on-site impacts of soil erosion can be conducted at various hierarchical scales. The discussion above focused predominantly on cropping systems or the field and the farm household as the decision-making unit, although including the potential effects of employment and income generating off-farm opportunities moved the discussion to a higher hierarchical level, such as the region or the nation. What happens at one scale usually influences the outcome at other scales. To stay with the example, means that demand for off-farm employment may have repercussions for what is happening on the farm, which may be in a different geographical location. These interactions should be considered when moving from one scale to the next.

Izac and Swift (1994) defined five hierarchical levels for measuring agricultural sustainability in small-scale farming in sub-Saharan Africa (p. 109):

- cropping system
- farming system
- village/catchment system
- regional system
- supra-regional system

For other parts of the world the supra-regional level may be less relevant and can be replaced with the national level, which is in fact the level most authors have used for aggregating their cropping systems results.

According to Izac and Swift (1994) the lowest level in the hierarchy, the cropping system, is the smallest spatial unit, or the scale “at which specific biological processes such as nutrient uptake or plant competition are regulated and may be studied (p. 109)”. It is also the scale where most research on soil movement and the relationship of soil erosion and crop productivity is conducted. This is where the baseline information about the natural system is derived from. However, it is not the level of decision making. Decisions regarding crop choices and management practices are made at the farm. Here farmers respond to numerous incentives (e.g. prices for farm inputs and crops) and disincentives and numerous interactions occur with the next higher levels, especially the catchment system. This third level is important for considering the flow of nutrients and sediments and is therefore of particular relevance for quantifying the off-site impacts of soil erosion.

The on-site costs of erosion can be aggregated to any higher level from the lowest spatial unit upwards. The most important level is most likely the national, although it is desirable to aggregate by individual catchments, mountain ranges or administrative units in an intermediate step to identify “hot spots” or priority areas for soil-conservation investments.

Not all of the studies reviewed scaled their results up to a higher level. The ones that did (Table 7), chose the national level for aggregation and used national resource accounting procedures to integrate soil degradation concerns into traditional measures of national accounts, such as gross domestic product (GDP). The main objective of the national level studies is to “put a value on a natural resource that is ‘used up’ through agricultural production by applying a ‘national resource accounting’ approach to quantify the cost of soil degradation to the economy” (Grohs, 1994, p. 25).

Table 7. Annual on-site costs of erosion expressed in percent of agricultural GDP.

Author, year, and location	Number of landscape units used	% of AGDP
Wiggins and Palma, 1980 El Salvador	6 according to slope range and the presence of topsoil	n.a.
Bishop and Allen, 1989 Mali	6 representative map sheets	4 to 16
Magrath and Arens, 1989 Java, Indonesia	20 according to estimated soil type and soil loss Separate estimates for cassava	1.6
Grohs, 1994 Zimbabwe	5, according to average annual sheetwash erosion from crops	0.36
Bishop, 1995 Mali and Malawi	Mali: 6 representative map sheets Malawi: 8 according to erosion hazard	Mali: 3-13 Malawi: 17-55

Note: n.a. = not applicable.

The valuation techniques discussed above can be used at any level, although there are some severe limitations.

It is not possible to estimate the cost of erosion for each individual field or farm. Therefore, authors usually identify landscape units for which they expect the same or similar impacts. As the information in Table 7 shows, the development of landscape units follows different approaches. They are basically very similar to the approaches used for the spatial assessment of erosion risk (Batjes, 1996). The most straightforward approach is then to add up the annual costs of soil erosion for each unit and thereby derive the total cost due to erosion nationwide (Bishop, 1995). Once spatial data are stored in a geographic information system data manipulation and analysis becomes very simple.

The straightforward approach described above has a number of problems that are not immediately apparent when only aggregate figures are provided. First, as Bishop (1995) points out, they ignore possible price effects of increased agricultural production if erosion did not occur. Also, most studies do not allow for a change in crop choice over time. In response to declining productivity, farmers may change to less nutrient demanding crops.

If originally soil loss was measured on the smallest spatial unit, then the aggregation will also only deal with soil loss. Adding up all the soil losses basically means that deposition is ruled out. All the eroded material is treated as a negative externality. As a result, total cost to the national economy is overestimated. The problem of not accounting for the redistribution of soil and its potentially productivity enhancing deposition has been discussed above.

Investigating the parameters that delineate landscape units reveals that authors have exclusively relied on biophysical descriptors. As was stressed earlier, the cost of erosion depends on biophysical as well as economic processes. Variables such as crop prices, off-farm employment opportunities, discount rates, credit availability, and farmers' perspectives affect the cost of agricultural production and erosion as much as slope, soil quality, and rainfall intensity.

Off-site impacts and costs

Moving up to higher hierarchical levels leads to a situation where the costs of soil erosion are not internalized anymore through financial feedback (Bojö, 1996), i.e. declining productivity that directly translates into a loss of income to the farm household. Once soil and excessive runoff leave the boundary of individual farms they cause off-site or off-farm impacts and result in costs that are external to the farm household's decision making. Clark (1996) lists 16 off-site effects of which the most important are in-stream problems of water quality and quantity, sedimentation effects on reservoirs, the degradation of potable water, a decrease in the availability of irrigation water, increased dredging or siltation, accelerated runoff leading to localized flooding, reduced hydrological cycling and recharge of groundwater. The costs are not internalized and affect downstream landowners — Cruz *et al.* (1988) call them downstream costs of soil erosion — and water users in various ways. They are therefore termed externalities and can be positive or negative although most economists discuss only negative externalities and their impacts.

In developed economies, the main negative externality of soil erosion is nonpoint water pollution, which affects water supplies for residential and industrial purposes, results in water nutrient enrichment, and reduces the biological diversity of water bodies as well as the recreational and amenity values of water resources. In developing countries on the other hand, the main impact is probably the sedimentation of hydroelectric, flood control, and irrigation facilities.

Research and applied economics have concentrated on the on-site impacts of erosion and degradation; the analysis of off-site effects, despite being recommended now and again, has not yet progressed as far (Biot *et al.*, 1995). Authors of several of the studies reviewed stress the importance and potential magnitude of off-site impacts, although they opt to focus exclusively on on-site impacts (see Table 8 for the studies considering externalities[2]). As is the case

[2] The reader is especially referred to Grohs (1994) for an excellent empirical study of the off-site costs of erosion in Zimbabwe. for a review on the hydrological benefits of forests see Chomitz and Kumari (1996). Guidelines for valuing watershed functions of forests can be found in Gregersen *et al.* (1995).

with on-site damages, costs must be computed to alternative land uses. Not all authors compare exploitative cropping practices with conservation farming. Kramer *et al.* (1997) for example use intact tropical forests as a benchmark land use in their study in eastern Madagascar. It is therefore not possible to compare the studies directly.

Table 8. Estimating the off-site cost of soil erosion.

Author, year, and location	Impacts	Assessment approach
Wiggins and Palma, 1980 El Salvador	Reservoir sedimentation	Reduced hydroelectricity generating capacity valued in terms of least cost alternative sources of power
Veloz et al., 1985 Dominican Republic	Reservoir sedimentation	Lengthening of lifetime of dam valued in electricity produced
Attaviroj, 1986 Thailand	Reservoir sedimentation and increased flooding	Loss of irrigation capacity valued in terms of reduced cropping area, depletion of hydroelectricity capacity valued in terms of diminished electricity generation, annual costs of maintaining the drainage system
Briones, 1986 Philippines	Reservoir sedimentation	Reduced electricity production, loss of irrigation capacity valued in terms of foregone income, increased flood control
Cruz *et al*., 1988 Philippines	Reservoir sedimentation	Reduction in service life of the dam, reduction in active storage for irrigation and hydropower, opportunity cost of providing for substantial sediment storage capacity
Margrath and Arens, 1989 Java, Indonesia	Reservoir sedimentation	Foregone hydroelectric and irrigation benefits
Grohs, 1994 Zimbabwe	Reservoir sedimentation	1. Loss of irrigation capacity valued in terms of foregone income, increased ooperation, maintenance and dredging costs 2. Costs of replacing the life storage lost annually 3. Costs of constructing dead storage to anticipate the accumulation of sediments
Kramer et al., 1997 Madagascar	Flooding of agricultural	Flood damage valued in loss of income due to yield losses
Richards, 1997 Bolivia	Flooding and increased water availability	Estimation of losses due to floods Opportunity cost of water (net benefit)

Estimating the off-site economic impact of soil erosion

The off-site costs are normally measured in terms of the net present value of foregone net benefits from any loss of downstream economic activity (Barbier, 1996) or of additional operating costs, such as dredging costs for canals, reservoirs or port facilities. A wide spectrum of assessment approaches is used. Most authors focus on sedimentation and the reduction of a dam's service life, the annual reduction in life storage area, and the costs of preventive measures. The methodologies employed in calculating the off-site costs are specific to the type of downstream impacts and the actual or potential losses to be encountered. Kramer *et al.* (1997) for example concentrate on flooding of agricultural land because there are no reservoirs in the area. The following discussion summarizes available valuation methods briefly and turns then to the very complex issue of quantifying impacts, with a focus on sedimentation.

The costs of unexpected and excessive sedimentation of reservoirs can be calculated using one of the following three approaches (Grohs, 1994, p. 93):

- Change of productivity, i.e. evaluating the income foregone from not being able to irrigate fields caused by the reduction in dam yield, increased operation and maintenance costs of irrigation schemes, and the higher operation and maintenance costs for removing sediments through dredging and replacing damaged equipment such as turbines.
- Replacement cost, i.e. the costs of replacing the live storage lost annually.
- Preventive expenditures, i.e. the costs of constructing dead storage to anticipate the accumulation of sediments.

The methodologies for valuing the costs of sedimentation are rather similar to the earlier discussed approaches to on-site cost valuation. They are also applicable for other damages such as increased flooding, when for example the expenditures for constructing flood prevention structures are estimated (Gregersen *et al.*, 1995) or the impacts on marine life for which Hodgson and Dixon (1988) used the foregone benefits from fisheries and tourism as a proxy (see also Table 9).

Table 9. Summary of economic losses in eight watersheds in Bolivia (adapted from Richards, 1997).

	Baseline estimate $000	Adjusted normal year $000	Adjusted severe year $000
Dredging/preventive:			
CORDECO (210 000t)	653	568	1136
Palliative defensive works	162	141	282
Municipality	124	108	216
Damage to infrastructure and road cleaning	62	54	108
Industrial losses	234	204	408
Welfare services	27	24	48
Loss of crops	2529	2200	4400
Loss of livestock	176	153	1204
Cleaning/repair of irrigation ditches and land	104	90	1802
Total annual loss	4071	3542	7982

Note: CORDECO = Regional Development Corporation of Cochamba.

Grohs (1994) used in his study of the economic impacts of sediments on dams and irrigation all three approaches outlined above to estimate the annual costs of damages caused by sediments originating from agriculture. A comparison shows, that similar to the on-site cost calculations, off-farm costs also differ depending on the methodology used (Table 10).

Table 10. Annual off-site costs of agricultural erosion (adapted from Grohs, 1994).

Valuation method prices	Value estimate		
in million Z$ (1989)	Low	High	Single
Change of productivity	-	-	0.6
Replacement cost	0.8	8.8	3.3
Preventive expenditures	1	12.5	5.5

The replacement costs and the preventive expenditure approach are mutually exclusive or the impacts of sedimentation would be double-counted. The contribution of agricultural activities is assessed to be 50% (see also

9.2.2.1). The estimate for change of productivity consists of the costs for annual agricultural income foregone (Z$90,000) as well as dredging costs for maintaining the irrigation scheme (Z$500,000). The annual costs of replacing live storage capacity are based on the actual and estimated construction costs of surface storage capacities. The preventive expenditures are calculated according to the costs for allowing additional dead storage in new dams. The differences in the results between the three techniques are based on theoretical concepts. As Grohs (1994) explains, replacement costs take changes of the capital stock into account, whereas change of productivity treats the investment costs as sunk costs and only looks at the immediate relevant cost items.

Grohs' (1994) example indicates that the estimation of foregone income, additional operating costs or any other cost is fairly straightforward. What is disguised by the apparent ease is that many physical processes are only poorly understood to say the least. Most economic analyses are based on rather suspect or untested assumptions that can have quite dramatic effects on the final estimate, i.e. the total annual and the net discounted cumulative losses (Enters, in press). Some of the more critical issues of quantifying the off-site impacts of soil erosion are reviewed below. The following section addresses explicitly constraints and deficiencies that cannot be addressed by refining valuation methods. It highlights particularly the obscurity of some ecological assumptions and the key problem for many critics of extending economic analysis to its limits, i.e. the lack of knowledge about the true nature of economy-environment interactions (Winpenny, 1991; Hanley, 1992; Lutz *et al*., 1994; Aylward *et al.*, 1995; Enters, 1995; Chomitz and Kumari, 1996, Richards, 1997).

Quantifying the off-site impacts of soil erosion

The description of the world as a complicated place (Proops, 1989) highlights the problem of quantifying the off-site impacts of erosion. Most economists such as Barbier (1987; p. 104) recognize that "given that many of the qualitative dimensions of various trade-offs cannot be quantitatively measured, precise analysis of all benefits and costs cannot be assured". Though the effects of land degradation are often difficult to trace (Upstill and Yapp, 1987), only little attention is being paid to monitoring and measuring the downstream impacts of upstream erosion and runoff. Despite some advances that have been made in understanding downstream impacts of upstream human activities, many attempts to apply cost-benefit analysis to problems of erosion and soil conservation are not very convincing (Lockeretz, 1989) and are often frustrated by imperfect information (Chisholm, 1987). Thus, until today, for many locations it has been impractical or even impossible to judge the merits of alternatives with much confidence (Ray, 1984). Environmental economics as a discipline applied to the problems of developing countries has been described as a "fairly daunting subject to pursue" (Pearce *et al.*, 1990; p. ix). They continue that this is

> "due to the general 'fuzzy nature' of the subject. There are no neat solutions, such as those that appear in the professional journals in respect of more abstract questions, and there are formidable problems of obtaining data and even greater ones in assessing the reliability of what there is."

At this point it is useful to recall the basic methodology of economic analysis:

- identify and measure the environmental effects, and then,
- translate them into monetary terms in the formal analysis.

While the previous sections dealt with the translation into monetary values, the following discussion concentrates on the first step, the identification and measurement or quantification of impacts. According to Proops (1989, p. 71), the following questions will be pursued:

> "Are the problems growing in magnitude and becoming a qualitatively different type? Are things getting worse? If so, by what standards?"

The hydrological impacts of conversion and soil erosion

Forest catchments provide numerous goods and services. These include commodities such as water, timber, and nontimber forest products; and environmental services such as carbon storage, climate regulation, nutrient cycling, local flood control and biodiversity conservation (Mohd Shahwahid *et al.*, 1997). Important environmental services that are often cited as an economic justification for forest conservation strategies are catchment protection functions such as preventing soil erosion and regulating water flows, although the biophysical impacts of conversion to agriculture on water yields are far from being understood[3] (Aylward *et al.*, 1995, Richards, 1997) and the scientific literature has been questioning some of the received wisdom for more than fifteen years (Chomitz and Kumari, 1996). The conclusion that forests act as a sponge — soaking up water at times of moisture surplus and releasing it during the dry parts of the year — and their conversion depletes water yields of affected catchments is surprising as it is contrary to the results of many studies reported in the literature (Bosch and Hewlett, 1982; Hamilton and King, 1983; Cassells *et al.*, 1987; Smiet, 1987; Bruijnzeel 1990; Hamilton and Pearce, 1991, Alford, 1992).

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[3] Bruijnzeel (1990) provides an excellent state of knowledge review on the hydrology of moist tropical forests and the effects of conversion.

The evidence of on-site runoff generation suggests that land-use changes — that is, from forest to agriculture — result in soil compaction, the collapse of macropores and the decline of soil organic matter (Turkelboom *et al.*, 1991). These factors lead to decreased surface infiltration rates, thereby increasing runoff, as shown by Tangtham (1991; see also Tangtham 1994 and Table 11). However, this does not mean that increases in infiltration rates accompanying the adoption of soil-conserving land management significantly reduce the incidence of downstream flooding (Gilmour *et al.*, 1987) or landslides (Bruijnzeel, 1990).

Table 11. Runoff under different land-use practices (adapted from Tangtham, 1991).

Land use	Runoff in mm	Runoff in percent of rainfall	Slope steepness
Unburnt mixed deciduous forest	77	5.5	15
Unburnt dry dipterocarp forest	51	3.6	15
SWC practices	102-113	7.5-8.4	30-40
	29-87	2.1-3.2	25-30
	38-105	2.3-6.4	20-50
	21-61	1.8-5.1	18-40
Burnt mixed deciduous forest	153	10.9	15
Burnt dry dipterocarp forest	85	6.1	15
Traditional upland rice	204	12	54
	135	10	30-40
	117	8.5	25-30
	150	9.1	20-50
	35	2.9	18-40
Bare soil	111.8	9.4	40
	149	11	30-40
	210	12.7	20-50
	150	12.5	18-40
	21.5	1.8	n.a.

Enters (1992) investigates the relationships between discharge and rainfall for the Ping River in Northern Thailand. Though his conclusions should be viewed as tentative, significant changes in river flow patterns linked to land cover transformations at the macroscale cannot be detected (Figure 1). Investigations of small catchments down to plot size, however, do indicate runoff and flow responses due to changes in land cover and land management (see also Dyhr-Nielsen, 1986; Alford, 1992; TDRI, 1995).

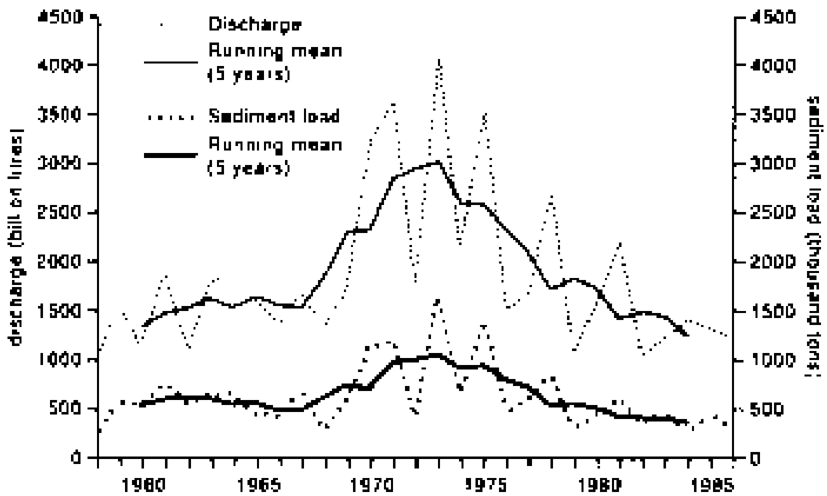

Figure 1. Discharge and sediment load for the Ping River in Northern Thailand, 1958-86.

With regard to assessing the economic impacts, a crucial issue is whether they are viewed as a cost or a benefit to downstream land users. While it is generally believed that an increase in available water poses a problem, Fujisaka (1991, pers. comm.) and Gibson (1983) report that increased runoff early in the wet season is viewed as a benefit by wet-rice planting lowlanders because it allows earlier planting and reduces crop failure. In his study in Costa Rica, Aylward (1997, pers. comm.) views increased water yields as a benefit valued as additional hydroelectricity generating capacity.

A final point needs to be made with regard to the hydrological impact before turning to the effects of sedimentation. The flooding of lowland areas — sometimes referred to as floodplains — is often viewed as the direct consequence of land-use changes in upland areas. It may not be “indiscriminate” land-use practices of upland farmers that contribute to increasing flood damage but rather land-use changes in the flood-affected area such as unplanned settlement, river channel constrictions, urbanization, surface sealing or excessive groundwater withdrawal leading to land subsidence. Poor watershed management practices and conversion from forests to fields may exacerbate the effects of floods, particularly local events, but they are not the cause of major floods in downstream areas. Also, the rate of rise and fall of hydrographs is controlled more by rainfall characteristics, soil and subsoil properties and the storage geometry of river channels than by vegetation types (Hamilton and Pearce, 1991).

Understanding the complex biophysical interactions within a watershed is a major analytical problem (Dixon, 1997; Gilbert and Janssen, 1997) and it will not be possible to progress much further if research is not directed towards some fundamental environmental science issues (see for example Gregersen *et al.*, 1996). As the examples of land subsidence and downstream land-use changes illustrate, research on the impacts of erosion and forest conversion should not be restricted to dynamic developments in upstream areas but needs to consider the transformation of downstream areas as well, in order to understand accurately why “things are getting worse”. Examining catastrophes such as weather irregularities in their historical context may also reveal that droughts and floods are not only incidents of the recent past (see Enters, 1992 for examples from Thailand).

The impact of sedimentation

Fertile flood plains, alluvial fans, and deltas have been formed in the past and are today the sites of intensive and high value agriculture. From this perspective, upstream soil erosion is beneficial for the lowland economies. For example, people protesting against the Aswan Dam claimed that the dam traps the rich sediments of the Nile (Seckler, 1987), which are no longer deposited on their fields. The annual loss of nitrogen contained in the sediments of the Nile was valued at US$150 000 (Shalaby, 1988; cited in Dixon *et al.*, 1989a), a considerable foregone benefit. To enhance the process of sediment deposition, ground cover has sometimes been destroyed in watersheds to accelerate soil erosion (Seckler, 1987) and the positive effects of a continuous flow of silt-bearing irrigation water on disease control was noted by Ignatieff and Lemos (1963).

In contrast to some of the misconceptions regarding the hydrological impacts of land-use changes on water yields and water regimes, the presence of sufficient ground cover and the application of soil-conserving agricultural practices minimize erosion and thus sedimentation (Hamilton 1986; Cassells *et al.*, 1986). But, as Hamilton (1986, p. 40) writes, it is important to remember that “streambank erosion and streambed degradation are normal processes, and much sediment that causes mischief derives from these sources”. Notwithstanding these qualifications, a recent study in Yunnan found the following (Whitmore *et al.*, 1994, p. 70):

"1. Transport rates of sediments and nutrients from watersheds to lakes are substantially higher in recent centuries than in the geologic past.
2. Changes in transport rates coincide with increased human activities and were anthropogenically induced. (climatic effects were probably not significant with respect to anthropogenic influence in the past several centuries).
3. Present rates of soil loss, nutrient exports from watersheds, and sediment infilling of lakes are likely to have serious consequences for the future sustainability of agricultural production and the local economies in Yunnan watersheds."

The studies reviewed conclude that upstream erosion leads to quite substantial downstream costs. Attention to the potential effects of sedimentation has increased with the realization that many watersheds drain into major dam and reservoir systems that provide irrigation, hydroelectricity, and flood control services. It is therefore not surprising that most authors focus on reservoir sedimentation as the major cost component (Table 12).

Table 12. Estimated costs of sedimentation in the Pantabangan and Magat reservoirs (adapted from Cruz *et al.*, 1988).

Source	Annual sedimentation costs in Philippine pesos			
	Per hectare		Per ton	
	Pantabangan	Magat	Pantabangan	Magat
Reduction in service life	1.11	0.10	0.02	0.01
Reduction in active storage				
- for irrigation	12.99	n.a.	1.19	n.a.
- for hydropower	2.91	n.a.	0.15	n.a.
Opportunity cost of dead storage for irrigation	575.55	365.61	28.78	18.00
Total	592.56	365.71	30.14	18.01

Valuing the impacts of sedimentation (see 9.1) is far more straightforward than actually quantifying what needs to be valued. A major drawback to studying changes in sediment levels is the paucity of historical data. Where data exist they may be of dubious quality or they may not show—yet — what is usually expected, i.e. a dramatic increase in sediment loads (cf. Figure 1).

While claims of excessive sediment loads are common (Milliman and Meade, 1983), it is not the absolute level that is of interest in the economic valuation but instead the relative increase caused by land-use changes and accelerated erosion. Often, gully erosion (Zhang *et al.*, 1997) and mass-wasting mechanisms (e.g. landslides) contribute more to erosion than surface erosion phenomena in uplands and highlands, even without human influences (El-Swaify, 1997). Knowing the contribution of upland agriculture to total sediment loads is therefore crucial if cost estimates are to be meaningful, although it is difficult to separate accelerated erosion from natural erosion because human influence on erosion is ubiquitous (Whitmore *et al.*, 1994).

There are at least four aspects that need further consideration before it is possible to estimate foregone income or damages due to the off-site impacts of erosion. They include:

- potential sediment sources;
- spatial displacement and sediment delivery;
- time dimension; and
- reliability of sediment load estimates.

Sediment sources

It should be obvious that without identifying and quantifying the sources of stream sediment in specific catchments it is impossible to evaluate the impacts of soil erosion or soil conservation (Bruijnzeel and Critchley, 1996). Most of the economic analyses referred to above assume that increases in sediment load are the direct result of forest conversion to soil-eroding agricultural practices. An exception is Grohs (1994) who attributes only 50% of silt loads in reservoirs to erosion from agricultural lands.

Quantitative analyses of contributions of various sediment sources to total sediment loads for large watersheds are rare. Kraayenhagen (1981) concludes in his study that more than 80% originated from riverine and road erosion for a small watershed. In Thailand, 31% of all sediment yields are caused by mining activities (Chunkao, 1986). Henderson and Witthawatchutikul (cited in O'Loughlin, 1985) show how road construction significantly increased sediment loads, while Sheng (cited in Maathuis 1990) concludes that the annual soil loss per kilometre of unpaved road is roughly equivalent to erosion on an agricultural area of 35 *rai* (5.6 ha). In particular, unpaved roads were identified as significant source areas for erosion producing overland flow and sediment sources by Dunne (1979), Richardson (1982), Hamilton with King (1983), Schweithelm (1988; cited in Brooks *et al.*, 1990), Rijsdijk and Bruijnzeel (1990 and 1991, cited in Bruijnzeel and Critchley, 1996), Tapp (1990), Haigh *et al.* (1990) and Ziegler and Giambelluca (1995). While it is difficult to determine the exact contributions of various sediment sources, it is misleading to treat all sediments as originating from accelerated erosion and to attribute all increases in sedimentation rates to agriculture.

Spatial displacement and sediment delivery

It has long been recognized that only a fraction of the sediment eroded within a drainage basin is transported directly to the channel network and finds its way to the basin outlet and thus is represented in the sediment yield (Higgitt, 1993). Temporary or permanent storage of soil particles may occur at various locations downslope. The relative magnitude of this loss tends to increase with basin size (Walling, 1983).

The term “sediment delivery” is commonly used to describe the processes taking place between on-site erosion and downstream sediment loads. The “sediment delivery ratio” is the expression describing the ratio between sediments delivered at a specified outlet and the observed gross erosion rates. Particularly in large basins, sediment storage in the form of colluvium and alluvium appears to be much greater than sediment yield (Lal, 1986). While the sediment delivery ratio for a 1ha basin may be 90%, Bremmer (1987) suggests that for very large basins, such as the Ganges drainage basin, the ratio would be well below 10% or even as low as 1% (Stocking, 1996). This means that more than 90% of the eroded material is stored—permanently or temporarily — in one way or the other and does not appear in the sediment yield. Cooper *et al.* (1987; cited in Walling, 1988) show that even in small basins (8.4 and 13.9 km^2) between 84 and 90% of eroded material is trapped. Substantial quantities of sediment were trapped in floodplain swamps with most deposition occurring within 100 m of the field margins in forested riparian areas.

Drainage basin size is only one factor that influences sediment delivery. Others include (Walling, 1983, p. 211) “the nature, extent and location of sediment sources, relief and slope characteristics, the drainage pattern and channel conditions, vegetation cover, land use and soil texture”. Transport factors are so variable that the concept of sediment delivery ratio should be treated with great caution (Amphlett and Dickinson, 1989).

Finding a plausible delivery ratio for situations where only erosion rates derived from plot measurements are available, may not always be possible. A preferred method is to use reservoir deposits and caesium-137 measurements to estimate the erosional response particularly of small catchments. Zhang *et al.* (1997) estimated the relative contributions of two sediment sources to total reservoir deposits, demonstrating the usefulness of Caesium-137 measurements.

Time dimension

The time dimension is of major importance when assessing at what point in time downstream costs of soil erosion or benefits of soil conservation are likely to become relevant. As Hamilton (1987) notes, only very small changes may be expected in the amount of sediment carried by major rivers for centuries. In the studies reviewed, only Briones (1986) considers the time delay by keeping sediment rates constant for five years after programme initiation.

A study from India showed that long-term soil- and water-conservation programmes reduced sedimentation rates by 16 to 32% (Gupta, 1980; cited in Tejwani, 1984). Trimble (1981) on the other hand reports that even after 50 years of soil conservation, which severely curtailed upland erosion, sediment yields in a 360 km^2 drainage basin in Wisconsin changed very little. Hunting Technical Services (1961; cited in Megahan and Chima., 1980) report almost negligible results from 30 years of erosion control efforts in the Jhellan River catchment above the Mangla reservoir in Pakistan. Nearly 20 years later the Pakistan Water and Development Authority (WAPDA, 1980; cited in Khan, 1985) concluded for the same area that sedimentation was continuing at a consistent or slightly rising rate despite the watershed management activities. The reason for this phenomenon is the enormous amount of stored sediments in the system that form a long-term supply. Pointing to the Pantabangan reservoir for which Cruz *et al.* (1988) evaluated the costs of sedimentation, Dixon *et al.* (1989b, p. 195) note that “even if all on-farm erosion ended tomorrow, sedimentation of the reservoir would continue for many years.”

Sufficient material may be available to satisfy the transporting capacity of flows. Hence, sediment yields may not diminish significantly in the short term (Amphlett and Dickinson, 1989). In fact, reductions in erosion rates from catchment conservation programmes may not be reflected in the sediment yield at catchment outlets for decades, or even centuries for large catchments. Lawrence (1996, p. 15) concludes that “the store of easily erodible sediments within catchments and river systems continue to be reworked and contribute to sediment yields, even if ‘source erosion’ is completely cut off”. The sometimes substantial lag time not only complicates the evaluation of erosion reduction activities but it also points out that some of the effects of land degradation may be delayed to such an extent that they have not become obvious yet (Blaikie and Brookfield, 1987).

Reliability of sediment load estimates

All rivers transport sediments depending on catchment and channel characteristics. The sediments that have entered the transport system above a reservoir ultimately reach it. Therefore, feasibility studies for reservoir systems take sediment rates into account when calculating their expected operating life. As long as no sedimentation rate increases are observed after construction, the reservoirs and dams can fulfill their functions according to the earlier estimates. In recent years, however, it has been observed that shortly after the start of reservoir operations sedimentation rates increase drastically. For example, studying the sedimentation rates for 21 reservoirs in India, Gupta (1980; cited in Tejwani, 1984) concluded that the annual siltation rate was 40 to 2166 times higher than assumed during the pre-project feasibility study. Only for one reservoir were lower rates measured. Unexpectedly high sedimentation rates can cause more immediate costs (e.g. abrasion damages and more frequent maintenance of equipment) but the most significant cost is the shortening of the reservoir's useful life. If a dam was constructed for the purpose of producing energy the usefulness of the project is terminated when sediments reach the power intakes of a dam, while other functions of a reservoir would be affected only later.

The example of the Magat Dam in the Philippines may highlight what appears to be a universal problem for dam projects. Before the construction of the dam, mean catchment erosion rates were estimated to be about 20 t ha^{-1} y^{-1} and the sediment pool capacity of the dam was designed to accommodate this rate. A follow-up study (Madecor, 1982; cited in Cruz *et al.*, 1988) determined that a higher sedimentation rate of 34.5 t ha^{-1} y^{-1} was occurring and 21 months after impoundment the first reservoir survey, in 1984, indicated an erosion rate of 38 t ha^{-1} y^{-1} (White, 1988). It appears that erosion rates had almost doubled. According to one estimate this reduced the dam's useful life from 95 to 55 years (Cruz *et al.*, 1988) and according to another one, from 100 to 25 years (White, 1988). The two estimates indicate foregone benefits for between 40 and 75 years, respectively. Which one of the estimates is correct? The difference of 35 years is important in an economic analysis, especially when low discount rates are applied.

Other examples from the Asian region show predicted rates of between two to 16 times lower than the actual measured rates (White, 1988); Kattelmann (1987) concludes that in almost all Himalayan reservoir projects, sedimentation was grossly underestimated.

White (1989) identified three contributing factors in explaining these discrepancies. First, with the construction phase of the project and the provision of infrastructure people are drawn to the area. The catchment attractiveness increases for a number of reasons and more land is cleared. Jiwalai and Prapinmongkolkarn (1981), for instance, detected an above normal deforestation rate in the vicinity of the Bhumibol reservoir in Thailand between 1973 and 1977. Potential future land-use changes are, however, rarely included in feasibility studies of reservoir projects. Neglecting the potential effects of these changes explains underestimation for many situations.

Second, the relationship between instantaneous discharge and sediment concentration is not linear, but exponential (White, 1989). It is therefore vital to consider the variation of discharge through the year when assessing sediment yields.

Third, prediction techniques are not reliable and it is obvious that original project estimates of expected sedimentation rates are often faulty (Magrath and Doolette, 1990). Frequently they are based on a limited data set collected during only one or two years. Depending on the flow regime of the river during this time, calculated rates may misrepresent actual rates. Sometimes data are also transferred without any verification from locations with completely different geomorphological features (Bruijnzeel, 1992 pers. comm.) with the result that estimates are wrong outright.

There may also be a fourth contributing factor. The benefits of a reservoir project are of importance to the national economy. Interest groups within any government or the industry may also be interested in a project for their own personal benefits. Since a reservoir's value rises with the period of its life, lower estimates of sediment yields indicate a more profitable investment than higher estimates. Vested interests in the project construction and operation phases benefit especially, whether the forecasts are realistic or not. This may explain why most estimates are lower in the pre-project stage than during the early operational stages.

The discussion on quantifying the off-impacts of erosion and using existing data for comparative purposes indicates the complexities involved in attempting to answer questions such as the ones posed by Proops (1989), although the issue of whether all sediment deposits should be viewed as negative externalities in all cases has not been covered. It was stressed earlier that erosion means, in a strict sense, soil movement and not soil loss. In most economic analyses the potential positive effects of soil erosion are only mentioned in passing. Monetary values are usually only attached to the negative externalities that increased water yields and sediments may inflict on downstream water users. A notable exception is the recent and not yet completed study of a large hydropower reservoir in Lake Arenal, Costa Rica[4]. The study investigates the economic incentives for watershed protection and assesses as a major component economic and environmental functions by comparing forests with grassland. Preliminary results indicate large positive externalities from changes in water yield (US$200 to US$1400 ha^{-1}) and minimal negative externalities associated with increased sediment yields (US$20 to US$60 ha^{-1}) (Aylward, 1997, pers. comm). This raises the question why in the other studies water yield increases were only translated into increased flooding and not into a useful resource for electricity generation or irrigation.

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[4] Richards (1997) also estimates the positive impacts of increased groundwater recharge in his Bolivian study.

A similar question might be asked regarding the costs of sedimentation. Its costs can be valued according to the cost of dredging (see 9.1), which is often presented as an alternative to costly watershed management. De Graaff (1996, p. 129) points to a perceived problem of this approach when he asks "where to leave the silt". Perhaps the question should rather be whether we can, in each case, make a clear distinction between costs and benefits and whether we should treat, within the framework of assessing soil erosion, soil resources only as an input to agricultural production or also as an input to other economic activities. Dredging may not always be faced with a disposal problem. Sediment deposits composed of particularly coarse material can be and are used for construction purposes. In this way what is believed to be a renewable resource becomes a convertible resource. Examples from Thailand indicate that not all dredging operations are undertaken to reduce the off-site impacts of soil erosion, but also to provide the construction industry with a raw material of substantial value (Enters, 1992).

This last aspect should not distort the overall picture of the off-site impacts of soil erosion, but should highlight that off-site impacts are just as location-specific as on-site impacts. Generalizations should therefore be avoided. Upscaling off-site impacts and costs is performed in accordance to upscaling on-site impacts and costs, although great care is needed to avoid double-counting. The same material can only be trapped or dredged once. Also, what is counted in one micro- or mesowatershed as a negative externality may turn out to be a benefit contributing to income generation in other locations.

Summary

The review discussed a range of issues surrounding the economic assessment of soil erosion. It focused on cost-benefit analysis as the preferred valuation methodology. The following summarizes the main points pertaining to the identification, quantification and valuation of the on- and off-site effects of soil erosion.

The effects of erosion on crop yields are controversial. The review of quantifying the impact of erosion on crop yields brings out five critical issues:

- Declines in crop yields can take place for a number of reasons (Biot *et al.*, 1995). The proportion of yield decline that can be attributed to soil erosion needs to be separated from the contribution of nutrient depletion to yield decline. Where soils are mined for their nutrients, yields decline under "no erosion" conditions.
- The more reliable information that is available for some soils and crops cannot be generalized. However, if the productivity change approach (see

6.2) is chosen for the economic assessment, then estimates of erosion-yield effects have to be derived with reasonable accuracy. If the relationship is unrealistic, results may be distorted significantly. Simplistic assumptions, such as a fixed-yield decline, have to be avoided because they lead to unacceptable biases (Pagiola, 1992).

- In upscaling results from the plot to the field and higher hierarchical levels such as the farm or a microwatershed more attention needs to be paid to the redistribution of soil — particularly the fertile topsoil — and its potentially productivity enhancing deposition. These are complex environmental and very location-specific processes that necessitate the use of simulation models. Such models can potentially be extrapolated in order to quantify impacts on a microcatchment or regional basis and to evaluate them in monetary terms.
- The most critical question is not the cost of soil erosion *per se* but rather whether the long-term benefits of reduced erosion and soil degradation make the current costs of abatement worth bearing. The use of technologically unattainable standards as the basis for measuring soil-erosion costs should be avoided (Fox and Dickson, 1988). Any reduction in erosion rates has to enter the analysis as an investment cost. Some studies have been criticized for failing to recognize that profit from crop production may be lower in the near term if soil-conserving technologies are applied (Barrett, 1997). Hence soil erosion and erosion-yield decline estimates are only a partial input in any cost calculations, independent of the economic approach chosen.
- Soil is only one essential input to agricultural production. Next to identifying and quantifying erosion and related crop responses, information has to be available on other inputs and outputs as well as farmers' responses in light of their own resources (Current *et al.*, 1995). More attention has to be paid to numerous explanatory variables of the economic system that determine farmer decision making and the costs that farm households face. Different types of farmers face different investment costs. Next to a decision on valuation methodology, a clear understanding of the nature of factor markets particularly for land, labour, and capital are important (Pender and Kerr, 1996).

The valuation of on-site impacts is complex and the review highlights the need for a significant research effort on the biophysical as well as the socio-economic aspects of valuation studies. It is especially important to validate assumptions made at the onset of any study. The most important lessons from the review of the on-site costs of soil erosion are:

- As the discussion of the property valuation, replacement cost, and the change of productivity approaches indicates, a universally acceptable methodology does not exist. The replacement cost approach takes changes in the capital stock into account even if such changes have no immediate effect on outputs. The change in productivity approach on the other hand, considers only the immediate relevant cost items.

- Notwithstanding its deficiencies, the change in productivity approach, if carefully applied, is judged to be the most appropriate. It does not rely on proxy measures and considers the input differences between erosive and conserving practices, which is, from the farmers' perspective, an important criterion.
- Most analysts focus their studies on erosion and its potential effects on crop yields. The measurable losses are often compared against a hypothetical and unattainable benchmark, in other words: soil conservation is left out of the equation. Only few authors spend an equal effort on the analysis of the economic system and the constraints that farmers are operating under. The rationale for choosing a particular discount rate, time horizon, and opportunity cost of labour is often not provided, although it is clear that these variables drive the results in the same way — perhaps even more — than erosion or productivity estimates.
- Also, the assessment of soil-conservation projects poses an additional problem, which is also relevant in upscaling results. Only rarely will all farm households of a community or watershed benefit equally. There will always be some who benefit more than others, and sometimes there will be losers next to gainers. This aspect needs particular attention in selecting "representative" fields or farms.

Similar to the findings concerning on-site issues, there is a need for a significant research effort on the biophysical as well as the socioeconomic issues of off-site impacts if valuation studies are to become more useful. The most important lessons from the review of the off-site costs of soil erosion are:

- The actual valuation of off-site impacts is a straightforward approach. The following three approaches are common:
  - change of productivity;
  - replacement cost; and
  - preventive expenditures
- The change of productivity approach appears to be the most straightforward for off-site impacts (cf. on-site impacts), although scaling up remains problematic, and often leads to double-counting. Also, the issue to which degree increases in sediment loads and water availability should be termed negative or positive externalities is not resolved.
- Most valuation studies focus on the potential changes in the uplands and spend little time on analyzing the situation in the location where the off-site impacts are causing the greatest costs, i.e. the lowlands. Damage estimates have been continuously augmented in the past particularly be-

cause of land-use changes and economic development in the flood-affected areas.

- Most studies reviewed do not rely on data in a strict sense. Assumptions are made about complex environment-economy interactions for which the knowledge base is still rather weak. Several studies can certainly be criticized for the obscurity of ecological assumptions on which estimations are based. Richards (1994, p. 313) even goes as far as calling them "arbitrary and questionable". Data are transferred from other studies without proper verification. Historical information is lacking in most studies. In general, most studies rely more on guesstimates although the abundance of spreadsheets and the performance of sensitivity analyses leaves the reader with the impression that the orders of magnitude are correct. That this is not necessarily the case has been stressed recently (Enters, in press).
- Benefits must be compared relative to alternative land use in order to provide relevant information for policy purposes (Chomitz and Kumari, 1996). It is not obvious in several studies whether what was valued was total sediment yields or the incremental sediment yields due to accelerated erosion, increased incidence of flooding, and augmented silt deposits. Furthermore, studies have chosen different benchmarks. Exploitative cropping practices can be compared with a variety of land uses that may have very different ecological characteristics. Aylward's (1997, pers. comm.) cost estimates for increased sedimentation are so low because he compared forests with grassland. A comparison with exploitative monocropping would have probably dramatically increased the cost estimates. The following land uses will produce very different results in a comparative study:
    - conservation forests;
    - production forests (available for timber harvesting; destructive or reduced impact logging);
    - shifting cultivation;
    - tree plantations (for wood and nontimber forest products) and fruit orchards;
    - soil-conserving permanent cropping; and
    - grassland (sustainably managed or degraded).

The quantification of off-site impacts is still a major obstacle to their valuation. The following issues need more attention and a substantial research effort:

- sediment sources, particularly the contribution of roads to sedimentation rates;
- spatial distribution of sediment and delivery ratios;
- time horizons; and

- reliability and objectivity of measurements.

Downstream or off-site costs of erosion have been omitted in the majority of economic analyses. This is not because authors thought them to be negligible. It is rather the paucity of relevant data and the limited knowledge of people-environment interactions that economists shy away from. This limited knowledge has led frequently to unrealistic assumptions, the use of guesstimates, and finally to substantial over- or underestimates of costs.

Concluding remarks

Economists appear to agree on the general approach. Cost-benefit analysis is the preferred method for valuing the costs of soil erosion, whether from a private or social perspective. Methodologies for cost estimation and/or cost measures differ within the framework of cost-benefit analysis. For on-site impacts the recent trend has been to use the change of productivity approach although the use of replacement costs is not ruled out. From the farmers' perspectives it appears to be the most relevant method of estimating the on-site costs of soil erosion and demonstrating on-site benefits of soil conservation.

The cost of soil erosion is very location-specific. Each geographical location is characterized by a specific mix of biophysical and socioeconomic variables. In terms of biophysical aspects it is imperative to differentiate the impacts of soil erosion from the impacts of nutrient depletion. This requires a comparative approach to cost estimations, in which erosive practices are compared with less erosive or conserving practices. In terms of socioeconomic variables, it is imperative to cost inputs and outputs realistically. This requires a much better understanding of the socioeconomic conditions as is the case in most studies.

The redistribution of soil, a particular problem in scaling up results, has not been tackled yet in economic analyses. In most economic analyses soil is not moved but lost. This erroneous assumption results in cost overestimates.

In general, the review indicates that valuation methodologies are far more advanced than our understanding of environmental interactions. This deficiency calls for major multidisciplinary research efforts in order to make economic assessments more useful and their results more credible. This also requires an interest in operational participatory research with all stakeholders. Participation improves the research input and consequently its output. In addition, it distributes the ownership of the research results to the various players and ensures that results are used as input in decision making at the farm and in the environmental planning process at higher levels.

References

ALFORD, D. 1992. Streamflow and sediment transport from mountain watersheds of the Chao Phraya basin, Northern Thailand: a reconnaissance study. *Mountain Research and Development* 12: 257-268.

ALFSEN, K.H., DE FRANCO, M.A., GLOMSRØD, S. and JOHNSEN, T. 1996. The cost of soil erosion in Nicaragua. *Ecological Economics* 16: 129-145.

ALFSEN, K.H., BYE, T., GLOMSRØD S. and WIIG, H. 1997. Soil degradation and economic development in Ghana. *Environment and Development Economics* 2: 119-143.

AMPHLETT, M.B. and DICKINSON, A. 1989. Dallao soil erosion study Magat Catchment, The Philippines. Summary Report 1984 - 1987. Report OD 111. Wallingford: HR Wallingford.

ANGELSEN, A. and SUMAILA, U.R. 1995. Hard methods for soft policies. Environmental and social cost-benefit analysis. Working Paper 1. Bergen, Norway: Chr. Michelsen Institute.

ATTAVIROJ, P. 1986. Soil erosion and degradation, Northern Thai uplands. Paper presented at the International Conference on the Economics of Dryland Degradation and Rehabilitation. 10-14 March, 1986 in Canberra.

AYLWARD, B., ECHEVERRÍA, J. and BARBIER, E.B. 1995. Economic incentives for watershed protection: A report on an ongoing study of Arenal, Costa Rica. CREED Working Paper Series No. 3, Amsterdam: Vrije Universiteit and London: International Institute for Environment and Development.

BARBIER, B. 1996. A method for bioeconomic modelling at the microwatershed level for the Central American hillsides. Washington: Fragile Lands Program. Environment and Production Technology Division, IFPRI.

BARBIER, E.B. 1987. The concept of sustainable economic development. *Environmental Conservation* 14: 101-110.

BARBIER, E.B. 1996. The economics of soil erosion: theory, methodology and examples. EEPSEA Special Paper. Singapore: Economy and Environment Program for Southeast Asia.

BARBIER, E.B. and BISHOP, J.T. 1995. Economic values and incentives affecting soil and water conservation in developing countries. *Journal of Soil and Water Conservation* (March-April): 133-137.

BARRETT, S.,1989. Optimal soil conservation and the reform of agricultural pricing policies. LEEC Paper 89-08. London: International Institute for Environment and Development.

BARRETT, S. 1997. Microeconomic responses to macroeconomic reforms: the optimal control of soil erosion. In: *The Environment and Emerging Development Issues, Volume 2*, eds. P. Dasgupta, and K.-G. Mäler, 482-501. Oxford: Claredon Press.

BATJES, N.H. 1996. A qualitative assessment of water erosion risk using 1:5 M SOTER data - An application for northern Argentina, south-east Brazil and Uruguay. Report 96/04. Wageningen: International Soil Reference and Information Centre.

BETTERS, D.R. 1988. Planning optimal economic strategies for agroforestry systems. *Agroforestry Systems* 7: 17-31.

BIOT, Y., BLAIKIE, P.M., JACKSON C. and PALMER-JONES, R. 1995. Rethinking research on land degradation in developing countries. World Bank Discussion Paper

289. Washington, DC: The World Bank.

BISHOP, J. 1995. The economics of soil degradation: an illustration of the change in productivity approach to valuation in Mali and Malawi. LEEC Paper DP 95-02. London: International Institute for Environment and Development.

BISHOP, J. and ALLEN, J. 1989. The on-site costs of soil erosion in Mali. Environment Working Paper #21, Environment Department. Washington: The World Bank.

BLAIKIE, P. and BROOKFIELD, H. 1987. Land Degradation and Society. London and New York: Routledge.

BOJÖ, J. 1986a. A review of cost-benefit studies of soil and water conservation projects. Report No. 3. Soil and Water Conservation and Land Utilization Programme, Maseru.

BOJÖ, J. 1986b. An introduction to cost-benefit analysis of soil and water conservation projects. Report No. 6. Soil and Water Conservation and Land Utilization Programme, Maseru.

BOJÖ, J. 1996. The costs of land degradation in Sub-Saharan Africa. *Ecological Economics* 16: 161-173.

BOSCH, J.M. and HEWLETT, J.D. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3-23.

BREMMER, C.N. 1987. The Role of Vegetation and Land Use in Flooding, Erosion and Mass Wasting in the Ganges Drainage Basin, India. Department of Hydrology & Geographical Hydrology, Faculty of Earth Sciences, Vraje Universitels, Amsterdam.

BRIONES, N.D. 1986. Estimating soil erosion costs. a Philippine case study in the Lower Agno River Watershed. In: *Watershed Resources Management. An Integrated Framework with Studies from Asia and the Pacific*, eds. K.W. Easter, J.A. Dixon and M.M. Hufschmidt. Studies in Water Policy and Management. No. 10. 205-218. Boulder and London: Westview Press.

BROOKS, K.N., GREGERSEN, H.M., LUNDGREN, A.L. and QUINN, R.M. 1990. Manual on watershed management, project planning, monitoring and evaluation. ASEAN-US Watershed Project, College, Laguna, Philippines.

BRUIJNZEEL, L.A. 1990. Hydrology of Moist Tropical Forests and Effects of Conversion: A State of Knowledge Review. Paris: UNESCO International Hydrological Programme. A Publication of the Humid Tropics Programme.

BRUIJNZEEL, L.A. and CRITCHLEY, W.R.S. 1996. A new approach towards the quantification of runoff and eroded sediment from bench terraces in humid tropical steeplands and its application in South-Central Java, Indonesia. In: *Advances in Hillslope Processes, Volume 2*, eds. M. G. Anderson and S.M. Brooks, 921-937. Chichester, New York, Brisbane, Toronto, Singapore: John Wiley & Sons Ltd.

CARTER, V.G. and DALE, T. 1955. Topsoil and Civilization. Norman: University of Oklahoma Press.

CASSELLS, D.S., GILMOUR, D.A. and BONELL, N. 1986. Research for watershed land use planning and management: problems and possibilities. Paper presented at the Intl. Symposium on Tropical Forest Hydrology and Application. June 11-14, 1986. Chiang Mai.

CASSELLS, D.S., BONELL, M., HAMILTON, L.S. and GILMOUR, D.A. 1987. The protective role of tropical forests: a state-of-knowledge review. In: *Agroforestry in the Humid Tropics. Its Protective and Ameliorative Roles to Enhance Productivity and Sustainability*, eds. N.T. Vergara and N.D. Briones, 31-58. Hawaii, USA: Environment and Policy Institute, East-West Center, Honolulu, and College, Laguna, Philippines: Southeast Asian Regional Center for Graduate Study and Research in Agriculture.

CHANDRAKANTH, M.G. and ROMM, J. 1990. Groundwater depletion in India - Institutional management regimes. *Natural Resources Journal* 30: 485-501.

CHANG, J.-H. 1968. The agricultural potential of the humid tropics. *The Geographical Review* 58: 333-361.

CHISHOLM, A.H. 1987. Rational approaches to environmental issues. In: *Land Degradation. Problems and Policies*, eds. A. Chisholm and R. Dumsday, 341-356 (Appendix A) Published in Association with Centre for Resource and Environmental Studies, Australian National University. Cambridge: Cambridge University Press.

CHOMITZ, K.M. and KUMARI, K. 1996. The domestic benefits of tropical forests. Policy Research Working Paper 1601. Washington, DC.: Policy Research Department, The World Bank.

CHUNKAO, K. 1986. Soil erosion and sediment yields. predictions in practices for watershed management in ASEAN countries. In: *Proceedings of the Seminar on Watershed Research and Management Practices*. ASEAN-US Watershed Project and RFD. Aug. 20-23, 1986 in Khon Kaen.

CLARK, R. 1996. Methodologies for the economic analysis of soil erosion and conservation. CSERGE Working Paper GEC 96-13. Norwich: University of East Anglia.

CLARK, R., MANTHRITHILAKE, H., WHITE R. and STOCKING, M. 1996. Economic valuation of soil erosion and conservation - A case study of Perawella, Sri Lanka. Paper presented at the 9th Conference of the International Soil Conservation Organisation, 26-30 August, Bonn.

CLARKE, W.C. 1976. Maintenance of agriculture and human habitats within the tropical forest ecosystem. *Human Ecology* 4: 247-259.

CRUZ, W., FRANCISCO, H.A., and TAPAWAN-CONWAY, Z. 1988. The on-site and downstream costs of soil erosion. Working Paper Series No. 88-11. Los Baños: Philippine Institute for Development Studies, University of the Philippines.

CURRENT, D., LUTZ, E. and SCHERR, S.J. 1995. The costs and benefits of agroforestry to farmers. *The World Bank Research Observer* 10 (2): 151-180.

DE GRAAFF, J. 1993. Soil conservation and sustainable land use - An economic approach. Amsterdam: Royal Tropical Institute.

DE GRAAFF, J. 1996. The price of soil erosion. An economic evaluation of soil conservation and watershed development. Mansholt Studies 3. Wageningen: Agricultural University.

DE GRAAFF, J. and NIBBERING, J.W. 1996. Indicators for monitoring and evaluating watershed development. Paper presented at the 9th Conference of the International Soil Conservation Organisation, 26-30 August, Bonn.

DIXON, J.A. and FALLON, L.A. 1989. The concept of sustainability: origins, extensions, and usefulness for policy. *Society and Natural Resources* 2: 73-84.

DIXON, J.A., TALBOT, L.M. and LE MOIGNE, G.J.-M. 1989a. Dams and the environment. World Bank Technical Paper Number 110. Washington, DC.: The World Bank.

DIXON, J.A., JAMES, D.E. and SHERMAN, P.B. 1989b. Economics of dryland management. London: Earthscan Publications Ltd.

DIXON, J.A. 1997. Analysis and management of watersheds. In*: The Environment and Emerging Development Issues, Volume 2*, eds. P. Dasgupta and K.-G. Mäler, 371-398. Oxford: Claredon Press.

DUNNE, T. 1979. Sediment yield and land use in tropical catchments. *Journal of Hydrology* 42: 281-300.

DYHR-NIELSEN, M. 1986. Hydrological effect of deforestation in the Chao Phraya Basin in Thailand. Paper presented at the International Symposium on Tropical Forest Hydrology and Application. June 11-14, 1986. Chiang Mai.

EATON, D. 1996. The economics of soil erosion: a model of farm decision-making. Discussion Paper 96-01. Environmental Economics Programme. London: International Institute for Environment and Development.

EHUI, S.K., HERTEL, T.W. and PRECKEL, P.V. 1990. Forest resource depletion, soil dynamics, and agricultural productivity in the tropics. *Journal of Environmental Economics and Management* 18: 136-154.

EKBOM, A. 1992. Economic Impact Assessment of Implementation Strategies for Soil Conservation. Unit for Environmental Economics, Department of Economics. Göteborg: Gothenburg University.

EL-SWAIFY, S.A. 1997. Factors affecting soil erosion hazards and conservation needs for tropical steeplands. *Soil Technology* 11: 3-16.

EL-SWAIFY, S.A. and DANGLER, E.W. 1982. Rainfall erosion in the tropics: a state-of-the-art. In: *Soil Erosion and Conservation in the Tropics*, 1-25. Proceedings of a Symposium at Fort Collins, Colorado. Madison, Wisconsin: American Society of Agronomy and Soil Science Society of America.

ELLIS-JONES, J. and SIMS, B. 1995. An appraisal of soil conservation technologies on hillside farms in Honduras, Mexico and Nicaragua, 1995. *Project Appraisal* 10(2): 125-134.

ENTERS, T. 1992. Land degradation and resource conservation in the highlands of Northern Thailand: the limits to economic evaluation. PhD dissertation. Canberra: The Australian National University. Unpublished.

ENTERS, T. 1994. Now you see it, now you don’t: the effects of the ecocrisis theory on research. Paper presented at the IUFRO, FORSPA, CIFOR, FAO/RAPA Workshop on The Barriers to the Application of Forestry Research Results, 24-28 October 1994, Bangkok.

ENTERS, T. 1995. The economics of land degradation and resource conservation in Northern Thailand: challenging the assumptions. In: *Counting the Costs: Economic Growth and Environmental Change in Thailand*, ed. J. Rigg, 90-110. ISEAS Environment and Development Series. Singapore: Institute of Southeast Asian Studies.

ENTERS, T. in press. The economics of forest conversion in Northern Thailand: challenging assumptions. In: *The Living Forest: Non-Market Benefits of Forestry,* eds. C.S. Roper, and A. Park. London: The Stationery Office.

FOX, G. and DICKSON, E.J. 1988. What’s economic about the economic costs of soil erosion to Canadian farmers? Discussion Paper DP88/3. Department of Agricultural Economics and Business, University of Guelph, Guelph, Ontario.

GACHENE, C.K.K., JARVIS, N.J., LINNER H. and MBUVI, J.P. 1997. Soil erosion effects on soil properties in a highland area of Central Kenya. *Soil Science Society of America Journal* 61: 559-564.

GIBSON, T. 1983. Toward a stable low-input highland agricultural system. Ley farming in *Imperata cylindrica* grasslands of Northern Thailand. *Mountain Research and Development* 3: 378-385.

GILBERT, A.J. and JANSSEN, R. 1997. The use of environmental functions to evaluate management strategies for the Pagbilao Mangrove Forest. CREED Working Paper Series No. 15, Amsterdam: Vrije Universiteit, and London: International Institute for Environment and Development.

GILMOUR, D.A., BONELL, M. and CASSELLS, D.S. 1987. The effects of forestation on soil hydraulic properties in the Middle Hills of Nepal: a preliminary assessment. *Mountain Research and Development* 7: 239-249.

GITTINGER, J.P. 1982. Economic analysis of agricultural projects. EDI Series in Economic Development. Baltimore and London: Johns Hopkins University Press.

GOETZ, R.U. in press. Diversification in agricultural production - A dynamic model of optimal cropping to manage soil erosion. *American Journal of Agricultural Economics*.

GREGERSEN, H.M., ARNOLD, J.E.M., LUNDGREN, A.L. and CONTRERAS-HERMOSILLA, A. 1995. Valuing forests: context, issues and guidelines. FAO Forestry Paper 127. Rome: Food and Agriculture Organization of the United Nations.

GREGERSEN, H.M., BROOKS, K.N., FFOLLIOT, P.F., HENZELL, T., KASSAM, A. and TEJWANI, K.G. 1996. Watershed management as a unifying framework for researching land and water conservation. *Land Husbandry* 1(1&2): 23-32.

GREPPERUD, S. 1997a. The impact of policy on farm conservation incentives in developing countries: what can be learned from theory? Documents 97/2. Oslo: Statistics Norway, Research Department,.

GREPPERUD, S. 1997b. Soil depletion choices under production and price uncertainty. Discussion Paper No. 186. Oslo: Statistics Norway, Research Department.

GROHS, F. 1994. Economics of Soil Degradation, Erosion and Conservation: A Case Study of Zimbabwe. Arbeiten zur Agrarwirtschaft in Entwicklungsländern. Kiel: Wissenschaftsverlag Vauk Kiel KG.

GOETZ, R.U., 1997. Diversification in agricultural production - a dynamic model of optimal cropping to manage soil erosion. Unpublished manuscript. Department of Agricultural Economics. Zürich: Swiss Federal Institute of Technology.

HAIGH, M.J., RAWAT, J.S. and BISHT, H.S. 1990. Hydrological impact of deforestation in the central Himalayas. In: *Hydrology of Mountainous Areas*. ed. L. Molnar. *IAHS Publication 190*, pp. 419-433.

HAMILTON, L.S. 1986. Towards clarifying the appropriate mandate in forestry for watershed rehabilitation and management. Reprint No. 94. East-West Environment and Policy Institute. Reprinted from: Strategies, Approaches and Systems in Integrated Watershed Management. Food and Agriculture Organization of the United Nations. pp. 32-51.

HAMILTON, L.S. 1987. What are the impacts of deforestation in the Himalayas on the Ganges-Brahmaputra lowlands and delta? Relations between assumptions and facts. *Mountain Research and Development* 7: 256-263.

HAMILTON, L.S. with KING, P.N., 1983. Tropical forested watersheds. hydrological and soils response to major uses of conversion. Boulder, Colorado: Westview Press.

HAMILTON, L.S. and PEARCE, A.J. 1991. Biophysical aspects in watershed management. In: *Watershed Resources Management - Studies from Asia and the Pacific*, eds. K.W. Easter, J.A. Dixon and M.M. Hufschmidt, 33-52. Singapore. ISEAS, and Honolulu: East-West Center.

HANLEY, N. 1992. Are there environmental limits to cost-benefit analysis? *Environmental and Resource Economics* 2(1): 33-59.

HARPER, D.E. 1986. Sustainable agriculture on slopes: the effectiveness of international development projects in fostering soil conservation in north Thailand. PhD dissertation. University of Hawaii. Ann Arbor: University Microfilms International.

HIGGITT, D.L. 1993. Soil erosion and soil problems. *Progress in Physical Geography* 17(4): 461-472.

HODGSON, G. and DIXON, J.A. 1988. Logging versus fisheries and tourism in Palawan, Occasional Paper No. 7. Honolulu, Hawaii: East-West Environment and Policy Center.

HOEKSTRA, D.A. 1985. Choosing the discount rate for analysing agroforestry systems/technologies from a private economic viewpoint. *Forest Ecology and Management* 10: 177-183.

HOEKSTRA, D.A. 1987. Economics of agroforestry. *Agroforestry Systems* 5: 293-300.

HUDSON, N.W. 1985. A world view of the development of soil conservation. *Agricultural History* 59: 326-339.

HUETING, R. 1991. The uses of the discount rate in cost-benefit analysis for different uses of a humid tropical forest area. *Ecological Economics* 3(1): 43-57.

HUFSCHMIDT, M.M., JAMES, D.E., MEISTER, A.D., BOWER, B.T. and DIXON, J.A. 1983. Environment, natural systems and development. An economic valuation guide. Baltimore and London: The Johns Hopkins University Press.

HUMBERT-DROZ, B. 1996. Integrating indigenous knowledge in soil conservation in a watershed development programme. In: *Soil Conservation Extension*, eds. S. Sombatpanit, M.A. Zöbisch, D.W. Sanders and M.G. Cook, 67-76. Lebanon: Science Publishers, Inc.

IGNATIEFF, V. and LEMOS, P. 1963. Some management aspects of more important tropical soils. *Soil Science* 95: 243-249.

IZAC, A.-M.N. and SWIFT, M.J. 1994. On agricultural sustainability and its measurement in small-scale farming in Sub-Saharan Africa. *Ecological Economics* 11: 105-125.

JIWALAI, W. and PRAPINMONGKOLKARN, P. 1981. Post impoundment study of upper watershed on deforestation and sedimentation. In: *Proceedings on ASEAN-UNEP Workshop on Environmental Impact Assessment for Water Resource Development Projects*. Feb. 15-20, 1981. Srinakarin Dam, Kanchanaburi.

KATTELMANN, R. 1987. Uncertainty in assessing Himalayan water resources. *Mountain Research and Development* 7: 279-286.

KELLMANN, M. 1980. Geographic patterning in tropical weed communities and early secondary successions. *Biotropica* 12: 34-39.

KHAN, S.M. 1985. Management of river and reservoir sedimentation in Pakistan. *Water International* 10: 18-21.

KRAMER, R.A., RICHTER, D.D., PATTANAYAK, S. and SHARMA, N.P. 1997. Ecological and economic analysis of watershed protection in Eastern Madagascar. *Journal of Environmental Management* 49: 277-295.

KRAAYENHAGEN, J. 1981. Watershed management and conservation farming in Northern Thailand. Working Paper 15. Mae Sa Integrated Watershed and Forest Land

Use Project, Chiang Mai.

LAL, R. 1986. Deforestation and soil erosion. In: *Land Clearing and Development in the Tropics*, eds. R. Lal, P.A. Sanchez, and R.W. Cummings, Jr., 299-315. Rotterdam and Boston: A.A. Balkema.

LAL, R. 1990. Soil erosion in the tropics: principles and management. New York: McGraw-Hill, Inc.

LAWRENCE, P. 1996. Guidelines on field measurement procedures for quantifying catchment sediment yields. Report OD/TN 77. Wallingford: HR Wallingford.

LINDERT, P.H. 1996. The bad earth? China's agricultural soils since the 1930s. Working Paper Series No. 83. Davis, California: Agricultural History Center, University of California.

LINDERT, P.H. 1997. A half-century of soil change in Indonesia. Working Paper Series No. 90. Davis, California: Agricultural History Center, University of California.

LINDGREN, B.-M. 1988. Economic evaluation of a soil conservation project in Machakos District, Kenya. International Rural Development Centre. Working Paper 95. Uppsala: Swedish University of Agricultural Sciences.

LITTLEBOY, M., COGLE, A.L., SMITH, G.D., RAO, K.P.C. and YULE, D.F. 1996. Soil management and production of alfisols in the semi-arid tropics. IV. Simulation of decline in productivity caused by soil erosion. *Australian Journal of Soil Research* 34: 113-125.

LOCKERETZ, W. 1989. Problems in evaluating the economics of ecological agriculture. *Agriculture, Ecosystems and Environment* 27: 67-75.

LUTZ, E. and MUNASINGHE, M. 1994. Integration of environmental concerns into economic analyses of projects and policies in an operational context. *Ecological Economics* 10: 37-46.

LUTZ, E., PAGIOLA, S. and REICHE, C. (eds.) 1994. Economic and institutional analyses of soil conservation projects in Central America and the Caribbean. Environment Paper 8. Washington, DC: The World Bank.

MAATHUIS, B.H.P. 1990. The watershed classification versus the GEO-ecological mapping approach. Chiang Mai: Department of Geography, Chiang Mai University. Unpublished.

MAGRATH, W. and ARENS, P. 1989. The costs of soil erosion on Java: a natural resource accounting approach. Environment Department Working Paper #18. Washington, DC: The World Bank.

MAGRATH, W.B. and DOOLETTE, J.B. 1990. Strategic issues in watershed development. In: *Watershed Development in Asia*, eds. J.B. Doolette and W.B. Magrath, 1-34. World Bank Technical Paper Number 127. Washington, DC: The World Bank.

MEGAHAN, W. F. and CHIMA, A.M. 1980. Watershed management in Pakistan - past, present and future. *Journal of Forestry* 78: 217-219.

MILLIMAN, J.D. and MEADE, R.H. 1983. World-wide delivery of river sediment to the oceans. *Journal of Geology* 91: 1-21.

MOHD SHAHWADID, H.O., AWANG NOOR, A.G., ABDUL RAHIM, N., ZULKIFLI, Y. and RAGAME, U. 1997. Economic benefits of watershed protection and trade-off with timber production: a case study in Malaysia. EEPSEA Research Report Series. Singapore: Economy and Environment Program for Southeast Asia.

MOLL, H.A.J. 1989. Farmers and finance: experience with institutional savings and credit in West Java. Wageningen: Agricultural University.

MOODY, K. 1982. Changes in weed population following forest clearing in Oyo State, Nigeria. *Tropical Agriculture (Trinidad)* 59: 298-302.

NELSON, R.A., DIMES, J.P., SILBURN, D.M. and CARBERRY, P.S. 1996a. Erosion/productivity modelling of maize farming in the Philippine uplands. Part I: a simple description of the agricultural production systems simulator. SEARCA-UQ Uplands Research Project. Working Paper No. 12. Los Baños.

NELSON, R.A., CRAMB, R.A., MENZ, K. and MAMICPIC, M.A. 1996b. Bioeconomic modelling of alternative forms of hedgerow intercropping in the Philippine uplands using SCUAF. *Imperata* Project Paper 1996/9. Canberra: CRES, The Australian National University.

NELSON, R.A., GRIST, P., MENZ, K., PANINGBATAN, E and MAMICPIC, M.A. 1996c. A cost-benefit analysis of hedgerow intercropping in the Philippine uplands. *Imperata* Project Paper 1996/2. Canberra: CRES, The Australian National University.

NELSON, R.A., DIMES, J.D., SILBURN, D.M., PANINGBATAN, JR., E.P., CRAMB, R.A. and MAMICPIC, M.A. 1997. Long-term effects of land management of soil erosion, crop yield and on-farm economics in the Philippines. In: *A New Soil Conservation Methodology and Application to Cropping Systems in Tropical Steeplands*, eds. K.J. Coughlan and C.W. Rose, 111-140. ACIAR Technical Reports 40. Canberra: Australian Centre for International Agricultural Research.

NORSE, D. and SAIGAL, R. 1992. National economic cost of soil erosion in Zimbabwe. In: *Environmental Economics and Natural Resource Management in Developing Countries*, ed. M. Munasinghe, 229-240. Washington, DC: The World Bank.

NYE, P.H. and GREENLAND, D.J. 1960. The soil under shifting cultivation. Technical Communication No. 51., Commonwealth Bureau of Soils, Harpenden, England.

O'LOUGHLIN, C. 1985. The influence of forest roads on erosion and stream sedimentation - comparisons between temperate and tropical forests. Working Paper. Honolulu, Hawaii: East-West Center.

OLDEMAN, L.R., HAKKELING, R.T. and SOMBROEK, W.G. 1991. World map of the status of human-induced soil degradation. Explanatory Note. Nairobi, Wageningen: UNEP-ISRIC.

OLSON, K.R., LAL, R. and NORTON, L.D. 1994. Evaluation of methods to study soil erosion-productivity relationships. *Journal of Soil and Water Conservation* 49(6): 586-590.

OSUJI, G.E. 1989. Splash erosion under sole and mixed cropping systems in southwestern Nigeria. *Journal of Environmental Management* 28: 1-9.

PAGIOLA, S. 1992. Estimating the yield effect of soil degradation. *Journal of Soil and Water Conservation* 47:486-490.

PAGIOLA, S. 1993. Soil conservation and the sustainability of agricultural production. PhD Dissertation. California: Stanford University.

PAGIOLA, S. 1994. Soil conservation in a semi-arid region of Kenya: rates of return and adoption by farmers. In: *Adopting Conservation on the Farm*, eds. T.L. Napier, S.M. Camboni, and S.A. El-Swaify, 171-188. Ankeny: Soil and Water Conservation Society.

PARNWELL, M.J.G. and TAYLOR, D.M. 1996. Environmental degradation, non-timber forest products and Iban communities in Sarawak. In: *Environmental Change in South-East Asia*, eds. M.J.G. Parnwell and R.L. Bryant, 269-300. London and New York: Routledge.

PEARCE, D., BARBIER, E. and MARKANDAYA, A. 1990. Sustainable Development. Economics and Environment in the Third World. London: Edward Elgar Publishing Ltd.

PENDER, J. and KERR, J. 1996. Determinants of farmers indigenous soil and water conservation investments in India's semi-arid tropics. EPTD Discussion Paper #17. Washington, DC: International Food Policy Research Institute.

PHILLIPS, J.D. 1989. Predicting minimum achievable soil loss in developing countries. *Applied Geography* 9: 219-236.

PRASAD, R. and GOSWAMI, N.N. 1992. Soil fertility restoration and management for sustainable agriculture in South Asia. In: *Soil Restoration*, eds. R. Lal and B.A. Stewart, 37-77. Advances in Soil Science. Volume 17. New York: Springer-Verlag.

PREDO, C., GRIST, P., MENZ, K. AND RAÑOLA, Jr., R. F. 1997. Two approaches for estimating the on-site costs of soil erosion in the Philippines: 2) The replacement cost approach. *Imperata* Project Paper 1997/8. 25-36. Canberra: CRES, The Australian National University.

PRICE, C. and NAIR, C.T.S. 1984. Cost-benefit analysis and the consideration of forestry alternative. *Journal of World Forest Resource Management* 1: 81-104.

PROOPS, J.L.R. 1989. Ecological economics: rationale and problem areas. *Ecological Economics* 1: 59-76.

PURWANTO, E., and BRUIJNZEEL, L.A. 1996. Soil conservation on rainfed bench terraces in upland West Java, Indonesia: Towards a New Paradigm. Paper presented at the 9th Conference of the International Soil Conservation Organisation, 26-30 August, Bonn.

QUINE, T.A., WALLING, D.E., ZHANG, X. and WANG, Y. 1992. Investigation of soil erosion on terraced fields near Yanting, Sichuan Province, China Using Caesium-137. Erosion, Debris Flow and Environment in Mountain Regions. *IAHS Publication* No. 209: 155-168.

RAY, A. 1984. Cost-benefit analysis. issues and methodologies. A World Bank Publication. Baltimore and London: The Johns Hopkins University Press.

RENARD, K.G., FOSTER, G.R., YODER D.C. and MCCOOL, D. 1994. RUSLE revisited: status, questions, answers and the future. *Journal of Soil and Water Conservation* 49(3): 213-220.

RENAUD, F. 1997. Financial cost-benefit analysis of soil conservation practices in Northern Thailand. *Mountain Research and Development* 17: 11-18.

RICHARDS, M. 1994. Towards valuation of forest conservation benefits in developing countries. *Environmental Conservation* 21(4): 308-19.

RICHARDS, M. 1997. The potential for economic valuation of watershed protection in mountainous areas: a case study from Bolivia. *Mountain Research and Development* 17(1): 19-30.

RICHARDSON, J.H. 1982. Some implications of tropical forest replacement in Jamaica. *Zeitschrift für Geomorphologie N.F., Supplement Band* 44: 107-118.

RIGG, J. 1997. Southeast Asia - The Human Landscape of Modernisation and Development. London and New York: Routledge.

RODER, W., PHENGCHANH, V and MANIPHONE, S. 1997. Dynamics of soil and vegetation during crop and fallow period in slash-and-burn fields of northern Laos. *Geoderma* 76: 131-144.

SANDERS, J.H., SOUTHGATE, D.D. and LEE, J.G. 1995. The economics of soil degradation: technological change and policy alternatives. SMSS Technical Monograph No. 22. Indiana: Purdue University, West Lafayette.

SCHERR, S. J. and YADAV, S. 1996. Land degradation in the developing world: implications for food, agriculture, and the environment to 2020. Food, Agriculture, and the Environment Discussion Paper 14. Washington, DC: International Food and Policy Research Institute.

SCHREIER, D.F. 1989. Agricultural project investment analysis. In: *Agricultural Project Analysis. Tools for Economic Development*, ed. L. Tweeten, 238-277. Boulder & San Francisco/London: Westview Press/IT Publications.

SECKLER, D. 1987. Economic costs and benefits of degradation and its repair. In: *Land Degradation and Society*, eds. P. Blaikie and H. Brookfield, 84-96. London: Methuen & Co. Ltd.

SMALING. E.M.A., FRESCO, L..O. and DE JAGER, A. 1996. Classifying, monitoring and improving soil nutrient stocks and flows in African agriculture. *Ambio* 25(8): 492-496.

SMALING, E.M.A. and FRESCO, L.O. 1993. A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON). *Geoderma* 60: 235-256.

SMIET, F. 1987. Tropical watershed forestry under attack. *Ambio* 16(2-3): 156-158.

SÖDERBAUM, P. 1994. Towards a microeconomics for ecological sustainability. *The Journal of Interdisciplinary Economics* 5: 197-220.

SQUIRE, L., and VAN DER TAK, H.G. 1975. Economic analysis of projects. A World Bank Research Publication. Baltimore and London: The Johns Hopkins University Press.

STOCKING, M. 1987. Measuring land degradation. In: *Land Degradation and Society*, eds. P. Blaikie and H. Brookfield, 49-63. London: Methuen & Co. Ltd.

STOCKING, M. 1995. Soil erosion in developing countries: where geomorphology fears to tread. *Catena* 25: 253-267.

STOCKING, M. 1996. Soil erosion - breaking new ground. In: *The Lie of the Land*, eds. M. Leach and R. Mearns, 140-154. London: Viliers Publication.

STOCKING, M. and ABEL, N. 1993. Labour cost: critical element in soil conservation. In: *Soil Conservation for Survival*, eds. K. Tato and H. Hurni, 206-218. Ankeny, Iowa: Soil and Water Conservation Society.

STOORVOGEL, J.J., SMALING, E.M.A. and JANSSEN, B.H. 1993. Calculating soil nutrient balances in Africa at different scales. *Fertilizer Research* 35: 227-235.

SUGDEN, R. and WILLIAMS, A. 1978. The principles of practical cost-benefit analysis. Oxford: Oxford University Press.

SYERS, J.K. 1997. Managing soils for long-term productivity. *Philosophical Transactions of the Royal Society, London.* 352: 1011-1021

TACCONI, L. 1995. Rethinking the economic analysis of forests: theory and practice. *Forest Ecology and Management* 73: 229-238.

TANGTHAM, N. 1991. Erosion study and control in Thailand. Paper presented in the Workshop on Soil Erosion and Debris Flow Control organized by the Indonesian Institute of Science under UNDP-UNESCO-IRTCES-LIPI Regional Training Programme on Erosion and Sedimentation for Asia, 5-8 November 1991. Yogyakarta.

TANGTHAM, N. 1994. The hydrological role of forests in Thailand. *TDRI Quarterly Review* 9(3): 27-32.

TAPP, N. 1990. Squatters or refugees. Development and the Hmong. In: *Ethnic Groups across National Boundaries in Mainland Southest Asia*, ed. G. Wijeyewardene, 149-172. Singapore: Institute of Southeast Asian Studies.

THAILAND DEVELOPMENT RESEARCH INSTITUTE (TDRI) 1995. The economics of watershed protection: a case study of Mae Taeng. Bangkok: Thailand Development Research Institute.

TEJWANI, K.G. 1984. Reservoir sedimentation in India - its causes, control, and future course of action. *Water International* 9: 150-154.

THENG, B.K.G. 1991. Soil science in the tropics - the next 75 years. *Soil Science* 151: 76-89.

THOMPSON, M. and WARBURTON, M. 1985. Uncertainty on a Himalayan scale. *Mountain Research and Development* 5: 115-135.

TIFFEN, M. 1996. Blind spots in the study of the ‘resource-poor’ farmer. In: *The Lie of the Land*, eds. M. Leach and R. Mearns, 140-154. London: Viliers Publication.

TRIMBLE, S.W. 1981. Changes in sediment storage in Coon Creek Basin, Driftless Area, Wisconsin, 1853-1975. *Science* 214: 181-183.

TRIVEDI, S.N. 1986. Financial appraisal for some afforestation species in Bihar (India) under the risk of illicit felling. *Forest Ecology and Management* 17: 261-277.

TURKELBOOM, F., ONGPRASERT, S., VAN LOOK, K. and VLASSAK, K. 1991. Soil dynamics under traditional and alternative cropping systems in the highlands of Northern Thailand. Text of a poster presented at The International Workshop on Evaluation for Sustainable Land Management in the Developing World. Workshop held Sept. 15-21 in Chiang Rai.

UPSTILL, G. and YAPP, T. 1987. Offsite costs of land degradation. In: *Land Degradation. Problems and Policies*, eds. A Chisholm and R. Dumsday, 99-108. Published in Association with Centre for Resource and Environmental Studies, Australian National University. Cambridge: Cambridge University Press.

VAN DER POL, F. 1992. Soil mining. Bulletin 325. Amsterdam: Royal Tropical Institute.

VELOZ, A., SOUTHGATE, D., HITZHUSEN, F. and MACGREGOR, R. 1985. the economics of erosion control in a subtropical watershed: a Dominican case. *Land Economics* 61: 143-155.

WALLING, D.E. 1983. The sediment delivery problem. *Journal of Hydrology* 65: 209-237.

WALLING, D.E. 1988. Erosion and sediment yield research - some recent perspectives. *Journal of Hydrology* 100: 113-141.

WARNER, K. 1991. Shifting cultivators. Community Forestry Note 8. Rome: Food and Agriculture Organization of the United Nations.

WASBERG, J. 1989. Economic analysis of forestry projects in developing countries: theory versus practice. Sub-thesis. Canberra: Department of Forestry, The Australian National University.

WHITE, S. 1988. Sediment yield and availability for two reservoir drainage basins in Central Luzon, Philippines. *IAHS Publication* 174, pp. 575-581.

WHITE, S. 1989. Sediment yield assessment using a geographical information system. OD/P 62. Overseas Development Unit. Wallingford: Hydraulics Research.

WHITMORE, T.J., BRENNER, M., ENGSTROM, D.R. and SONG XUELIANG 1994. Accelerated soil erosion in watersheds of Yunnan Province, China. *Soil and Water Conservation* 49(1): 67-72.

WIGGINS, S.L. and PALMA, O.G. 1980. Acelhuate River Catchment Management Project, El Salvador. Cost-benefit analysis of soil conservation. Project Report 104. Land Resources Development Centre. Surbiton: Overseas Development Administration.

WINPENNY, J. 1991. Environmental values and their implications for development. *Development Policy Review* 9(4): 381-390.

WISCHMEIER, W.H. and SMITH, D.D. 1978. *Predicting rainfall erosion losses - a guide to conservation planning*. USDA Handbook 537, Washington, DC.

ZHANG, X., WALLING, D.E., QUINE, T.E. and WEN, A. 1997. Use of reservoir deposits and caesium-137 measurements to investigate the erosional response of a small drainage basin in the rolling loess plateau region of China. *Land Degradation and Development* 8: 1-16.

ZIEGLER, A. D. and GIAMBELLUCA, T. W. 1995. Horton overland flow generation on rural roads: a preliminary investigation of runoff and accelerated soil erosion in Northern Thailand. Paper presented at the Symposium on Montane Mainland Southeast Asia in Transition, November 12-16, Chiang Mai.

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