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Successful combat against desertification in The fruits of success Baluchistan, Iran. Photo: F. Cardy

Cover: Neem trees grown along a river bank for soil conservation in Niger. Photo: ICRAF

Desertification - A fresh approach

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More than one hundred countries are affected by the consequences of *desertification*: degradation of their dry lands resulting from climatic variations and human activities. The dry lands referred to are productive lands with harsh climates, but not including hyper-arid deserts. As many as 900 million people live in these areas and are at risk from the effects of this loss of productivity.

Populations of the drylands, struggling daily with persistent and almost universal poverty, have limited means to maintain or improve their lands and so continue to degrade them further. Traditional technologies have not kept up with the present rate of population growth and the increased demands for food, fuelwood and shelter. Eventually the land becomes exhausted and stops producing; the people must migrate to richer lands, get food from elsewhere, or die.

Famine relief in the form of food aid treats the symptoms but not the disease itself, which is land degradation. The problem is compounded when drought increases the stress on drylands. Widespread malnutrition may be followed by starvation and the death of thousands of people, as has happened in Somalia and Ethiopia during recent years. Mass migration, civil strife, political disturbances, regional unrest and even military intervention are the result; these are now recognised as global concerns.

A global issue

The world is becoming interdependent; stability, security, humanitarian and economic concerns are all contributing to the recognition of the Earth as a "global village" or, more specifically, a global ecosystem made up of interdependent states. This was demonstrated in June 1992 at the UN Conference on Environment and Development (UNCED) when over 100 Heads of State met and adopted *Agenda 21*, a blueprint for international action to protect the environment. Land degradation is highlighted in several Chapters, most notably Chapter 12 which is devoted specifically to the problems of desertification and drought (see below).

World food markets

Desertification directly affects the balance of global food supply, increasing the pressure of demand from the ever-growing population. Some of the surplus commercial food produced under subsidies is not distributed through normal market channels but rather through food aid programmes, distorting the world food market.

Few citizens of the planet are unaffected by desertification: inhabitants of the drylands who are directly affected must receive regular food aid in order to survive; those who are living in prosperity, outside affected areas, contribute this aid in order to help the peoples affected and, ultimately, to ensure their own security and prosperity. The whole international community is involved.

In 1989 (a relatively good year) 10 million tonnes of cereals were exported in the form of aid from the producing countries to those in need. This was about 3% of their production. Every year the world donor community spends several billion dollars on food relief, 90-95% of which goes to drylands. The costs are increasing annually while desertification continues unabated and is coupled with recurrent drought. Confident expansion of agriculture in marginal lands during wet periods leads to increased hardships when the dry periods return. The costs will continue to increase as long as the productivity of the world's land, especially the drylands, is allowed to decline through degradation. The situation is still more aggravated by political strife and civil wars which often result from the shortage of resources.

The distorted world food market also contributes to the decline in the rate of food production per capita among the ever-growing population. Governments of donor countries provide higher and higher subsidies to their agricultural sector, yet subsidized production of agricultural surpluses using large quantities of inputs distorts world produce markets and deprives the South of the benefit of freer trade. The difficult negotiations on the GATT Uruguay round are critical in this area. Subsidies in the North undermine the agricultural sector of developing countries, whether they are affected by desertification or not. They also put heavy pressure on the land and water resources of the North, resulting in extensive agricultural pollution. This increases land degradation in humid lands and reduces its productive capability. A 1985 estimate by Environment Canada suggested that Canada was losing $1 billion-worth of production per year because of land degradation.

Migration and environmental refugees

Before food aid is delivered there is often large scale migration. Millions of people (at least 10 million by one estimate in 1988) have become environmental refugees from their exhausted lands. In the first half of 1992 alone, some 300,000 Somalis and 100,000 Sudanese are estimated to have moved to Northern Kenya because of territorial battles and hunger. But Kenya is not well-equipped to handle this influx, especially when its own food-producing capacity is being reduced by drought. Other major transboundary migrations occur elsewhere - over a million people are said to have left Burkina Faso in the decade between the mid 1970s and 1980s. Migration also occurs to much more distant places - for example, Somalis have moved to Finland through Russia and there are now "African Boat People" who are trying to cross the Straits of Gibraltar to enter Europe illegally. This adds extra costs and social tensions to the northern nations.

Urbanization

Throughout the developing countries, land degradation and drought are a major factor in the migration of subsistence farmers to the cities. In the two decades between the mid 1960s and the mid 1980s the urban population of the Sahel countries quadrupled. Urbanization in the dry land countries of Africa is running at 7% per annum or more; this places enormous stress on urban infrastructures (where they exist) and on the people, both residents and immigrants. All of them still require food. Inadequate infrastructure leads to health and security problems and demands for massive infusions of foreign capital to pay for infrastructure improvements. Urbanization has a major impact on other resources, notably water and biomass, which often results in further degradation of the land.

What is desertification?

Land degradation is worldwide in its geographical spread, leaving no continent unaffected; it is global in its environmental and socio-economic impacts. Over 100 countries, including more than 80 developing countries, are affected by land degradation in their drylands. Drylands, excluding hyper-arid deserts, cover over one third of the land area of the Earth. At present 40 million people are said to be suffering from malnutrition in the drylands of Africa alone. Of these, some 2 million are believed to be suffering from starvation and are on the verge of death. Hundreds die daily because of their inability to feed themselves from exhausted desertified dryland soils.

Unfortunately, there has been much confusion over the meaning of *desertification*. The largely invalid concept of expanding deserts and advancing sand dunes has become a more permanent image in the public eye than the less visible and much more serious phenomenon of land degradation in drylands which is addressed here. This is the issue that affects so many people and is largely man-made. If fully recognized and tackled, it should be resolvable by man.

Desertification, as defined by UNEP, is land degradation in arid, semi-arid and dry sub-humid areas resulting mainly from human activities. This definition was modified by the 1992 UN Conference on Environment and Development (UNCED), to read as follows:

Desertification is land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities.

This definition has been internationally negotiated and approved at UNCED as the operational standard for Agenda 21. Unfortunately, however, it does include the three separate elements of short-term drought, long term climate fluctuations and land degradation induced by human beings. Each of these is different and needs to be addressed in different ways, although there are interactions.

Droughts are natural phenomena which recur periodically and can be prepared for. Severe and prolonged drought in degraded drylands results in increased demands on the production of humid lands (see above). In case of prolonged drought in certain key areas, global food security is already at a precarious state and this situation will become critical if desertification continues unabated.

Costs of desertification and drought

Unfortunately, there are no exact and reliable figures available for global losses induced by desertification and drought, nor are there many for specific *local* conditions where accurate data are most needed for practical management purposes. Existing data have been obtained through various estimates and indicate only the general magnitude of the problem. However, evidence is accumulating on soil loss at several localities where there have been attempts to evaluate these losses in economic terms.

One unpublished World Bank study estimated that the equivalent of 20% of the annual GDP of one Sahelian country could be lost through capital depletion of natural resources. That is why new knowledge and directly measured hard data must be acquired; this is essential for any programme that aims to combat desertification and manage drought. However, this is costly and cannot be carried out without the involvement of the whole international community. Estimates that have already been made of the average income foregone through drylands degradation amount to approximately US $42 billion a year.

The economic factors

The global significance of the desertification problem is economic but it has not yet been recognized as such. Global resource economists are only now beginning to recognize that we cannot continue relentlessly to exploit our land resource capital base for ever, even though, at present, it is regarded as a (relatively) free commodity that is rarely taken into account in cost-benefit equations.

Many economists still do not take into account the depletion of capital resources for which there is no effective active market. Natural resources are not shown as capital assets in national accounts and appear only as contributions to GDP when they are exploited. However, common sense - the foundation of economics - clearly indicates that if you pull down your house to use the wood for firewood so as to keep yourself warm, you are on a path to disaster. Common sense must equally show that an ever-increasing global population cannot go on degrading the soil to the point of total exhaustion.

Desertification depresses the economy of countries in which it occurs. In poor countries, depressed economies lead to political destablization and social unrest. Such economies are not good markets and thus the market potential of desertification-prone regions is greatly reduced. Existing foreign investments in these countries become increasingly at risk; the risks for new investments increase, the perception of hopelessness expands and a downward spiral commences. Past civilizations have disappeared forever as the result of similar events.

Desertification is closely linked in other ways to the economies of both North and South. Actions by the North, in the North, can actually result in the over-exploitation of land resources in the South. For example, rangeland degradation is occurring in Botswana due to increased meat exports to the European Economic Community at subsidized prices. In this way, Northern economic policies lead to desertification in the South. If the farmers of some of the most productive agricultural land in the world in Europe and North America need subsidies from their Governments, how can the farmers of the least-productive lands in harsh climates be expected to compete or even survive without greater support?

Biological diversity

Desertification entails the destruction of vegetation and loss of many dryland plant and animal species. Many crops (wheat, barley, sorghum, millet, etc) and fodder plants that form the backbone of world agriculture and animal husbandry originate and are related to wild species in arid and semi-arid territories. Hundreds of wild plant species that are native to drylands are sources of valuable medical materials. Loss of these plants through desertification represents loss of valuable and irreplaceable genetic material. The loss of germplasm resources through desertification may be, from an economic point of view, no less severe than that through deforestation. A large indigenous pharmaceutical industry is dependent on local biodiversity, and this is already seriously endangered.

International waters

The loss of vegetation in watersheds leads to erosion and siltation which create particularly difficult problems in international waterways. The result is the siltation and pollution of inland waterways and of sensitive mangrove habitats and coral reefs in coastal areas. The problems of degradation of international waters will only be resolved through improved management practices of the watershed lands. It is clear that, unless the unsustainable management practices that lead to desertification are arrested, continued degradation of international waters is inevitable.

Climate

Desertification also affects and is affected by climate. Deprived of their natural vegetation, degraded dryland areas modify the energy balance in the lower atmospheric layers through changes in radiation absorption, reflection and emission properties (albedo). Similarly, changes in evaporation rates and rainfall retention potential have an impact on the water balance of areas suffering from desertification processes. Increased dust emissions from uncovered soil can modify the scattering and absorption of solar radiation in the atmosphere. Extensive areas of low or nil productivity will provide little or no capacity for absorption of carbon dioxide - the most important "green-house gas". The enormous extent of the drylands affected by land degradation is indicative of the impact that desertification processes have on global climate change mechanisms.

So what has to be done?

A comprehensive programme to combat desertification should include all of the following:

(a) Preventive measures
Implement programmes of direct preventive measures in productive drylands that are not desertified or only slightly desertified (about 30 per cent of productive drylands).

(b) Corrective Measures
Implement a programme of direct corrective measures in productive drylands that are moderately desertified (areas with 10 to 25 per cent loss of productivity in croplands and 25 to 50 per cent in rangelands).

(c) Rehabilitation Measures
Implement a comprehensive programme of direct rehabilitation measures to combat desertification in all productive drylands.

These options may be considered as priority actions that could be adopted both globally and nationally; they could be modified as appropriate within the areas concerned. Coordination of effort should also be encouraged by promoting cooperation between industrialized and developing countries within the regions. Plans for combatting desertification should be integrated with plans to develop other natural resources in a comprehensive sustainable environmental management framework.

Costs of action

Past experience has shown that the amount spent by the world community during 1978-1991 (approximately US $0.5-0.85 billion a year) on direct or supportive actions to combat desertification was far below the amount needed to implement the UN Plan of Action to Combat Desertification (PACD). Financial assistance to the developing countries that are most seriously stricken by desertification and do not have the resources to cope with the problem was particularly inadequate. Likewise, existing mechanisms for mobilizing resources and financing to implement the Plan of Action to Combat Desertification (such as DESCON and the Special Account) are also inadequate.

Financial assistance to developing countries struggling against desertification should be over and above regular budgets and conventional extra-budgetary resources. Such assistance must be predictable, sustainable and prompt. Net additional financing and technical assistance to developing countries for combating desertification should be provided by the donor community and international institutions on terms that neither exacerbate debt nor aggravate further the trade problems of recipient countries. Rather, it should enhance their development process. It must be re-emphasized that the highest estimated annual costs of implementing all anti-desertification measures are less than half the estimated annual costs of losses resulting from desertification.

The need for global action

The need to address the global problem of desertification is urgent; it is a major cause and mechanism of global loss of productive land resources. Desertification contributes to loss of global biodiversity, loss of the earth's biomass and bioproductivity, and to global climate change. It can lead to economic instability and political unrest in affected areas; it puts pressures on the economy and the stability of societies outside the affected areas, and it prevents the achievement of sustainable development in affected areas and countries. Current estimates for global, direct, on-site financial losses (ie, income foregone) due to desertification amount to about US $42 billion annually. Indirect off-site and social costs of desertification are even greater. A comprehensive, world-wide programme to combat desertification would cost only a fraction of this.

With 900 million people potentially affected, there is an enormous pool of talent and effort available to reverse the seemingly irreversible trend towards a desertified and degraded world. But even if the Global Environment Facility and the proposed Convention on Desertification and Drought provide the financing, there is still much to be done to motivate enthusiasm at the local level. Successes do exist and can be replicated. It is known that success can be achieved, that progress can be made at the community level, and that the global decline towards a degraded world can be prevented and reversed.

The UNCED Programme

Chapter 12 of Agenda 21 emphasizes the global nature of desertification and is a major step forward in gaining international recognition of the need for concerted action world-wide. It contains detailed recommendations for action at national, regional and international levels in six specific (but inter-related) programme areas. These are:

- A Strengthening the knowledge base and developing systems for assessment, monitoring and information;
- B Intensifying soil conservation, afforestation and reforestation activities;
- C Eradicating poverty and promoting alternative life-styles through integrated development programmes;
- D Integrating comprehensive anti-desertification programmes into national environment and development plans;
- E Setting up drought-preparedness schemes for drought relief and to assist environmental refugees;
- F Promoting popular participation and education, with a focus on desertification control and management of the effects of drought.

Chapter 12, Paragraph 12.40 also recommends the General Assembly at its forty-seventh session to establish, under the aegis of the General Assembly, an intergovernmental negotiating committee (INC) for the elaboration of an international convention to combat desertification, in those countries experiencing serious drought and/or desertification, particularly in Africa, with a view to finalizing such a convention by June 1994. This has now been done and the Committee started its work with an organizational meeting in January.

Immediate actions

The challenge for the INC, and for all those agencies and individuals involved in the battle against desertification is to find the means to implement Agenda 21. The Plan of Action to Combat Desertification adopted in 1977 has had less success than necessary because of a lack of awareness of the social dimension of the problem, lack of political will, insufficient resources, and uncertainties about effective means of implementation. The resulting emphasis on planning rather than action now has to be reversed. Much data has been collected and millions have been spent on agricultural research; the challenge now is to find practical ways of implementing the grand plans of the PACD and the tasks of Agenda 21.

In order to do this, in addition to the ongoing programmes of planning, pilot projects, monitoring and research, the following need to be addressed now, so that the way will be clear towards implementation of a truly global anti-desertification effort.

1. First is to make the world community realize that this is a major global problem. Its effects are happening *now* and growing worse *now*. 900 million people may already be at risk and much of the rest of the world's population is indirectly affected. Forty million individuals are believed to be affected by malnutrition in Africa alone and perhaps 2 million are on the verge of death from starvation. Asia contains as much dryland as Africa (about one third of the world total).
2. Second is the need to more thoroughly expose the economic costs of land degradation/desertification - the economic costs of opportunity loss, productivity loss and the world wide economic implications and linkages, involving trade, subsidies, commodities, fiscal policies etc.
3. Third is to thoroughly expose the social costs of land degradation/desertification: the suffering, the famine, the migration, the tensions and strife, the social and political disruptions, the civil and international wars, the deaths, the despair, the disruption of markets, the relief efforts that result.
4. Fourth, during the 15 years since UNCOD much has been learnt from many failures but, most importantly, there have also been successes. Many of these have received little publicity and these must now be shared with a wider audience. They not only show what can be done but can also help create a renewed mood of confidence that the problem of desertification can be tackled successfully. The common theme

throughout is individual and community effort.

5. Fifth, the fundamental, practical and administrative difficulties inherent in the development and implementation of successful anti-desertification projects must be targeted and effective solutions identified, drawing on the accumulated experience. The challenge of delivering the needed services through sectoral organizations at the international, regional and national levels, in a coordinated and effective fashion to those that actually need them on the ground, in the field, has to be directly and effectively addressed. What is needed are effective mechanisms capable of delivering these services to the field activities.

With these ideas and others in mind, all those involved in desertification control, need to focus particularly on the problems of:

a) Bringing about world wide realization of the nature, scope and importance of the problem of desertification and of the need at the political, social and technical level to support it;
b) Improving the economic evaluation of all aspects of desertification and its control, including the costs of inaction and of necessary actions;
c) Improving the assessment of the social implications and costs of desertification and its control;
d) Identifying successes and disseminating information and recommendations on successful replicable approaches;
e) Making practical recommendations on how funding provided internationally can be applied successfully at the local level where the action is needed.

Conclusion

For those who have worked on desertification control for many years, it is gratifying to see such an increase in recognition of this problem in the last year. There is far to go, however, and the resources of all interested parties will be stretched to the full. There is a well known catch-phrase circulating now that says "Think Globally, Act Locally". All those working on desertification control must do exactly this.

Combatting desertification is a very special challenge because the problem has global impact and will only be solved through a global effort and approach; yet the solutions will have to be found at the forefront of the battle on the ground, in the field. The front-line troops in the battle are frequently extremely impoverished, functionally illiterate and most often female, overworked and undersecured, peasant-farmers. The challenge to provide real support to them in the way they need it, is a major one. It is essential that practical measures be developed to enable action to be taken in the field.

Fifteen years of work have provided much experience, but much more still needs to be done. It truly requires the imagination and support of all the globe to bring about the effective actions that are needed locally across more than one third of the land surface of the world, in order to reverse this suicidal degradation and its increasing global impact.

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Soil Erosion and Productivity: A Brief Review

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Summary

Investments in soil conservation have to be justified not only in terms of environmental sustainability but also on the grounds of providing an economic return on investment and maintaining food production levels. In other words, with special regard to policy and decision making, we need to calculate the negative impact of unchecked soil erosion, ie, the real on-site and off-site costs of degradation processes and therefore the potential benefits of conservation investments.

This paper looks at the effects of erosion and land degradation on soil productivity. In particular, it summarizes already published research carried out on this issue and related aspects.

In the first section the main features characterizing the erosion/productivity relationship are recalled. The principal agroeconomic consequences of soil erosion on yields and farm economics, on the use of land, on socio-economic systems, etc, are briefly summarized in section two. Estimates of soil erosion costs in temperate and tropical areas are reported in sections three and four. Finally, in the last section, some conclusive remarks are made, with particular reference to policy making and the future development of research.

Introduction

The main purpose of this paper is to look at the effects of erosion and land degradation on soil productivity. In particular, it is to be seen as a short review of what has been published on this issue and related aspects, both in terms of research methods and main findings.

There is no point in emphasizing once again the "desperate need" for an economic assessment of the problem. What is clear is that soil scientists, agriculturists, economists and, above all, policy-makers all need factual evidence of the damage caused by erosion processes and therefore the cost of foregoing conservation practices (ie, the hidden cost of not investing in soil conservation). Demonstrating that erosion reduces soil productivity is clearly essential if conservation policies are to be justified in economic terms.

Estimates of on-farm and off-farm costs of erosion can actually change our perception of the erosion problem, both at national and international level. At the same time, they can be extremely useful elements for deciding the level and how financial resources should be allocated.

Finally, since the main corpus of research focuses on on-site erosion effects in temperate areas, most of the findings and estimates provided fall into this category. Only in the 1980s has substantial attention been directed toward tropical soils. However, we will try to look at the tropical lands whenever the existing literature makes it possible.

Erosion-Productivity: A "Troublesome Relationship"

Following the work of M. Stocking and R. Lal, two authors who have been particularly active in this field, the principal features characterizing the erosion-soil productivity relationship are summarized below.

Once accepted that productivity is the productive potential in terms of vegetation of a soil system (Stocking and Peake, 1985) and before considering the central question of how erosion causes loss in soil productivity, there is an important initial observation to be made.

Although crop yield can be used as an estimator of soil productivity, it should not be confused as a simple measure of productivity. "Productivity" actually includes the potential for future production which cannot be assessed by an historical crop yield. Consider the common case where erosion causes some loss in productivity or some extra-costs. The losses may be compensated for by additional inputs such as fertilizers or extra labour or even putting more land into production. It follows that yields can be maintained even though the real soil productivity is decreasing. (Stocking and Peake, 1985). The two concepts should therefore be distinguished, even though yield levels are often used as indicators of soil productivity.

The causes and mechanisms of productivity losses can be described as follows (Stocking, 1984):

Soil fertility

Erosion changes soil characteristics. This will alter the fertility of a soil, thereby affecting its ability to support productive agriculture. In other words, progressive soil erosion increases the magnitude of soil-related constraints to production. There are many factors that individually may be soil constraints:

Water holding capacity and rooting depth

"There is a general consensus in the literature about the pre-eminence of loss in available water capacity in explaining the link between erosion and productivity." (Stocking, 1984). Erosion, for example, affects water-holding properties of a soil by reducing the amount of clays and soil organic matter. The erosion process, being selective, usually sorts out the fine particles and leaves the coarser sands which have little water retaining capacity. This process, moreover, brings high strength soil layers closer to the surface and consequently limits the rooting zone. Lower available water capacity may sometimes hide other limiting factors. However, it seems to be the most common parameter used in explaining productivity losses.

Soil strength and compaction

There appears to be a direct association between soil strength and productivity because hard soils limit root development. Splash erosion in the tropics, for example, causes surface crusting and compaction, and this often prevents plant germination. Moreover, a compacted soil will have lower organic matter, reduced infiltration and less plant-available water. Clearly, though soil strength and compaction definitely play an active part, it is difficult to separate these factors from those previously mentioned (lower organic matter, etc).

Soil nutrients

Erosion remove nutrients from soils. Although the limiting effect of lack of nutrients on productivity varies according to soil type and degree of erosion, it has repeatedly been shown that soil nutrient losses decrease productivity levels. This is even more evident when we consider that usually the application of fertilizers partially restores yields on eroded soils. In particular it should be recalled that eroded sediments usually contain a proportionally larger amount of organic matter and nutrients than that of the topsoil from which they are derived. The difference is called the "enrichment factor". This additional loss of nutrients shows up most for nitrogen and phosphorus, "but will also be significant for any nutrient associated with the cation exchange or with organic matter" (Stocking, 1986).

Further causes and mechanisms

Erosion also affects the structural stability of the soil and, on the whole, can have "harmful effects on seedbed preparation, tilth, organic matter, type and amount of clay, surface water storage and other physical and chemical aspects, all of which in turn affect the soil productivity." (Stocking, 1984).

In addition, toxicities and pH-related deficiencies may occur. "Where erosion is rife in the tropics, acidification often results, which in turn causes aluminium toxicity and renders other nutrients ions unavailable to plants" (Stocking, 1986).

Finally, erosion affects the way the soil can be used: non-uniform erosion clearly affects the use of machinery and fertilizer, pesticides and herbicides applications. Erosion also has effects on the timing of farming operations: late planting, delayed germination, etc.

Besides the problems related to those cases where a forced change in land use and farming systems becomes necessary, all these impacts have relevant effects in terms of yield decreases.

Some soil attributes such as soil nutrients can, generally speaking, be considered replaceable. Others, such as water holding capacity, are thought of as irreplaceable, at least in a reasonable time span. However, we will see how this is a simplified approach and that, in reality, it is difficult to restore long-term productivity completely. (This is particularly true in the case of poor soils, such as many soils in the tropics, where fertilizer application would not be enough and additional mulching and manuring would be necessary for restoring most of the lost productivity).

One fundamental difference between tropical and temperate soils should be recalled when reading different estimates of the various areas covered: the adverse impacts of erosion on soil productivity are generally more dramatic and intense on the shallow and impoverished soils in tropical Africa than on the deeper and more fertile soils of Western Europe or North America. As Lal has recently written: "Loss of the top 4 to 8 inches (10-20 cm) of soil on many uplands in tropical Africa represents an irretrievable loss. In comparison, such severe erosion losses on deep soils in North America may cause an estimated reduction of only 1.7 to 7.8 percent in productive potential under current technology after 100 years". (R. Lal, 1988).

The lesser effects of erosion on yields of temperate zone soils are mainly due to inherently higher soil fertility, mild climate and the use of, and responsiveness to, improved technologies and additional inputs. However, in tropical Africa where "old" and highly weathered low-fertility soils are common, the greater erosion effect on yields is caused by the fact that most plant-available nutrients are found in the top few inches of the soil and that erosion preferentially removes organic matter and clay which hold these nutrients. (R. Lal, 1988). For evident economic reasons, African subsistence farm-

Gully erosion at Makuini-Arusha, Tanzania. Photo: D. Ponzi.

ers, unlike North American farmers, do not have the means to add additional inputs (fertilizers) and thus erosion can have full negative impact on yields. Poor crop growth on these eroded soils is mainly caused by nutrient deficiency, increased drought stress due to reduced water holding capacity and greater run-off, and lower resistance to pests and pathogens.

In short, as Lal wrote: "In soils with edaphologically inferior subsoil and a shallow rooting depth, crop yield will decline as surface soil thickness is reduced. Furthermore, fertilizer cannot compensate for surface soil loss. Soil mismanagement can readily lead to irreversible soil degradation and loss of the natural resource base" (R. Lal, 1985).

Even for those tropical soils with a medium rooting depth and surface thickness, soil loss cannot be completely compensated for by fertilizer application. Symptoms of accelerated erosion are often masked by technological improvements and the longer it takes to recognize these signs the more difficult it becomes to restore soil productivity.

Obviously, highly negative socio-economic impacts follow on from this. "If severe yield reductions occur by a mere loss of 1 to 4 inches of topsoil, the forfeited production and economic loss in Africa as a result of past erosion are vast in comparison with the food deficit experienced in the region today" (R. Lal, 1988).

To summarize, it should be noted that, in general:

(1) Changes in the physical, chemical and organic conditions of soil all contribute to loss in productivity.

(2) Erosion and productivity are not independent and both are influenced by other factors. Moreover, the loss in productivity set in motion by accelerated soil erosion is a self-sustaining process: loss of production on eroded soil further degrades its productivity which, in turn, accelerates soil erosion.

(3) Soil erosion losses by volume or weight of sediments are poor indicators of productivity decreases. Loss in yield per unit of erosion is extremely variable. As the majority of existing soil erosion experiments do not usually report yield levels, it follows that in general they are not particularly useful for the purpose of analyzing productivity changes.

(4) Technology and additional inputs may mask the decline in productivity. The introduction of technological inputs into soil may sometimes cover what is an irreversible decline in the productive resource base.

(5) There is no evidence that crop type has any major influence other than affecting the rate of erosion. Initial indications are that most crops follow the same trend in declining yields with erosion.

With regard to tropical soils:

(1) For equivalent volumes of soil loss, tropical soils tend to suffer

significantly higher rates of crop-yield reductions than temperate soils.

(2) Productivity decline is greatest on "old", highly weathered, low fertility tropical soils where there is a high concentration of organic matter in the topsoil.

(3) As will be seen later, most of the research to date has stressed that, especially in the tropics, yield decline is most rapid for the first 10-20 cm of soil loss, after which the rate of reduction decreases exponentially. Thus the erosion-yield relationship is generally exponential in form (M. Stocking, 1984).

(4) If the negative exponential relationship is confirmed, it follows that a relevant loss in yield will result if an area with little prior erosion is allowed to further erode. The opposite will happen for those areas already intensively eroded. This means that, in general, it would be more convenient to invest conservation resources in those areas where productivity is still high and erosion has not gone too far. However, this conclusion is strictly economic in principie and other social and environmental factors may have to be taken into consideration.

Productivity Losses: Main Agro-Economic Consequences

If it is accepted that more erosion leads to larger productivity losses which in turn leads to more erosion at an accelerating rate, we can summarize the main consequences as follows (M. Stocking, 1984):

(1) Negative effects on the soil

Erosion brings about various detrimental effects on the soil's natural nutrient balance, structure, water-holding capacity and sustainability at producing crops. M. Stocking (1984) describes the main effects on different soil types.

With regard to nutrient loss, on which many reports have focused their attention, in temperate areas where physical parameters such as limited rooting depth are not relevant, lack of nitrogen and phosphorus seem to be considered the main limiting factors to crop productivity. In the tropics, the little research that has been carried out provides some evidence that it is feasible to restore productivity by applying additional fertilizers only for the lowest level of erosion.

(2) Impact on yields

Some general conclusions can be drawn.

(a) The nature of the relationship between erosion and yield loss is generally soil-specific and, to a lesser extent, crop-specific.

(b) Erosion appears to have greater effects on tropical yields.

(c) Absolute yield losses on tropical soils are particularly serious due to lower initial yields.

(d) Tropical soils initially show very high rates of yield loss which decelerate as erosion progresses. This means immediate large yield decreases for low amounts of erosion. Moreover, reduced soil productivity provides less vegetation cover and the erosion rate itself accelerates.

(e) Finally, as has already been said, science and technology (improved plant breeding, additional fertilizers, etc) can mask declining land productivity by raising farm production, a process that demands large amounts of inputs and ever-increasing costs, both financial and in terms of energy (manpower).

(3) Effects on farm economics

Soil erosion causes significant decreases in productivity and increased production costs. Research coming from the USA, Australia and other developed economies has shown an interesting common mechanism in terms of erosion effects at the farm level. Although improved technology increases production, the potential productivity of the resources (ie, long term soil productivity) actually decreases. This is demonstrated, inter alia, by increasing costs at the farm level - ie, both the general costs in terms of reduced potential food productivity and increased use of energy and technology have been high. With regard to fossil energy, for example, the costs of using extra fertilizer, fuel, chemicals, equipment and other inputs to offset the decline in productivity are generally very high. To put it simply, to get a higher output, more and more inputs are necessary. In tropical areas such a situation would be even worse since, on tropical soils, indiscriminate mechanization usually accelerates erosion. It is therefore difficult to attain the performances of developed farming systems.

There are also close links between erosion/productivity and changes in farming systems (M. Stocking, 1985). For example, these changes could take the form of:

(1) Increased role of cattle

Once farmers realize the effects of erosion, they may "rationally" decide to increase the number of cattle to counteract losses in productivity and environmental stress risks. However, this shift to pastoral practices often leads to overgrazing and further erosion.

(2) Increased intensity of land use

This process, especially in tropical areas, can augment erosion. In some cases it has been noted that losses in productivity were compensated by a larger use of agrochemicals with the effect, on the one hand, of decreasing weed cover (leading to more erosion) and, on the other, of increasing the intensity and duration of cropping (shorter rest period leading to further drop in soil fertility).

(3) More extensive use of land

Another logical strategy adopted by farmers to face productivity losses is to increase the area of land under cultivation, a process which has to be recalled when considering trends and performances (total outputs, average yields, etc) of the different agricultures.

(4) Changes in specific agropractices

Soil erosion and productivity decline also cause changes in types of crop and methods of farming, and this leads often to lower fertility conditions.

(5) Socio-economic effects on local society

The principal socio economic effects are:

(a) Abandonment of land and migration. A dramatic collapse of local agriculture often results in major migrations and relocation of people. Apart from the evident socio-economic impact, this process can create pressure on adjacent lands.

(b) Rural-urban migration. Productivity decline and the following marginalization of the traditional rural system, together with other factors, has frequently caused young active males to migrate to the towns for cash employment (especially in Africa). Women, who are already taking care of children and the elderly, are left alone to cope with the responsibility of looking after the fields and this, despite their efforts, causes further marginalization and productivity declines, with farming areas increasingly dependent on cash remittances from the town.

(c) Disease, malnutrition and other negative effects on human development. Child malnutrition, poorer average diet, increased susceptibility to disease and death and other socio-economic consequences have frequently been reported. It is clearly difficult to differentiate the various causes of rural poverty but, nevertheless, productivity decline is to be considered one of the main factors.

(6) Effects on national economies and international relations

Erosion and losses in productivity have numerous impacts on national economies and on international economic relations: off-site costs for the entire community, welfare payments and subsidies to the farmers, higher development project costs, increased cost of aid, increasing dependence of the developing countries on food and relief aid from the developed world with the consequent disrupting impact on their already fragile rural systems, foreign debt problems, etc.

Soil Erosion Costs in Temperate Zones: Some Global Estimates

One of the first estimates was made in the USA as part of the 1980 Resources Conservation Act (RCA) process. It showed that if 1977 rates of erosion (as calculated by the Soil Conservation Service in the 1977 National Resources Inventory) were to continue for 50 years, crop yields at the end of the period would be about 8 per cent less than otherwise (no-erosion) (P. Crosson, 1984).

Two years later, a group of soil-scientists at the University of Minnesota followed the RCA process and developed a model to calculate yield reductions. They found that if 1977 erosion rates continued for 100 years, at the end of this period crop yields would be 5 to 10 percent less than they would have been otherwise (P. Crosson, 1984).

In *Resources for the Future* (1983), 1977 National Resources Inventory data were used to find the erosion effects on crop yields between 1950 and 1980. The results showed that yields were 2 to 3 per cent less than otherwise (P. Crosson and A. Stout, 1983).

As P. Crosson noticed (1984), given the completely different methods used in those three studies, the similarity of the results was quite impressive (2-3 per cent in 30 years, 8 per cent in 50 years and 5-10 per cent in 100 years).

In the same work Crosson made another calculation with regard to yield decreases for corn and soybeans. Using the Minnesota model results he estimated that the present value of 100 years of national soil productivity loss in the USA, with some US \$40 million of losses per year, with 10 per cent discount, would have been slightly more than US \$4 billion at 1984 levels and, with 5 per cent discount, the value would have been US \$17 billion (assuming that corn and soybeans yields declined 10 per cent over 100 years, that the decline was in equal annual increments, that the price per bushel of corn was US \$3 and soybeans US \$7 and, finally, that there were 70 million acres in each crop each year).

These last figures did not include the costs for additional inputs (fertilizers and others) or for conservation practices, let alone the off-site damages which, following a Conservation Foundation study of the same period (Clark *et al*, 1985), ranged between US \$3 and US \$13 billion per year at 1980 levels. (In this research, the off-site damages included siltation of lakes, reservoirs and harbours, clogging of irrigation, losses of recreational values and costs of water cleaning.)

Later, Crosson again estimated the total cost of erosion (including the cost of erosion control) to be US \$1.7 billion to US \$1.8 billion. More specifically, for the year 1983, he estimated the crop production losses at US \$420 million. Fertilizer losses were valued between US \$100 and US \$160 million and some US \$1.2 billion were the costs of erosion control in federal government expenditures.

Other estimates made by Benbrook *et al* (1984), P. Myers (1985) and other authors over the national losses to farmers from sheet and rill erosion ranged from around US \$500 million to US \$1 billion per year. They show the same order of magnitude as Crosson's assessment (US \$420 million).

Using the Erosion Productivity Impact Calculator (EPIC) and the Erosion Productivity Index Simulator (EPIS) erosion productivity models, Colacicco *et al* (1989) have recently quantified the value of yield and fertilizer losses from soil erosion in economic terms. They applied prices for the crops and fertilizers to changes in these items as simulated by the two models and discounting appropriately. The result was that the present value of the profit loss from soil erosion averaged over cropland in the USA is around US \$0.50 per ton. They also found that most of the economic losses in the eastern farm regions come from permanent yield losses. In the western regions, most of the losses come from fertilizer losses which are (usually) temporary. The average value of the losses caused by erosion ranged from US \$0.20 per ton in the Mountain States to US \$0.93 per ton in the Lake States. On the whole, soil erosion would cost farmers in the USA more than US \$1.2 billion per year.

Finally, on-farm economic damages would be concentrated on land eroding at rates greater than 3T. These acres comprise only 13 per cent of cropland in the USA but they suffer more than half of the total damage. More than 80 per cent of the damage exceeding US \$10 per acre per year occurs on land eroding at rates higher than 3T. The concentration of the damage is further proof, if it is needed, that although overall productivity losses may be considered small, the damage on certain soils cannot be ignored.

B. Davis and G. Condra (1989) focus on the state of New Mexico, USA, to examine the on-site costs of wind erosion with regard to erosion control, damage to crops by wind-eroded soil and for reduced soil productivity. The main findings indicate that on site costs from all sources of wind erosion amount to some US $10 million annually in the state.

Outside the USA, other countries such as Australia (with mostly arid and semi-arid land) have produced yield decline and economic assessments.

According to M. Blyth and A. McCallum (1987), yield reductions can range between 5-10 per cent to 40-50 per cent depending on the soil loss. In New South Wales, Australia, for example, for a 75 mm/ha soil loss event in five different wheat growing locations, yield declines range from 6 per cent to 46 per cent with estimates of lost income ranging between Australian $13 and $138 per hectare, based on a price of Australian $137/t for 1984/85 (Hamilton, 1970; Blyth and McCallum, 1987).

Two large-scale studies on Australian erosion costs provided some interesting figures although they focused on the costs of salinity degradation only. The first, produced by the Working Party on Dryland Salting in Australia (1982), concentrated on scalding which is the major form of dryland salting in Australia, and affects some 3.78 million ha. The results indicated that the annual productivity losses to agriculture amounted to Australian $5.4 million (1982).

According to Peck *et al*'s (1983) study on salinity degradation, the total benefits foregone (with zero salinity level) to agriculture because of the existence of dryland and irrigation salinity were Australian $28 million per year (1982).

One last interesting aspect of the Australian work is the monitoring of wheat quality with erosion. According to Molnar (1964), average protein content decreased by 6-23 per cent with 75 mm of soil loss.

With regard to the off-site damages, E. Clark and J. Harerkamp (1985) restricted their study to the analysis of problems caused by sediment and associated agricultural pollutants entering waterways in the USA. The main damage considered was divided in two groups: in-stream effects and off-stream effects. The first comprised effects on recreational values, water storage facilities, navigation and other in-stream uses. The second group included flood damage and effects on water conveyance facilities, water treatment facilities and other off-stream uses.

The single-value estimate for the cost of in-stream and off-stream damage attributable to land degradation was US $ 6 billion per year in 1980, of which cropland accounted for US $2.2 billion. These figures refer to total annual current costs with no deduction for the investments or other losses incurred in reducing this damage. In addition, no estimates were provided on the costs of biological damage although, as the authors suspect, these costs may be very significant.

M. Ribaudo (1986) refined the Clark data and generated estimates by farm production regions for cropland. Results showed that off-farm damage can be several times greater than on-farm damage. In some cases, the first could be even ten times higher than the latter (in the Delta and Southeast regions for example, where, on the one hand we have relatively low yield loss per ton of soil loss and, on the other, we have the high value of the surface water to off-farm users). Ribaudo's estimates for the total off-site losses, in terms of annual damage in 1983, ranged between some US $4 billion and US $15 billion with the "best" estimate around US $7 billion.

One of the off-site costs which has been most investigated is the damage to water storage reservoirs. E. Clark (1985) estimated this damage to be between US $310 million and US $1.6 billion (single value estimate US $690 million).

More recently, B. Crowder (1987) used a regional approach to estimate sediment damage in lakes and reservoirs. His calculations indicated that 0.22 per cent of the nation's water storage capacity is lost annually. Of this, an average of 24 per cent is due to soil erosion on cropland.

In the central USA the greatest water storage capacity losses resulted from deposited sediment originating on cropland. Annual national damage to storage ranged from US $597 million to US $819 million, with the cropland contribution being between US $144 million and US $197 million.

Soil Erosion Costs in Tropical Areas

One of the most frequently cited works on tropical soils is the FAO-funded research led by M. Stocking entitled *The cost of soil erosion in Zimbabwe in terms of the loss of three major nutrients* (Rome, 1986).

Drawing upon an important series of experiments on soil loss, run off and nutrient losses conducted in Zimbabwe during the late 1950s and early 1960s. Stocking and his colleagues took the opportunity to assess the effects of erosion in terms of the loss of nitrogen, phosphorus and organic carbon, as this impact had not been analyzed at the time. More specifically, the experiments consisted of over 2,000 individual storm soil loss events in five years on four soil types and numerous crops, treatments and slopes. Such a data base on nutrient loss was unequalled in any developing or tropical country.

The main aim of the project was to see if there is any relationship between nutrient losses and erosion and, if so, whether an economic estimate could be made of the damage caused by the present levels of erosion in Zimbabwe.

From the summary of the research we can draw several main conclusions. Statistical analysis showed highly significant relationships between soil loss and nitrogen, phosphorus and organic carbon losses from the experimental plots. Relationships were such that regression equations were calculated that would predict statistically valid rates of nutrient loss, given different levels of erosion. Moreover, analysis of variance showed that for most purposes there was little difference in predicted nutrient losses with variations in seasons, soil type, crop or degree of erosion.

Enrichment ratios were on average about 2:5. This means that there is a significant selective removal of nutrients from the soil by the erosion process. On

Flow diagram illustrating the calculation of the financial cost of erosion

	Soil Group 1	Soil Group 2
Description	Farming systems	Farming systems
Tonnes/ha	Estimated rate of erosion of each system	Estimated rate of erosion of each system
Tonnes/ha	Soil loss/ nutrient regressions	Soil loss/ nutrient regressions
Hectares	Area of major farming systems	
Tonnes	Zimbabwe - total losses of * Nitrogen * Phosphorous * Organic Carbon	
Zimbabwe $/tonne	Fertilizer prices	
Zimbabwe $	Financial cost as measured by nutrients in fertilizers	

Source: Stocking, M., 1986. The cost of soil erosion in Zimbabwe in terms of the loss of three major nutrients, *AGLS, FAO, Rome.*

tropical Alfisols and Ultisols - soils with low reserves of nutrients - the enrichment ratio was also the highest, thus exacerbating the already serious situation.

Extrapolating the findings to the communal, commercial, grazing and arable farming systems of Zimbabwe, it was calculated that, on average, 1.6 million tons of nitrogen, 15.6 million tons of organic matter and 0.24 million tons of phosphorus are lost annually by erosion. The arable lands alone lose 0.15 million tons, 1.5 million tons and 0.02 million tons respectively. These nitrogen and phosphorus losses from arable land were about three times the level of total fertilizer application in Zimbabwe in the season 1984/85 and they do not include losses of nutrients dissolved in runoff water.

The total financial cost of lost nitrogen and phosphorus from all of Zimbabwe's lands was US $1.5 billion per year (1985). Total financial cost of losses from the arable lands was US $150 million. On a per hectare per year basis, the financial cost of erosion varied from US $20 to US $50 on arable land, and US $10 to US $80 on grazing lands, depending on the degree of erosion.

Therefore, the erosion process has a massive "hidden" cost on the economy of Zimbabwe, especially in terms of its natural resource base depletion.

With regard to the costing estimates, the main assumption made by the research group concerns the difficulty of relating losses of nutrients, many of which are in organic matter and only slowly available to plants, to a form of the nutrients in fertilizer which is quite different.

Most importantly, it should be remembered that the loss of nutrients is only part of the impact of soil erosion. Stocking states at the end of his research summary that: "If all on-site costs such as yields decreases, loss of organic matter and other nutrients, and further forms of degradation were to be included, the impact of erosion would be far greater than the figures in this analysis suggest". All off-site costs, both financial and socio-economic, would also be additional.

Further important conclusions about the erosion/productivity relationship in tropical areas come from different authors and countries.

Lal and colleagues from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, have produced some of the most interesting works on tropical areas. In particular, they have carried out more than a decade of experiments on an Alfisol (Oxic Paleustalf), relating erosion to yield on soil loss/run off plots that have been subject to natural rainfall. Maize and cowpeas have been monitored on four slopes, ranging from 1 to 15 per cent, under natural rainfall.

The results show that in all cases an exponential relation best described the fall in yield with cumulative erosion. More specifically, the pattern in yield loss for both maize and cowpeas was similar: it was most severe on the shallowest slopes where 10 mm of erosion would produce a remarkable 90 per cent yield loss. On 1 per cent slopes, yields were halved after only about 30 tons per hectare of soil loss. Based on these figures, Lal suggests that the soil loss tolerance rate on such soils may be as low as 0.5 ton/ha/year, about one twentieth of the normally quoted tolerance level of soil loss. This highlights the high sensitivity of some tropical soils. This outcome is very significant because it shows how rapid the initial decline in productivity that occurs with erosion can be. Lal attributed most of this decline to an erosion-induced decrease in clay and organic matter content, a reduction in rooting depth with its associated water holding capacity and poorer water infiltration.

These experiments and other later ones also confirmed that, where erosion was simulated artificially by desurfacing, the method seriously underestimated the effects of erosion on yields.

Further confirmation of these trends in crop yield losses from the erosion of Alfisols (soils that are common in tropical Africa) come from other experiments realized in the USA, Indonesia and Australia, the results of which have been analyzed and summarized by M. Stocking and L. Peake (1986). As they state in the abstract of their article: "Data sources from Nigeria and the United States, with supplementary information from Indonesia and Australia, are used to establish the form of the relationship between cumulative erosion and yield level of crops. For the most critical types of Alfisol - those with a strong textural and/or chemical contrast between topsoil and subsoil - initial yield decline is dramatic. The implication is that yield decline under tropical conditions may be at least an order of magnitude greater than under equivalent temperate conditions, but that much more information is urgently needed in order to cost accurately the on-site impacts of allowing erosion to continue unchecked."

This empirical evidence and especially the conclusions (partially reported in the first part of this paper as far as they concern tropical soils in general) apply to Alfisols, but may also be relevant to Ultisols and Oxisols.

Few other global economic estimates on erosion costs in tropical areas have been produced. It is probably worth mentioning Hurny's study on Ethiopia which represents just one of these few attempts to calculate the costs of erosion damages. Hurny estimated that 1986 costs were Ethiopian Birh 59 million (some US $30 million) and would rise to Ethiopian Birh 1,800 million (US $900 million) by the year 2035. Nearly 80 per cent of the cost would reflect crop production losses; 20 per cent would be lost in terms of livestock production. More than 45 per cent of these losses would occur because of land eroding so badly that it would go out of production. As H. Dregne writes (1990): "If that figure for abandoned land is anywhere near correct, it spells catastrophe for Ethiopia".

Recently, Y. Biot (1988) has produced a general modelling approach for a first level assessment of future soil productivity in rangeland areas. In particular, the available water storage capacity (AWSC) of the soil is proposed as the productivity index, and the impact of erosion on this index is modelled by making up a simple balance sheet of AWSC gains from soil formation and losses from erosion. Biot illustrates the potential of the model for use in the field with an example from semi-arid rangeland in Botswana. Using the proposed model, a residual economic life of the land of 428 years is forecasted. Although this prediction puts this land beyond the usual timescale for economic/financial analysis, the general trend can be used to forecast the rate of decline of primary production and hence cattle production in the coming decades due to sheet and rill erosion.

Conclusions

With regard to policy and decision-making, we have already noticed that investments in soil conservation have to be justified not only in terms of environmental sustainability but also on the grounds of providing an economic return on investments and maintaining food production levels. In other words, we need to foresee and calculate with some degree of precision the negative consequences of unchecked erosion, ie, the real on-site and off-site benefits of investment in soil conservation.

At present, such costs and benefits are only rarely and inadequately built into plans for rural development. Clearly, this situation must change if realistic and efficient land use approaches are to be adopted.

This means that assessing the degree of land degradation is a necessary first step but is not sufficient in itself: estimates of productivity losses due to erosion must also be provided to the decision-maker.

However, as we have seen, most of the research already undertaken on erosion is directed towards measuring the rates of soil loss and modelling the interaction of parameters that cause erosion. Obviously, this is not enough and new research into the problem should primarily focus on the real economic impact of erosion expressed in a way that can be easily understood by the people affected and the policy-makers concerned.

In short, new investigations must answer the most pressing questions: what is the socio-economic effect of erosion? What is the benefit for farmers and national economies in applying soil conservation measures? What are the best land conservation strategies and plans to be developed and implemented?

In particular, the following research activities should be encouraged and supported:

(1) Further fundamental research on the dynamic interrelationships in eroding soils, especially on the erosion/productivity relationship with specific regard to soil type, land use, agroecology and technology. Data are still limited on the effect of erosion on the physical and chemical characteristic of specific soils and on how these relate to changes in soil productivity.

(2) Country studies quantifying the national cost of erosion-induced productivity losses.

(3) Farm-level financial/economic studies on which to base rational conservation programmes and projects.

(4) International cooperation and coordination in order to standardize research methods and organize dissemination of results and access to funding sources.

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