THE GLOBAL IMPACT OF SOIL EROSION ON PRODUCTIVITY

I: Absolute and Relative Erosion-induced Yield Losses

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Published studies relating erosion and productivity have been generally based on information derived from expert opinion on the extent and severity of soil erosion and on limited data on its impact on soil productivity, resulting in widely varying yield and economic loss estimates. In contrast, this report estimates the impact of soil erosion on productivity by collating, synthesizing and comparing the results from published site-specific soil erosion-productivity experiments at a global scale. Using crop yield as a

The views expressed here are those of the authors, and may not be attributed to Appalachian State University, The Ohio State University, or the Economic Research Service.

Advances in Agronomy, Volume 81

DOI 10.1016/S0065-2113(03)81001-5

proxy measure for soil productivity, this analysis uses the data from 179 plot-level studies from 37 countries identified in the soil science literature to calculate absolute and relative yield losses per Mg or cm of soil erosion for various crops, aggregated by continent and soil order. The results show that effects of past erosion on yields differ greatly by crop, continent and soil order. However, aggregated across soils on the continental level, absolute differences in productivity declines Mg^{-1} of soil erosion are fairly small. However, depending on the specific crop and soil, relative erosion-induced yield losses Mg^{-1} or cm^{-1} of soil erosion were two to six times smaller in North America and Europe than in Africa, Asia, Australia and Latin America. The higher losses in the latter continents are due primarily to much lower average yields, so that with identical amounts of erosion, yields decline more rapidly in relative terms. Studies using management practices as their experimental method to determine effects of present erosion showed much greater absolute and relative yield losses, which may be an artefact of the combined effect of erosion and variable management practices. Comparing the results of past and present erosion studies indicates that inappropriate soil management may amplify the effect of erosion on productivity by one or several orders of magnitude. Good soil management for effective erosion control and maintaining productivity, therefore, is imperative to meet the needs of the world's present and future population.

I. INTRODUCTION

Soil, a basic resource on which all life depends (Perrens and Trustum, 1984), is degrading in many parts of the world. One of the main processes of soil degradation is accelerated erosion. Erosion is a natural process that has occurred for as long as the earth has been in existence (Larson *et al*., 1983). Some of the most productive soils in the world (e.g., loess and alluvial soils) are the result of erosional processes. However, human activities have accelerated the naturally occurring rates of erosion (Davis and Browne, 1996). Erosion is both the most visible and the most widespread form of soil degradation. Quantitative, objectively measured data on the dimension and extent of soil erosion are, however, scarce and are still typically lacking in many regions of the world (Erenstein, 1999). Brown (1984) estimated global soil loss to erosion to be 26 billion Mg yr^{-1} (an average of 16 Mg ha^{-1} yr^{-1}). Lal and Stewart (1995), Oldeman (1994), and Scherr (1999) estimated that 5–12 million hectares of land (0.3–0.8% of the world's arable area) are rendered unsuitable for agriculture each year due to different forms of soil degradation. In the first attempt to assess the status of soil degradation on a global scale (GLASOD), Oldeman *et al*. (1991) compiled the opinions of soil experts around the world to create a map of the extent, nature, and severity of human-induced soil degradation. They concluded that human-induced soil degradation has affected nearly 2 billion hectares, or 15% of the earth's total land area since the middle of the twentieth century. Water or wind erosion accounted for about 84% of this area (1094 and 548 million hectares, respectively) (Oldeman, 1994). Fig. 1 provides an overview of the distribution of eroded land areas by continent, and of the extent of soil erosion as a percentage of the total area of degraded soil.

Most researchers agree that erosion is a serious problem. There is less agreement with regard to its onsite effect on agricultural production and soil productivity (van Baren and Oldeman, 1998). Productivity can be defined and measured in many ways, such as output per unit of land, labor or other input(s). In the context of soil productivity, it is the productive potential of the soil system that allows the accumulation of solar energy as biomass (Stocking, 1984). Production is the total accumulation of energy, irrespective of how quickly, over what area or with what input it accumulates. Agronomic yield or output per unit area over a given time period, is a measure of production which can be used as an indicator of productivity. However, it is an imperfect indicator as yield is an expression of historical production, whereas productivity is a measure of potential (future) production (Tengberg and Stocking, 1997). Dregne (1995) observed that production (i.e., total biomass) can remain constant or even increase as the soil progressively degrades. Stocking (1994) observed that crop yields may increase even though soil degradation may reduce long-term productivity, causing a loss to future economic returns to production.

Oldeman *et al*. (1991) estimated that "strong" or "extreme" erosion accounted for about 16% of the eroded area (and about 2% of the world's total land area), but no estimates of impact on productivity were provided. In a separate study, Dregne and Chou (1992) estimated productivity losses due to land degradation on cropland and rangeland in dry areas. Using the range of losses in Dregne and Chou, Crosson (1995) estimated total productivity losses in these areas at about 12%, or approximately 0.3% annually if assumed to occur over a 40-year period (as in Oldeman *et al*., 1991). Thus, despite millions of dollars invested in erosion research, it is difficult to state precisely what effect the loss of a unit of soil has on crop yield (Lal, 1987a). This is due in part, as Perrens and Trustum (1984) and Erenstein (1999) observed, to the fact that there is no direct, clear-cut relationship between erosion and productivity, making the assessment of the impact of erosion on productivity difficult. Productivity decline may not relate directly to the amount of soil loss (expressed in Mg or cm ha^{-1} yr^{-1}), but may be a result of erosion-induced changes in the physical, chemical, and biological qualities of soil that influence production (e.g., water holding capacity, soil organic matter (SOM) and nutrient contents, and bulk density). Moreover, soil is only one of the factors affecting productivity, as crop yield is a function of many variables (Perrens and Trustum, 1984; Lal, 1987a; Rabbinge and van Ittersum, 1994; Erenstein, 1999). Productivity reflects soil erosion if either yield declines with progressive severity of erosion or input use increases to compensate for erosion-caused declines in soil

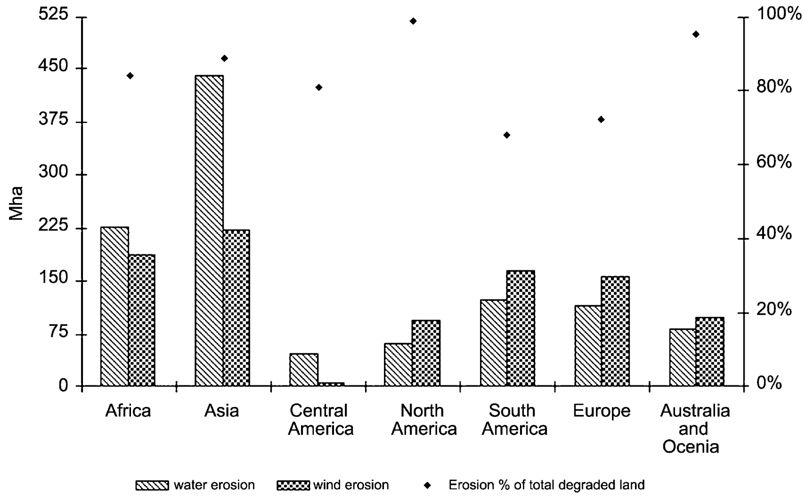

Figure 1 Global extent of soil erosion (in Mha and as a percentage of total degraded land) by continent (based on data from Oldeman, 1994).

quality (ERS, 1997). However, soils of poor physical quality (as measured by erosion and erosion-induced changes in texture, water holding capacity, or organic matter, etc.) may produce high yields without large increases in inputs (Vesterby and Krupa, 1993). Soil erosion rates by themselves are, therefore, poor indicators of the loss in productivity (Larson *et al*., 1983).

Much of the debate to date is based on information derived from expert opinion on the extent and severity of soil degradation, and on limited information on its effects on productivity. Few studies have systematically analyzed the data from field experiments relating erosion and productivity. Advances in spatially referenced data and analytical methods permit evaluation of these data more closely, and to draw inferences pertinent to large spatial scales.

This report complements a previous review on soil erosion and productivity for North America (den Biggelaar *et al*., 2001). Its objective is to estimate the impact of soil erosion on productivity by collating, synthesizing and comparing the results from published site-specific soil erosion–productivity experiments on a global scale. The present chapter includes the results from the North American erosion–productivity review to provide a comparative perspective of the impact of erosion in different continents. In accord with most studies reviewed, differential topsoil depth (TSD, in cm) and erosion-induced soil loss (in Mg) are used as independent variables. Crop yield was used as the indicator of soil productivity. This analysis uses the available data to calculate absolute and relative yield losses per megaram (Mg) of soil erosion for various crops, aggregated by continent and soil order. This information is then used to make soil-based, continent-level assessments of the impact of soil erosion on crop yields and total production over time. The results of this additional analysis will be presented in a companion chapter (den Biggelaar *et al.*, this volume).

II. DATA SOURCES AND ANALYSES

A. Data Sources

This review is limited to studies based on field research on soil erosion–productivity that reported quantitative yield results (e.g., bushels per acre, tons per acre, or megagrams (Mg) or kilograms (kg) per hectare (ha)). Studies which reported results only as a percentage decline in yield without specifying those yields were excluded. Also excluded were studies based on simulation models or regression analysis, unless they included data from field studies that were used to develop or test the models. Based on concerns articulated by Boardman (1998) about the "misinterpretation and uncritical use of original field data" in studies using secondary data, and the extrapolation of such data across soils and to all crops, this analysis is based on original studies conducted to determine crop- and soil-specific erosion-induced productivity declines.

Information on the area of soil orders by continent was obtained from the Global Soil Regions' map of NRCS's World Soil Resources Staff (1997). For the United States, soil series information was translated into the soil subgroup of the US Soil Taxonomy using the USDA-NRCS Soil Survey Division's Official Soil Series Descriptions on the Internet (Soil Survey Staff, 1999). Soils in other countries are often classified using a different classification system. In some articles and reports, soil classification in either the FAO or US Taxonomy was provided in addition to the local classification. Nomenclature based on the FAO soil classification was converted to the US Taxonomy equivalent using the comparative system provided by Landon (1984). In studies in which only a local classification was provided, the soil order and/or subgroup were derived from the Global Soil Regions' map (World Soil Resources Staff, 1997) based on the approximate location of the experiments.

Latitude and longitude information for the location of the experiments, if not provided in the articles and reports, was obtained from the USGS (2000) Geographic Names database and Natural Resources Canada (1995) Geographic Names of Canada for locations in North America, and from the Getty Thesaurus of Geographic Names (Getty Research Institute, 2000) or the GEOnet Names Server (NIMA, 2000) for experiments elsewhere.

B. Data Analysis and Interpretation

An Access database was developed to enter the information from the studies identified in the literature. As several studies comprised and reported on experimental results from more than one soil series, a separate record was created for each at the soil subgroup level. The database resulted in a total of 329 separate records, covering 161 soil subgroups from 37 countries (Table I). A total of 38 crops were used in these studies; crop information (i.e., type, yield, and erosion-induced yield loss), together with information on input use (if any), were entered as a nested table within each record. Some studies used differential input levels (such as fertilizers or irrigation) as subplots of the main erosion plots; the various crop-input combinations used in the studies resulted in 572 separate entries nested within the 329 records.

The yields reported in the literature were used to calculate absolute and relative mean yield decreases per centimeter or metric ton (Mg) of erosion-induced soil loss. For ease of calculation and comparison of the various studies, we assumed linear yield declines; even though, in most cases, observed yield declines were not linear. For studies using topsoil removal/addition and TSD as experimental methods, actual TSD values were used. To calculate yield impact per centimeter of soil loss in studies using soil phases as the experimental method, we assumed a difference of 7.5 cm between severely and moderately, and moderately and slightly eroded phases, and a difference of 10 cm between slightly eroded and depositional phases (Soil Survey Staff, 1999). Standard conversion factors employed for the US Census of Agriculture (NASS, 1999) were used for weights, measures and yields of various commodities.

Yield declines have generally been calculated using uneroded or slightly eroded phases as a reference, which may not be representative of farmers' conditions that consist of a range of soil depths or phases within one field. We therefore used the mean yields across all experimental plots as the reference yield from which to calculate erosion-induced yield declines. It would be more correct to use the mean yield for the various crops obtained under farmer management for the areas where the experiments were implemented, but such information is not available in the desired format (i.e., disaggregated by country, year, and soil order or subgroup).

C. Location of, and Methods Employed in, the Erosion–Productivity Studies

From a review of the literature, 179 field-based studies on soil erosion and productivity were identified. The studies are not evenly dispersed over the world, however, as shown in Fig. 2 in which the locations of the various experiments are overlaid on a map of soil orders. The majority of studies (59%) were carried out

Table I
Soil Orders, Subgroups and Crops Represented in the Studies Reviewed by Continent

Continent (countries represented)	Soil order	No. of records	No. of soil subgroups	Crops[a]
Africa (Benin, Botswana, Burkina Faso, Cameroon, Egypt, Ethiopia, Ghana, Kenya, Niger, Nigeria, Sierra Leone, Tanzania, Zimbabwe)	Alfisols	30	13	Beans, cassava, cotton, cowpeas, forage, maize, millet, pearl millet, peanuts
	Aridisols	2	1	Barley
	Entisols	1	1	Maize
	Inceptisols	4	1	Cotton, maize
	Oxisols	7	4	Cowpeas, maize
	Ultisols	9	5	Cowpeas, maize
Asia (China, India, Indonesia, Pakistan, Philippines, Sri Lanka, Thailand)	Alfisols	4	3	Cassava, maize, millet, mungbeans
	Aridisols	2	1	Maize, wheat
	Inceptisols	5	5	Barley, cabbage, chickpeas, maize, mustard, potatoes, soybeans, wheat
	Oxisols	1	1	Soybeans
	Ultisols	2	2	Maize, tea
	Vertisols	2	2	Soybeans
Australia (Australia)	Alfisols	10	7	Barley, pasture, wheat
	Aridisols	4	2	Potatoes, wheat
	Ultisols	1	1	Oats, potatoes
	Vertisols	5	5	Wheat

(*continued*)

Table I (*continued*)

Continent (countries represented)	Soil order	No. of records	No. of soil subgroups	Crops[a]
Europe (Bulgaria, Germany, Hungary, Russia, Serbia, United Kingdom, Ukraine)	Alfisols	3	3	Potato, rye, triticale, wheat, maize
	Entisols	1	1	Barley, wheat
	Inceptisols	5	5	Barley, maize
	Mollisols	10	6	Barley, millet, mustard, potatoes, rye, sunflower, sw. lupin, sw. sorghum, soybeans, wheat
Latin America (Argentina, Brazil, Colombia, Mexico, Peru, Trinidad, Venezuela)	Alfisols	2	2	Maize
	Entisols	6	5	Beans, carrots, cowpeas, maize, potatoes
	Inceptisols	8	5	Beans, carrots, cassava, maize, potatoes
	Mollisols	2	2	Maize, soybeans, wheat
	Oxisols	6	5	Beans, maize, soybeans, wheat
	Ultisols	4	4	Cowpeas, crotolaria, maize
North America (Canada, United States)	Alfisols	71	22	Beans, barley, hay, maize, oats, soybeans, wheat
	Aridisols	2	1	Alfalfa, barley, beans, maize, potatoes, sugar beets, wheat
	Entisols	2	2	Maize, soybeans
	Inceptisols	4	4	Grapes, potatoes, maize, soybeans
	Mollisols	93	34	Alfalfa, crested wheatgrass, maize, oats, Russian wildrye Sorghum, soybeans, Sudan grass, wheat

	Oxisols	1	1	Maize
	Spodosols	2	2	Potatoes
	Ultisols	22	9	Cotton, maize, oats, sorghum, soybeans, vetch
World (37 countries)	Alfisols	120	48	Crops listed above
	Aridisols	10	5	
	Entisols	10	9	
	Inceptisols	26	21	
	Mollisols	105	41	
	Oxisols	15	10	
	Spodosols	2	2	
	Ultisols	38	18	
	Vertisols	7	7	

[a]Alfalfa = *Medicago* spp.; beans = *Phaseolus vulgaris*; barley = *Hordeum vulgare*; cabbage = *Brassica oleracea* spp.; carrot = *Daucus carpta*; cassava = *Manihot esculentum*; chickpeas = *Cicer arietinum*; cotton = *Gossypium hirsutum*; cowpeas = *Vigna ungiculata*; crested wheatgrass = *Agropyron cristatum*; crotolaria = *Crotolaria juncea*; grapes = *Vitis vinifera*; maize = *Zea mays*; millet = *Panicum miliaceum*; mungbeans = *Phaseolus aureus*; mustard = *Brassica* spp.; oats = *Avena sativa*; peanuts = *Arachis hypogea*; pearl millet = *Pennisetum glaucum*; potato = *Solanum tuberosum*; Russian wildrye = *Psathyrostachys juncea*; rye = *Secale cereale*; soybeans = *Glycine max*; sugar beet = *Beta vulgaris*; Sudan sorghum = *Sorghum saccharatum*; tea = *Camellia sinensis*; triticale = *Triticosecale* spp.; vetch = *Vicia sativa*; sorghum = *Sorghum bicolor*; wheat = *Triticum aestivum*.

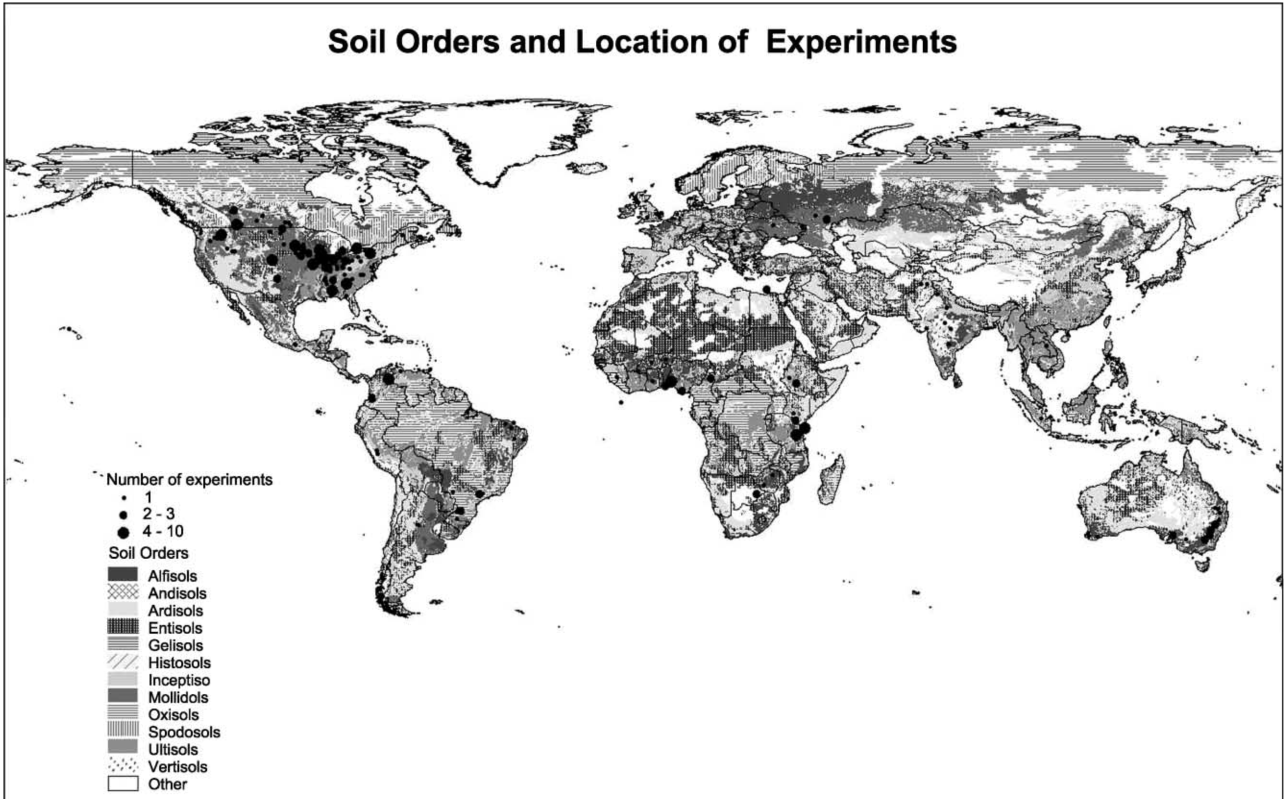

Figure 2 Location of the erosion–productivity studies in relation to soil orders. Size of dots is proportional to the number of studies at each site.

Table 2a
Number of Records in the Database by Experimental Methods Used in the Studies

Experimental method	No. (%) of records
Erosion phases	116 (35%)
Topsoil removal and addition	98 (30%)
Topsoil depth	61 (18%)
Management practices	38 (12%)
Depth of fragipan	14 (4%)
Soil survey	2 (1%)
Total	329 (100%)

in North America (i.e., the United States and Canada), with a secondary concentration of studies in Australia and Brazil.

Mollisols and Alfisols are the most frequently studied soils, followed by Ultisols and Inceptisols (Fig. 2 and Table II). In the United States and Canada, erosion–productivity studies have been carried out primarily on Alfisols and Mollisols, reflecting the importance of these soils for crop production in North America (den Biggelaar *et al*., 2001).

The investigation of yield differences on differentially eroded soil phases was the most commonly used method to determine the effect of erosion. This method was used in 35% of the cases, followed by topsoil removal and addition (29%) and TSD (18%). Depth to fragipan was used in 4% of the studies, whereas soil surveys were used in two studies. Variable management practices (notably tillage, terracing, and contour planting) were used in 37 cases. Experiments using erosion phases, topsoil removal and addition, TSD and depth to fragipan measure the effect of past erosion on crop yields, whereas experiments using variable management practices provide an indication of the effects of present erosion rates on crop yields. However, observed yield differences may not only be due to differential rates of erosion associated with different management practices, but also an artifact of the management systems. The results of studies using this method are, therefore, not comparable with those assessing the effects of past erosion. The results of studies investigating the effect on crop yields of past and present erosion will, therefore, be presented separately in this chapter for comparative purposes.

III. ASSUMPTIONS

A. Yield as a Measure of Productivity

As erosion reduces a soil's capacity to produce biomass, productivity is usually expressed in terms of crop yield or output per unit area over a given time period (NSE-SPRPC, 1981). Yield data are the way that farmers, policy makers, and the public typically consider agricultural production, and are also a basic measure of productivity in agricultural experiments (Tomlin and Umphrey, 1996). Crop yields are, therefore, used as the measure of productivity in this review.

B. Mean Yield Decline

The results of the studies must be compared cautiously, as they cover a variety of crops, soils, time periods, management practices, and experimental methods (Boardman, 1998). The effects of erosion may also vary from year to year due to fluctuations in climate and other non-controlled variables, so that long-term degradative effects are not easily apparent. We controlled some of the differences by calculating mean erosion-induced yield declines for each crop and soil order across methods, management practices and time periods.

C. Linear Relation

Results from field studies and simulation models show that there is a large variation in the way erosion affects soil quality and productivity (Maetzold and Alt, 1986). Some soils experience consistent productivity reductions with progressive soil degradation, while others suffer no loss until some critical point in one (or more) yield-determining factor(s) is reached, at which point significant yield losses begin (Biot and Xi, 1993; Sanders *et al*., 1995; Hoag, 1998). However, a linear relationship between erosion and productivity was assumed, implying that the loss in productivity remains the same for each Mg or cm of soil erosion over the entire range of soil depths considered in the experiment.

D. Average Bulk Density

Nearly all studies investigating the effect of past erosion measured yield losses over different TSDs. Using data in the studies reviewed, the mean yield loss per cm of soil erosion was calculated. In studies using management practices, on the other hand, yield differences between treatments were expressed per Mg of soil erosion. To compare the effects of past and present erosion, the yield losses per cm of soil erosion were converted into yield losses per Mg of soil erosion. For this conversion, an average bulk density of 1.5 Mg m^{-3} was assumed for all soils on all continents. Using this bulk density value, 1 cm of soil weighs 150 Mg ha^{-1}. Therefore, yield loss per cm of soil was divided by 150 to determine the yield loss per Mg of soil erosion. Based on the previous assumption, it was assumed that the rate of yield loss is uniform over the entire 1 cm depth of soil.

E. Relative Yield Decline

To determine the relationship between erosion and productivity, most studies compare yield declines with yields on uneroded or slightly eroded phases, and calculate a relative decrease in yield using the uneroded yield as the denominator. However, erosion is not normally uniform across an experimental plot (except when topsoil is artificially removed to a uniform depth), field or landscape. Therefore, in an effort to more closely approximate conditions faced by farmers, and to better reflect natural circumstances in a field or landscape that includes a range of TSD and erosion-induced soil loss, relative yield decline was calculated using the mean yields across all experimental plots for each crop and soil as the denominator. As the mean experimental yield is usually lower than the yield on the uneroded or slightly eroded plots, this method will lead to an overestimation of relative yield declines as is shown in the hypothetical example in the box below. For ease of analysis and comparison of the data, soil loss due to erosion was assumed to be uniform across each experimental plot.

Example of Yield Loss Calculations

TSD removal (cm)	Yield (Mg hs^{-1})	Yield loss (Mg ha^{-1} cm^{-1})
0	10	
10	8	(10 − 8)/10 = 0.20
20	6.5	(10 − 6.5)/20 = 0.18
30	6	(10 − 6)/30 = 0.13
Mean	7.6	0.17
Yield loss per Mg soil erosion		
at bd = 1.5 Mg m^{-3}:		0.17/150 = 0.0011 Mg ha^{-1} Mg^{-1}
Relative yield loss, using mean experimental yield as the reference yield:		
per cm soil erosion		0.17/7.6 *100% = 2.2% cm^{-1}
per Mg soil erosion		0.0011/7.6 *100% = 0.014% Mg^{-1}
Relative yield loss, using the uneroded yield as the reference yield:		
Per cm Soil erosion		0.17/10*100% = 1.7% cm^{-1}
Per Mg Soil erosion		0.0011/10*100% = 0.011% Mg^{-1}

IV. RESULTS

A. Effects on Yield in Tsd Experiments

Erosion–productivity studies have been undertaken worldwide on a variety of crops. Although there are some studies on pasture and fodder crops (United States, Australia, Botswana), vegetables (mustard in India and Hungary, cabbage in Indonesia), and tea (Sri Lanka), the majority of studies involved grain crops, pulses and root crops. This review focuses on these three groups of crops only.

1. Grain Crops

Studies on the effect of erosion on grain crops primarily used maize (*Zea mais*) and wheat (*Triticum aestivum*) as the experimental crop (Table III). Maize was the predominant crop used in North America and Africa, whereas wheat was predominant in North America (United States and Canada) and Australia. A smaller number of cases involved sorghum (*Sorghum bicolor*) (US), millet (*Panicum miliaceum* and *Pennisetum glaucum*) (Niger, Burkina Faso, Russia and India), rye (*Secale cereale*) (Bulgaria), oats (*Avena sativa*) (Australia, US), and barley (*Hordeum vulgare*) (Australia, US, UK, Hungary, Ukraine, Egypt).

a. Maize

Mean experimental maize yields are the highest in North America (6.2 Mg ha^{-1}), and yield losses due to erosion are the lowest (Table III). Maize yields in North America decline 0.092 Mg ha^{-1} cm^{-1}. Not only are mean yields in Latin America (i.e., Central and South America and the Caribbean), Africa and Asia less than half of those in North America (2.9, 2.6, and 1.7 Mg ha^{-1}, respectively), but erosion-induced yield losses are also higher (0.215, 0.128, and 0.111 Mg ha^{-1} cm^{-1}, respectively). Nevertheless, when yield losses per cm of soil erosion are converted to yield losses per Mg of soil erosion (assuming an average bulk density for all soils on all continents of 1.5 Mg m^{-3}), the results are similar: maize losses of about 1 kg ha^{-1} Mg^{-1} of soil erosion, ranging from 0.62 kg ha^{-1} Mg^{-1} in North America to 1.44 kg ha^{-1} Mg^{-1} in Latin America. On a relative basis, maize yields in North America decline by 0.01% for each Mg of soil erosion. Compared to North America, even though still small, relative yield declines per Mg of soil erosion are three times higher in Africa (0.03%), four times higher in Asia (0.04%), and fives times higher in Central and South America (0.05%).

There are differences in relative yield losses of maize grown on soils of different soil orders. In North America, studies on Entisols showed that yields are

Table III
Impact of Past Erosion on the Yield of Grain Crops, by Crop and Continent

Crop	Continent	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Erosion-induced yield loss: Mg ha^{-1} cm^{-1} soil erosion, mean (range)	Erosion-induced yield loss: Kg ha^{-1} Mg^{-1} soil erosion[a]	Erosion-induced yield loss: % Mg^{-1} soil erosion	Sources
Maize	Africa	41	2	2.6	0.128 (0.003–0.715)	0.86	0.03%	Abate, 1994; Aune *et al*., 1998; Azontonde 1993; Boli Baboule and Roose 1998; Boli *et al.* 1993; Gachene 1995; Hudson and Jackson 1959; Hulugalle 1986; Kilasara *et al*., 1995; Lal, unpublished data, 1981, 1985, 1987b; Mbagwu, 1981; Mbagwu *et al*., 1984; Oyedele and Aina, 1998; Seather *et al*., 1997; Sessay, 1991; Tegene, 1992; Tenge *et al*., 1998; Vaje *et al*., 1998
	Asia	4	2	1.7	0.111 (0.097–0.143)	0.74	0.04%	Rimwanich and Na-Thalang, 1978; Shafiq *et al*., 1988; Sur *et al*., 1998
	North America	131	4	6.2	0.092 ((−0.080)–1.030)	0.62	0.01%	Adams, 1949; Alberts and Spomer, 1987; Barre, 1939; Blevins *et al*., 1987; Carlson *et al*., 1961; Chengere and Lal, 1995; Fahnestock *et al*., 1995; Frye *et al*., 1982, 1983; Gantzer and McCarthy, 1985; Gilliam *et al*., 1987; Gollany *et al*., 1992; Hajek and Collins, 1987;

(*continued*)

Table III (*continued*)

Crop	Continent	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Erosion-induced yield loss: Mg ha^{-1} cm^{-1} soil erosion, mean (range)	Erosion-induced yield loss: Kg ha^{-1} Mg^{-1} soil erosion[a]	Erosion-induced yield loss: % Mg^{-1} soil erosion	Sources
								Henning and Kalaf, 1985; Langdale *et al*., 1979; Lindstrom *et al*., 1986, 1987; McDaniel and Hajek, 1985; Miller, 1985; Mokma and Sietz, 1992; Murray *et al*., 1939; Musgrave, unpublished data; Odell, 1950; Olson and Nizeyimana, 1988; Olson and Carmer, 1990; Olson *et al*., 1999; Olson, 1977; Schertz *et al*., 1985; Schertz *et al*., 1989; Schumacher *et al*., 1994; Shaffer *et al*., 1994; Smith, 1946; Stallings, 1957; Stone *et al*., 1985; Swan *et al*., 1987; Thompson *et al*., 1991, 1992; Tyler *et al.* 1989; Xu *et al.* 1997; Weesies *et al*., 1994; Wright *et al*., 1990; Yost *et al*., 1985
	Latin America[b]	15	2	2.9	0.215 (0.007–1.640)	1.44	0.05%	Albuquerque *et al*., 1996; Coelho Silva *et al*, 1985; Flores and Fernandez, 1995; Hernani *et al*., 1997; Nieto *et al*., 1998; da Silva *et al*., 1999;

								da Silva and Silva, 1997; Sparovek *et al.*, 1991; Tengberg *et al.*, 1997a, b; da Veiga *et al.*, 1998
Wheat	Asia	4	2	3	0.101 (0.097–0.143)	0.69	0.02%	Agnihotri *et al.*, 1994; Bhatti *et al.*, 1998; Shafiq *et al.*, 1988
	Australia	16	4	1.2	0.081 ((−0.003)–0.355)	0.54	0.04%	Barr, 1957; Davies *et al.*, 1988; Elliott *et al.*, 1988; Hamilton, 1970; Hore and Sims, 1954; Littleboy *et al.*, 1992
	Europe	8	4	3.5	0.026 ((−0.058)–0.097)	0.17	0.00%	Burnham and Mutter, 1993; Duck, 1974; Evans and Nortcliff, 1981; Krisztian *et al.*, 1987; Krumov and Tzvetkova, 1998; Tikhonov, 1960; Vernander *et al.*, 1964
	North America	64	5	2.6	0.051 ((−0.033)–0.225)	0.34	0.01%	Barre, 1939; Bramble-Brodahl *et al.*, 1985; Carter, *et al.*, 1985; Dormaar and Lindwall, 1984; Dormaar *et al.*, 1986, 1988; Frymire, 1980; Greb and Smika, 1985; Horner, 1960; Ives and Shaykewich, 1987; Izaurralde *et al.*, 1998; Larney and Janzen, 1997; Larney *et al.*, 1991, 1995a, b, 1998; Lowery *et al.*, 1990; Massee, 1990; Massee and Waggoner, 1985; Monreal *et al.*, 1995; Power *et al.*, 1981; Rasmussen and Rohde, 1991; Tanaka, 1995; Tanaka and Aase, 1989; Thompson *et al.*, 1991a; Verity and Anderson, 1990; Wetter, 1977

(*continued*)

Table III (*continued*)

Crop	Continent	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Erosion-induced yield loss: Mg ha^{-1} cm^{-1} soil erosion, mean (range)	Kg ha^{-1} Mg^{-1} soil erosion[a]	% Mg^{-1} soil erosion	Sources
	Latin Amercia[b]	1	3	2.1	0.062 (n.a)	0.41	0.02%	Tengberg *et al.*, 1998
Barley	Asia	1	1	1.8	0.142 (n.a.)	0.95	0.05%	Agnihotri *et al.*, 1994
	Australia	2	3	2.8	0.040 (0.036–0.044)	0.27	0.01%	Fawcett *et al.*, 1990
	Europe	11	3	2.5	0.052 ((−0.023)–0.174)	0.35	0.01%	Biot and Lu, 1993; Duck, 1974; Dzhadan *et al.*, 1975; Evans, and Nortcliff, 1978; Krisztian *et al.*, 1987; Lu and Biot, 1994; Tikhonov, 1960; Xu and Biot, 1994
	North America	2	3	3.5	0.057 (0.057–0.058)	0.38	0.01%	Carter *et al.*, 1985; Stallings, 1957
Millet	Africa	1	3	0.4	0.187 (n.a.)	1.25	0.29%	Buerkert and Lamers, 1999
	Asia	2	2	0.3	0.015 (0.012–0.017)	0.1	0.03%	Vittal *et al.*, 1991
	Europe	2	4	0.3	0.011 (0.005–0.018)	0.08	0.02%	Tikhonov, 1960
Oats	Australia	1	1	0.4	0.036 (n.a.)	0.24	0.06%	McFarlane *et al.*, 1991
	North America	5	3	2	0.045 (0.017–0.080)	0.3	0.01%	Adams, 1949; Barre, 1939; Lamb *et al.*, 1944; Murray *et al.*, 1939; Stallings, 1957
Sorghum	North America	17	3	4.2	0.014 ((−0.139)–0.108)	0.09	0.00%	Eck *et al.*, 1965; Eck, 1968, 1987; Langdale *et al.*, 1987

[a]Assuming a bulk density of 1.5 Mg m^{-3}.
[b]Latin America includes South America, Central America and the Caribbean.

not affected by erosion (i.e., they decline by less than 0.005% Mg^{-1} of soil erosion). Yields declined by 0.02% Mg^{-1} of soil erosion on Oxisols and Ultisols, and by 0.01% Mg^{-1} on Alfisols and Mollisols. Observed yield declines in Asia are slightly greater on Inceptisols (0.05% Mg^{-1}) than on Aridisols (0.04% Mg^{-1}). In Africa, relative yield losses are low on Inceptisols and Oxisols (0.01% Mg^{-1}), but four to five times greater on Alfisols and Ultisols (0.04 and 0.05% Mg^{-1}, respectively). The highest losses in maize yield in the studies reviewed occur on Inceptisols in Central and South America (0.33% Mg^{-1}); they are also fairly high for maize grown on Mollisols (0.07% Mg^{-1}). Relative yield declines for maize grown on Alfisols and Entisols in this continent, however, are low at 0.01% Mg^{-1} soil erosion.

b. Wheat

Studies with wheat have been conducted in five continents, with most studies (71%) done in North America (Table III). Mean experimental wheat yields are highest in Europe (3.5 Mg ha^{-1}). Yield losses as a result of erosion on this continent are very small (average of 0.026 Mg ha^{-1} cm^{-1}); relative yield losses per Mg of soil erosion are negligible for all soils on which wheat yield-productivity studies have been undertaken (i.e., Alfisols, Entisols, and Mollisols). Mean wheat yield is lowest in Australia (1.2 Mg ha^{-1}), declining 81 kg ha^{-1} - cm^{-1} or 0.04% Mg^{-1} of soil erosion. In Australia, yield losses are highest for wheat on Alfisols (0.05% Mg^{-1}), slightly less on Vertisols (0.04% Mg^{-1}), and lowest on Aridisols (0.02% Mg^{-1}). In North America, wheat yield averages 2.6 Mg ha^{-1}, and declines 51 kg ha^{-1} cm^{-1} or 0.01% Mg^{-1} of soil erosion. Relative yield declines are greater for wheat on Alfisols (0.02% Mg^{-1}) than on Entisols and Mollisols (0.01% Mg^{-1}). Mean wheat yield in Asia (3.0 Mg ha^{-1}) is slightly higher than that in North America, but erosion-induced yield decline is also higher (101 kg ha^{-1} cm^{-1}). On a relative basis, wheat yield decreases by 0.02% Mg^{-1} of soil erosion. In Asia, the yield decline of wheat on Aridisols is 50% greater (0.03% Mg^{-1}) than on Inceptisols (0.02% Mg^{-1}). Only one study was done with wheat in Latin America; the experiment was carried out on a Mollisol in Argentina. Average yield (2.1 Mg ha^{-1}) and yield decline (0.062 Mg ha^{-1} cm^{-1}) were lower than in Asia, but relative yield decline per Mg of soil erosion was the same (0.02% Mg^{-1}).

c. Barley

Studies on barley have been carried out in Asia (one study in India), Australia (one study), North America (2 studies in the USA), and Europe

(Hungary, Ukraine and the UK). Average barley yields are the highest in North America (3.5 Mg ha^{-1}) and lowest in Asia (1.8 Mg ha^{-1}), but erosion-induced yield declines are reversed: 142 kg ha^{-1} m^{-1} in Asia and 57 kg ha^{-1} cm^{-1} in North America (Table III). For soil erosion per Mg, the relative yield loss is five times greater in Asia (0.05% Mg^{-1}) than in North America (0.01% Mg^{-1}). The relative yield loss of barley on Alfisols in North America is twice that on Aridisols (0.02% vs. 0.01% Mg^{-1} of soil erosion). The average relative yield loss in Australia for barley grown on an Aridisol is equivalent to the relative yield loss in North America, although mean yield and yield decline per cm of soil erosion are lower (2.8 Mg ha^{-1} and 40 kg ha^{-1} cm^{-1}, respectively). Mean barley yields in Europe are slightly lower than in Australia (2.45 Mg ha^{-1}), with yield declines resulting from erosion slightly less than those in North America (5.2 kg ha^{-1} cm^{-1}); average yield declines per Mg of soil erosion are negligible (none for barley on Entisols, and 0.01% Mg^{-1} on Inceptisols and Mollisols).

d. Oats

Oats were used as the experimental crop in four studies, one in Australia on an Ultisol, and three in the United States, one each on an Alfisol, a Mollisol, and an Ultisol (Table III). Mean oats yield in the United States studies was 2.0 Mg ha^{-1}, declining at a rate of 45 kg ha^{-1} cm^{-1} or 0.01% Mg^{-1} of soil erosion. Yield decline was highest in oats on the Alfisol (0.03% Mg^{-1}) and lowest in oats on the Mollisol (0.01% Mg^{-1}); yield decline on the Ultisol was intermediate at 0.02% Mg^{-1} of soil loss. Mean experimental oats yield was low in the Australian study (0.4 Mg ha^{-1}); yields in this study declined at the rate of 36 kg ha^{-1} cm^{-1} with a relative loss of 0.06% Mg^{-1}.

e. Millet and Sorghum

Erosional effects on millet yield were investigated on Alfisols in India and Mollisols in Russia. Studies on sorghum were conducted only in the United States. While average millet yields were similar in India and Russia (0.3 Mg ha^{-1}, respectively), the decline in yield due to erosion was slightly higher in India than in Russia (15 and 11 kg ha^{-1} cm^{-1} of soil erosion, respectively) (Table III). The relative yield decline was 0.03 and 0.02% Mg^{-1} of soil erosion in India and Russia, respectively. Mean sorghum yield in the experiments in the United States was 4.2 Mg ha^{-1}, with (on average) no decline in relative yield. Relative yields declined by 0.01% Mg^{-1} soil erosion on Mollisols, but increased by a similar amount in experiments on Ultisols despite the progressive increase in erosion.

2. Leguminous Crops

With the exception of studies on soybeans in the United States, there have been few erosion–productivity studies on pulses. Besides the United States, soybeans have been used as the experimental crop in Brazil, Hungary, India, and Indonesia, cowpeas in Nigeria, Tanzania, Trinidad, and Brazil, and dry beans in Ethiopia, Brazil, Venezuela, and the United States (Table IV).

a. Soybeans

Average soybean yields are the same in the Americas (2.1 Mg ha^{-1}), but yield declines per cm of soil erosion in Latin America are twice those in North America (0.092 vs. 0.041 Mg ha^{-1} cm^{-1}, respectively) and relative yield declines are three times as high (0.01% vs. 0.03% Mg^{-1}, respectively) (Table IV). In South America, yield declines were higher on Oxisols (0.03% Mg^{-1}) than on Mollisols (0.02% Mg^{-1}). In the North American soybean studies, yield declines were highest in studies on Ultisols and Entisols (0.03% Mg^{-1}), intermediate on Inceptisols (0.02% Mg^{-1}), and lowest on Alfisols and Mollisols (0.01% Mg^{-1} soil erosion).

Mean experimental soybean yield is much lower in Asia (0.9 Mg ha^{-1}); as a result of erosion, average absolute and relative yields actually increase by 73 kg ha^{-1} cm^{-1} or 0.01% Mg^{-1} of soil erosion. Soybean yields in Asia were not affected by erosion of Inceptisols, decreased by 0.04% Mg^{-1} in experiments on Oxisols, and increased 0.02% Mg^{-1} on Vertisols. The sole study on soybeans in Europe was conducted in Hungary on a Mollisol. Yield and yield decline per cm of soil erosion were low (0.6 Mg ha^{-1} and 20 kg ha^{-1} cm^{-1}, respectively). The relative yield declined by 0.02% Mg^{-1} of soil erosion.

b. Cowpeas

Cowpeas were used as the experimental crop primarily in Africa (Nigeria, Tanzania, and Sierra Leone), and in one study in Brazil (Table IV). The African studies were conducted on Alfisols, Oxisols, and Ultisols, whereas the study in Brazil was done on an Entisol. The mean yield in the studies in Africa was 0.8 Mg ha^{-1}. As a result of erosion, yields declined on average at the rate of 44 kg ha^{-1} cm^{-1}, or 0.03% Mg^{-1}. Yield decline was 25% greater for studies on Ultisols (0.04% Mg^{-1}) than on Alfisols and Oxisols (0.03% Mg^{-1}). In Brazil, the mean yield (0.3 Mg ha^{-1}) and erosion-induced yield decline were lower than in the studies in Africa; absolute yield loss was 6 kg ha^{-1} cm^{-1} or 0.01% Mg^{-1} of soil erosion.

Table IV
Impact of Past Erosion on the Yield of Leguminous Crops, by Crop and Continent

Crop	Continent	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Erosion-induced yield loss: Mg ha^{-1} cm^{-1} soil erosion mean (range)	Erosion-induced yield loss: kg ha^{-1} Mg^{-1} soil erosion[a]	Erosion-induced yield loss: % Mg^{-1} soil erosion	Sources
Soybeans	Asia	4	1	0.9	−0.073 ((−0.344)–0.027)	−0.49	−0.05%	Shivaramu *et al*., 1998; Singh *et al*.,1999; Sudirman *et al*., 1986; Tiwari and Jain, 1995
	Europe	1	10	0.6	0.020 (n.a.)	0.13	0.02%	Krisztian *et al*., 1987
	North America	43	4	2.1	0.041 ((−0.001)–0.113)	0.27	0.01%	Bruce *et al*., 1995; Ebeid *et al*., 1995; Fahnestock *et al*., 1995; Gilliam *et al*., 1987; Hairston *et al*., 1989; Hajek and Collins, 1987; Henning and Khalaf, 1985; McDaniel and Hajek, 1985; Pettry *et al*., 1985; Rhoton, 1990; Salchow and Lal, 1999; Schertz *et al*., 1985; Schertz *et al*., 1989; Thompson *et al*., 1991a, b; Tyler *et al*., 1987; Weesies *et al*., 1994; Wetter, 1977; White *et al*., 1985; Yang *et al*., 1996

	Latin America[b]	4	4	2.1	0.092 (0.048–0.134)	0.61	0.03%	Tengberg *et al*., 1998; da Veiga *et al*., 1998
Beans	Africa	3	3	0.4	0.009 (0.003–0.019)	0.06	0.02%	Tegene, 1992
	North America	2	2	1.4	0.035 (0.030–0.040)	0.23	0.02%	Carter *et al*., 1985; Lamb *et al*., 1944
	Latin America[b]	5	3	1.1	0.055 (0.033–0.076)	0.37	0.03%	Delgado and Lopez, 1998; da Veiga *et al*., 1998
Cowpeas	Africa	21	1	0.8	0.044 (0.001–0.124)	0.29	0.03%	Aune *et al*., 1998; Kilasara *et al*., 1995; Lal, 1981; Mbagwu, 1981; Mbagwu *et al*., 1984; Sessay, 1991
	Latin Amercia[c]	1	1	0.3	0.006 (n.a)	0.04	0.01%	da Silva and Silva, 1997

[a]Assuming a bulk density of 1.5 Mg m^{-3}.
[b]Latin America includes South America, Central America and the Caribbean.

c. Beans

Experiments using beans were conducted on Alfisols in Ethiopia, Alfisols, and Aridisols in the United States, and Inceptisols and Oxisols in Venezuela and Brazil. Mean experimental yields were lowest in Ethiopia (0.4 Mg ha^{-1}) and highest in the United States (1.4 Mg ha^{-1}) (Table IV). Yield was intermediate in the Brazilian and Venezuelan experiments (1.1 Mg ha^{-1}), but the average yield declines due to erosion were highest in both absolute (55 kg ha^{-1} cm^{-1}) and relative terms (0.03% Mg^{-1} soil erosion). Relative yield declines in Ethiopia and the United States were identical (0.02% Mg^{-1}), although losses per cm of soil erosion were lower in Ethiopia (9 kg ha^{-1} cm^{-1}) than in the United States (35 kg ha^{-1} cm^{-1}). The yield loss in studies on Alfisols in the United States was three times higher (0.03%) than the yield loss on Aridisols (0.01%). The yield decline on the Oxisol in Brazil was double the loss on Inceptisol in Venezuela (0.04% vs. 0.02%, respectively).

3. Root Crops

a. Potatoes

Very few studies on the impact of erosion on productivity have been done with root crops. Experiments using potatoes were done in Australia on Aridisols and Ultisols, in the United States on an Aridisol, a Spodosol, and an Inceptisol, in Venezuela on an Entisol, and in Bulgaria and Russia on an Alfisol and a Mollisol, respectively (Table V). Mean yields and yield losses due to erosion were lowest in Europe (11.4 and 84 kg ha^{-1} cm^{-1}, respectively). Relative yield loss was less than 0.005% Mg^{-1} soil erosion. Average yield in Australia was 54.1 Mg ha^{-1}, with a mean yield decline of 542 kg ha^{-1} cm^{-1}. However, yield decline occurred only in the experiment on the Aridisol (i.e., 1.084 Mg ha^{-1} cm^{-1}, or 0.01% Mg^{-1} of soil erosion); yields remained the same on all depths of soil removal on the Ultisol. The potato study in Venezuela resulted in a mean yield of 20.2 Mg ha^{-1}, and decreased 101 kg ha^{-1} cm^{-1} of soil erosion; the relative yield loss was less than 0.003% Mg^{-1}. In the United States, the mean potato yield in the experiments was 30.5 Mg ha^{-1}; however, yield in the study on the Aridisol was more than twice the yield in the studies on either the Spodosol (14.7 Mg ha^{-1}) or the Inceptisol (24.1 Mg ha^{-1}). Average erosion-induced yield declined by 0.42% Mg^{-1} of soil erosion, ranging from no loss on the Aridisol to 0.78% Mg^{-1} on the Spodosol and 1.09% Mg^{-1} on the Inceptisol.

b. Cassava

Cassava was used as the experimental crop in two studies in Nigeria (Table V). The mean yield in these experiments was 15 Mg ha^{-1}, and declined at an average

Table V
Impact of Past Erosion on the Yield of Root Crops, by Crop and Continent

Crop	Continent	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Erosion-induced yield loss: Mg ha^{-1} cm^{-1} soil erosion, mean (range)	kg ha^{-1} Mg^{-1} soil erosion[a]	% Mg^{-1} soil erosion	Sources
Potatoes	Latin America[b]	1	1	20.2	0.101 (n.a.)	0.67	0.00%	Delgado *et al.*, 1998
	Australia	2	1	54.1	0.542 (0.000–1.084)	3.61	0.01%	McFarlane *et al.*, 1991
	Europe	2	5	11.4	0.084 (0.018–0.150)	0.56	0.00%	Krumov and Tzvetkova, 1998; Tikhonov, 1960
	North America	3	2	30.5	(n.a.)[c]	127	0.42%	Carter *et al.*, 1985; Hepler *et al.*, 1983; Lamb *et al.*, 1944
Cassava	Africa	2	4	15	0.594 (0.535–0.653)	3.96	0.03%	Lal, unpublished data; Lal, 1987b
Carrots	Latin America[b]	4	1	27.8	1.323 (0.000–2.678)	8.82	0.03%	Delgado *et al.*, 1998

[a]Assuming a bulk density of 1.5 Mg m^{-3}.
[b]Latin America includes South America, Central America and the Caribbean.
[c]Two studies measured erosion in Mg ha^{-1} and one in cm ha^{-1}; therefore, no mean yield losses per cm could be calculated.

rate of 594 kg ha^{-1} cm^{-1} of erosion. Both of these experiments were conducted on Alfisols. The relative yield loss was 0.03% Mg^{-1} of soil erosion.

c. Carrots

Lastly, two studies in Venezuela investigated the erosional effects on the yield of carrots, one study on an Entisol and another on an Inceptisol. Mean carrot yield in these experiments was 27.8 Mg ha^{-1}, and yield losses ranged from 0.0 to 2.7 Mg ha^{-1} cm^{-1} (Table V). The average relative yield loss was 0.03% Mg^{-1} of soil erosion, 0.05% Mg^{-1} on the Entisol and 0.02% Mg^{-1} on the Inceptisol.

B. Erosional Effects on Yield in Management Practices Studies

In several countries, researchers have investigated the effects of differential management practices on erosion and crop yields. Common management practices used in the studies include soil tillage methods, terracing and bunding, and use of different soil covers and cover crops. These studies measure the effect of management practices on both erosion rates and crop yields (i.e., erosion as it occurs during crop growth), whereas the results presented in the previous section represent the effects on yield of past erosion as reflected in different depths of topsoil, keeping management constant. However, differences in crop yields in studies using different management practices are due both to variable amounts of erosion associated with these management practices, and to other changes in soil properties. In other words, the observed yield differences cannot be attributed solely or entirely to differences in erosion rates. As the relative yield losses per Mg of soil erosion were quite different from relative yield losses in studies investigating the effects of past erosion, the results are presented separately as follows:

1. Grain Crops

The relative yield declines in grain crops in studies investigating the effects of past erosion ranged from 0.00 to 0.05% Mg^{-1}, whereas relative yield losses in studies evaluating the effect of present erosion rates were much greater, ranging from 0.21 to 11.13% Mg^{-1} of soil erosion (Table VI).

a. Maize

The average experimental maize yields ranged from 2.9 Mg ha^{-1} in Africa to 7.8 Mg ha^{-1} in North America (Table VI). In Africa, this mean yield is

Table VI
Impact of Present Erosion on the Yield of Grain Crops, by Crop and Continent

Crop	Continent	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Erosion-induced yield loss: Mg ha^{-1} Mg^{-1} soil erosion, mean (range)	Erosion-induced yield loss: kg ha^{-1} Mg^{-1} soil erosion[a]	Erosion-induced yield loss: % Mg^{-1} soil erosion	Sources
Maize	Africa	11	5	2.9	0.072 ((−0.373)–0.428)	72	2.45%	Azontonde, 1993; Mensah-Bonsu and Obeng, 1979; Moyo, 1998
	Asia	2	4	3.1	0.024 (0.003–0.045)	24	0.77%	Willet, 1994
	Europe	1	17	3.7	0.088 (n.a.)	87.9	2.41%	Djorovic, 1990
	North America	1	3	7.8	0.790 (n.a.)	790	10.12%	Bitzer *et al.*, 1985
	Latin America[a]	5	6	3.9	0.047 ((−0.171)–0.388)	46.6	1.18%	Gumbs *et al.*, 1985; Melo Filho and Silva, 1993; Nunes Filho *et al.*, 1987
Wheat	Europe	1	17	3.1	0.114 (n.a.)	114	3.62%	Djorovic, 1990
	North America	3	14	1.8	0.014 (0.000–0.0040)	14	0.75%	Horner, 1960; Monreal *et al.*, 1995
	Latin America[a]	1	7	2.2	0.009 (n.a.)	9	0.41%	Hernani *et al.*, 1997
Barley	Africa	2	1	1.0	0.002 (0.001–0.003)	2.2	0.21%	Afifi *et al.*, 1992; Wassif *et al.*, 1995
Millet	Africa	1	4	0.5	0.054 (n.a.)	54	11.13%	Fournier, 1963

[a]Latin America includes South America, Central America and the Caribbean.

comparable to the mean yield obtained in studies investigating past erosion (2.9 vs. 2.6 Mg ha^{-1}). In other continents, average yields in management practices experiments were higher than those reported in past erosion experiments. Yield decline per Mg of soil erosion was lowest in Asia (0.24 Mg ha^{-1} Mg^{-1}) and highest in North America (0.79 Mg ha^{-1} Mg^{-1}). The relative yield decline was 0.77% Mg^{-1} in Asia, 1.18% in Latin America, 3.01% in Africa, and 10.12% in the one study using management practices in North America. The average relative yield declines by continent mask differences observed among soils. In Latin America, maize yield declined 33.36% Mg^{-1} of soil erosion on Entisols in Brazil, but yields increased on Ultisols by 3.2% Mg^{-1} in Brazil and 0.19% Mg^{-1} in Trinidad. The loss in yield in Asia was larger on the Ultisol in Thailand (1.79% Mg^{-1}) than on Alfisol in the Philippines (0.08% Mg^{-1}). In Africa, yields increased by 2.93% Mg^{-1} of soil erosion on Alfisols, but declined 3.1% Mg^{-1} on Entisols, 11.5% Mg^{-1} on Inceptisols, 2.35% Mg^{-1} on Oxisols and 3.14% Mg^{-1} on Ultisols. The sole North American study was done on an Alfisol.

b. Wheat

Five studies were found that used management practices to investigate the effect of erosion on wheat yields, three in North America (two in Canada and one in the US) and one each in Europe (Serbia) and Latin America (Brazil) (Table VI). Mean yields obtained in these studies were similar to that in past erosion experiments in Brazil (2.2 vs. 2.1 Mg ha^{-1}, respectively), but much lower than in the studies in Europe (3.1 vs. 5.2 Mg ha^{-1}) and North America (1.8 vs. 2.6 Mg ha^{-1}) (comparison of results in Tables III and VI). The yield decline due to erosion was similar in Latin and North America (9 kg ha^{-1} Mg^{-1} in Brazil and 14 kg ha^{-1} Mg^{-1} in North America). In the study in Serbia, however, the decline was much higher at 114 kg ha^{-1} Mg^{-1}. The relative yield decline was 0.41% on an Entisol in Brazil, 0.75% in North America (0.04% on Alfisols and 1.09% on Mollisols), and 3.62% in the study on a Mollisol in Serbia.

c. Barley and Millet

Two studies on barley on Aridisols in Egypt had mean yields of 1.0 Mg ha^{-1}, declining by 2 kg ha^{-1} Mg^{-1} of soil erosion, or 0.21% (Table VI). Management practices studies on Alfisols in Burkina Faso and Niger with millet showed comparable yields (485 vs. 437 kg ha^{-1}). The decline in yield was, however, much greater in Burkina Faso, both in absolute (54 vs. 1 kg ha^{-1} Mg^{-1} of soil erosion) and relative terms (11.13 vs. 0.29% Mg^{-1} of soil erosion).

2. Leguminous Crops

Studies using management practices on leguminous crops were done on soybeans on a Vertisol in India and an Oxisol in Brazil; beans on Entisols in Brazil and Peru; cowpeas on Ultisols in Trinidad; and peanuts on an Alfisol in Burkina Faso (Table VII). Mean soybean yield was 0.9 Mg ha^{-1} in India and 2.2 Mg ha^{-1} in Brazil. The yield loss was 49 kg ha^{-1} Mg^{-1} of soil erosion or 5.19% in India, and 6 kg ha^{-1} Mg^{-1} of erosion or 0.28% in Brazil.

The mean yield of dry beans in the studies in Brazil and Peru was 1.0 Mg ha^{-1}; accelerated erosion had no effect on yields, however. In both studies, yields increased in spite of accelerated erosion at an average rate of 25 kg ha^{-1} Mg^{-1} soil erosion. The relative yield increase was 2.46% Mg^{-1} soil erosion.

In the study of peanuts on Alfisols in Burkina Faso, yield declined 7.11% Mg^{-1}, or 47 kg ha^{-1} Mg^{-1} of soil erosion from a mean yield of 660 kg ha^{-1}. Lastly, a study with cowpeas on Ultisols in Trinidad produced an average yield of 1.62 Mg ha^{-1}; yields in this study increased with progressive increase in erosion at a rate of 11.36% Mg^{-1} (184 kg Mg^{-1}).

3. Root Crops

Studies on potatoes were conducted on an Aridisol in the US, Inceptisols in Indonesia and Peru, a Spodosol in Canada, and an Entisol in Peru. Mean yields ranged from 20.6 Mg ha^{-1} in Peru to 36.2 Mg ha^{-1} in North America (Table VIII). Erosion-induced yield losses differed among continents and soils. In the Peruvian studies, average yields increased with increase in erosion at a rate of 0.327 Mg ha^{-1} Mg^{-1} or 1.59% Mg^{-1} of soil erosion. Yield on the Entisol in Peru decreased slightly (26 kg ha^{-1} Mg^{-1} or 0.19% Mg^{-1}) due to erosion, but increased on the Inceptisol by 0.68 Mg ha^{-1} Mg^{-1} or 2.49% Mg^{-1} soil erosion. In Indonesia, yield declined 9 kg ha^{-1} Mg^{-1} soil erosion from a mean yield of 26.4 Mg ha^{-1} or 0.03% Mg^{-1}. In North America, average yield decline was much greater: 2.921 Mg ha^{-1} Mg^{-1} or 8.01% Mg^{-1}. However, almost all of this decline was registered in the study on the Aridisol, in which yield declined by 5.845 Mg ha^{-1} Mg^{-1} or 15.05% Mg^{-1} of soil erosion. On a Spodosol in Canada, yield declined only 2 kg ha^{-1} Mg^{-1} or 0.01% Mg^{-1} of soil erosion.

In a study with cassava on Hunan Island, China, the mean yield was 24 Mg ha^{-1} (Table VIII), and yield increased slightly with increasing erosion (36 kg ha^{-1} Mg^{-1} or 0.15% Mg^{-1} of soil erosion). In the studies in Colombia on Inceptisols, the mean yield of cassava was 19.4 Mg ha^{-1}, and declined by 0.611 Mg ha^{-1} Mg^{-1} or 3.16% Mg^{-1} of erosion (Table VIII).

Table VII
Impact of Present Erosion on the Yield of Leguminous Crops, by Crop and Continent

					Erosion-induced yield loss			
Crop	Continent	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Mg ha^{-1} Mg^{-1} soil erosion, Mean (range)	Kg ha^{-1} Mg^{-1} soil erosion	% Mg^{-1} soil erosion	Sources
Soybeans	Asia	1	3	0.9	0.049 (n.a.)	49	5.19%	Shivaramu *et al.*, 1998
	Latin America[a]	1	7	2.2	0.006 (n.a.)	6	0.28%	Hernani *et al.*, 1997
Beans	Latin America[a]	2	11	1.0	−0.025 ((−0.034)–(−0.015))	−24.5	−2.46%	Felipe-Morales *et al.*, 1979; da Silva *et al.*, 1999
Cowpeas	Latin America[a]	1	1	1.6	−0.184 (n.a.)	−184	−11.36%	Gumbs *et al.*, 1985
Peanuts	Africa	1	4	0.7	0.047 (n.a.)	47	7.11%	Fournier, 1963

[a]Latin America includes South America, Central America, and the Caribbean.

Table VIII
Impact of Present Erosion on the Yield of Root Crops, by Crop and Continent

Crop	Continent	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Erosion-induced yield loss: Mg ha^{-1} Mg^{-1} soil erosion, mean (range)	Erosion-induced yield loss: Kg ha^{-1} Mg^{-1} soil erosion	Erosion-induced yield loss: % Mg^{-1} soil erosion	Sources
Potatoes	Asia	1	2	26.4	0.009 (n.a.)	9	0.03%	Sinukaban *et al.*, 1994
	North America	2	2	36.2	2.921 (0.002–5.845)	2921	8.01%	DeHaan *et al.*, 1999; Sojka *et al.*, 1993
	Latin America[a]	2	2	20.6	−0.327 ((−0.680)–0.026)	−327	−1.59%	Felipe-Morales *et al.*, 1979
Cassava	Asia	1	1	24	−0.036 (n.a.)	−35.9	−0.15%	CIAT, 1991
	Latin America[a]	4	2	19.4	0.611 (0.214–1.026)	611	3.16%	Reining, 1992; Ruppenthal, 1995

[a]Latin America includes South America, Central America, and the Caribbean.

C. Effects of Inputs

The results presented above are based on average yields and yield declines of the experiments reviewed across all levels of input use (e.g., fertilizer, lime, manure, irrigation). To determine the effect of the use of inputs on relative yield losses, we compared the results of studies conducted with and without inputs. The comparative assessment included maize, cowpeas, and cotton in Africa; soybeans, wheat, millet, and maize in Asia; and beans, maize, and soybeans in Latin America (Table IX). The differences shown are only indicative of the effect of inputs, as the number of studies being compared and/or their duration is too small to make definite conclusions.

1. Africa

In experiments reflecting past erosion, yields of maize and cowpeas were comparable; the yields with and without input were 2.6 and 2.5 Mg ha^{-1} for maize, and 0.76 and 0.89 Mg ha^{-1} for cowpea, respectively (Table IX). Yield declines per Mg soil erosion were similar regardless of input use (1.1 and 0.7 kg ha^{-1} Mg^{-1} for maize, and 0.26 and 0.35 kg ha^{-1} Mg^{-1} for cowpeas with and without inputs, respectively). The relative yield decline for maize, however, was 33% greater in plots without fertilizers compared to plots with inputs (0.04% vs. 0.03%, respectively). The situation was reversed for cowpeas, where relative yield decline was less in plots without inputs (0.03%) than with inputs (0.05%).

In management practices experiments, relative yield decline was larger in plots without inputs for maize and seed cotton than with inputs (3.21% vs. 0.61% Mg^{-1} for maize; 20.18% vs. 14.93% Mg^{-1} for seed cotton) (Table IX). For cotton yields, on the other hand, relative yield decline was less on plots without (0.42% Mg^{-1}) than with inputs (2.58% Mg^{-1}).

2. Asia

A comparison across input use in Asia is only possible for studies on the effects of past erosion. There was no difference in absolute and relative yield loss in maize. Although average yield was slightly higher on plots with inputs (1.7 vs. 1.5 Mg ha^{-1}), yield loss per cm was also higher (Table IX). Yield loss per Mg of soil erosion and relative yield loss were similar: 0.65 and 0.77 kg ha^{-1} Mg^{-1} without and with inputs, respectively, or 0.04% Mg^{-1}. The relative yield loss of millet on plots without inputs was twice that on plots with inputs (0.04% vs. 0.02% Mg^{-1}). For wheat, losses were 2.5 times larger on plots without than with inputs (0.02% vs. 0.05% Mg^{-1}), largely due to the much higher average yields in experiments using fertilizers (3.5 Mg ha^{-1}) than in those that did not (1.5 Mg ha^{-1}). For soybeans, however, yields declined by 0.01% Mg^{-1} on plots with fertilizers, and increased 0.22% Mg^{-1} without fertilizer use.

3. Latin America

Crop yields were higher in experiments on past erosion effects using inputs (beans 1.1 vs. 0.9 Mg ha^{-1}; maize 3.2 vs. 2.0 Mg ha^{-1}; and soybeans 2.4 vs. 1.8 Mg ha^{-1}). Yield losses per cm of soil erosion in plots with inputs were also higher for maize and soybeans, but slightly lower for beans (Table IX). Relative yield declines were identical for soybeans in experiments with and without fertilizer (0.03% Mg^{-1}), but larger for maize in experiments with than without fertilizers (0.05% vs. 0.03% Mg^{-1}, respectively). For beans, yield losses were 33% larger in experiments without than with fertilizer (0.04% vs. 0.03% Mg^{-1}).

The results of studies of present erosion effects in Latin America show that yield of beans and maize increased in spite of accelerated erosion, even when no inputs were used, although actual yields of these crops were much smaller than in experiments with fertilizers (Table IX). Bean yield increased with progressive erosion in both studies with and without fertilizer use, but the increase was larger in studies without (3.42% Mg^{-1}) than with fertilizer use (2.14% Mg^{-1}). Maize yield in the no-input experiment increased 9.44% or 171 kg ha^{-1} Mg^{-1} of soil erosion, whereas mean yield decreased 2.26% or 101 kg ha^{-1} Mg^{-1} soil erosion in experiments with fertilizers.

V. DISCUSSION AND CONCLUSIONS

Half of the 179 studies on soil erosion and productivity identified and compared in this review were conducted in North America (the United States and Canada). Even with this comparatively large number of studies, the extrapolation of the results to estimate the production lost as a result of erosion nationally, and to determine the economic value of this production loss, remains a debatable subject because of a statistically small sample (den Biggelaar *et al.*, 2001). As we were able to identify only 89 studies from which one can do similar extrapolations for the rest of the world, estimates of the impact of erosion on productivity at the global scale are even more debatable. Nevertheless, given the paucity of research undertaken on the subject, the present review provides the best information available to date to estimate the potential effects of erosion on productivity on a soil- and crop-specific basis. Our aim for this paper was to undertake the first necessary step for this estimation, namely the determination of erosion-induced yield losses per cm and Mg of soil erosion, both in absolute and

Table IX

Effect of Inputs (Fertilizers, Manure and/or Irrigation) on Mean Experimental Yield and Erosion-Induced Yield Losses for Selected Crops, by Continent (Results from Present Erosion Experiments in Shaded Rows)

						Erosion-induced yield loss		
Content	Crop	Inputs used	No. of records	Mean duration of experiments (yr)	Mean of mean experimental yield (Mg ha^{-1})	Mg ha^{-1} cm^{-1} soil erosion, mean (range)	Kg ha^{-1} Mg^{-1} soil erosion[a]	% Mg^{-1} soil erosion
Africa	Maize	N	18	2	2.5	0.158	1.1	0.04%
		Y	24	1	2.6	0.106	0.7	0.03%
	Cowpeas	N	14	1	0.9	0.039	0.26	0.03%
		Y	7	1	0.8	0.053	0.35	0.05%
	Maize	N	9	5	2.5	(n.a.)	81.6	3.21%
		Y	2	3	4.8	(n.a.)	29	0.61%
	Cotton	N	1	4	1.9	(n.a.)	8	0.42%
		Y	1	4	2.1	(n.a.)	55	2.58%
	Cotton-seed	N	1	2	1.1	(n.a.)	228	20.18%
		Y	1	2	1.2	(n.a.)	171	14.93
Asia	Maize	N	1	2	1.5	0.097	0.65	0.04%
		Y	3	1	1.7	0.115	0.77	0.04%
	Millet	N	1	2	0.2	0.012	0.08	0.04%
		Y	1	2	0.5	0.017	0.12	0.02%
	Soybeans	N	1	1	1	−0.344	−2.29	−0.22%

		Y	3	1	0.9	0.017	0.11	0.01%
	Wheat	N	1	2	1.5	0.106	0.71	0.05%
		Y	3	1	3.5	0.099	0.66	0.02%
Latin America[b]	Maize	N	4	2	2	0.094	0.38	0.03%
		Y	11	2	3.2	0.26	0.36	0.05%
	Soybeans	N	2	4	1.8	0.083	0.63	0.03%
		Y	2	4	2.4	0.101	1.73	0.03%
	Beans	N	1	20	0.4	(n.a)	− 15	− 3.42%
		Y	1	2	1.6	(n.a)	− 34	− 2.19%
	Maize	N	1	8	1.8	(n.a)	− 171	− 9.44%
		Y	4	6	4.5	(n.a)	101	2.26%

[a]Assuming a bulk density of 1.5 Mg m^{-3}.
[b]Latin America includes South America, Central America and the Caribbean.

relative terms. The extrapolations to calculate the amount of production lost globally due to erosion and its economic value for a selected number of crops constitute Part II of this report (den Biggelaar *et al*., *this volume*).

The results of the present analysis show that average crop yields and effects of past erosion on yields (measured in Mg yield decline per cm of erosion) differ greatly by crop, continent and soil order. However, aggregated across soils on the continental level, differences in productivity declines per Mg of soil erosion are fairly small. The absolute yield loss ranged between −0.49 and 1.44 kg ha^{-1} Mg^{-1} of soil erosion for grain and leguminous crops, and 0.69 and 127.0 kg ha^{-1} Mg^{-1} for root crops. However, due to differences in mean yields, the relative yield losses per Mg of soil erosion vary more, even though losses were generally small (≪0.1% Mg^{-1} of soil erosion). The exceptions to this general rule were studies on potatoes in North America, in which yields declined by 0.42% Mg^{-1}.

In general, relative erosion-induced yield losses for the various crops investigated were smallest in studies in North America (with the exceptions of the potato studies) and Europe. In other continents, relative yield losses were from two to six times greater per Mg of soil erosion depending on the specific crop and soil. The greater relative yield declines were due not so much to differences in the absolute amounts of yield of various crops being lost per cm or Mg of eroded soil, but mostly because of the much lower average yields of similar crops in different continents. With identical amounts of erosion, yields will decline more rapidly in Africa, Asia, Australia, and Latin America than they do in North America and Europe. The concentration of erosion–productivity studies in North America, therefore, appears to be inversely related to the seriousness of the problem of erosion-induced productivity loss at the global level. Nevertheless, the knowledge gained from experiments in North America provides an indication not only of the importance of reducing erosion rates, but also of the possibilities of reducing the relative impact of erosion by increasing crop yields, thereby making it more attractive to farmers to invest in conservation-effective technologies and practices.

There is no definite pattern in the relationship between erosion and productivity when comparing relative yield declines across soil orders globally, contrary to findings in North America by den Biggelaar *et al*. (2001). These authors found that, across the four crops considered (maize, wheat, soybeans, and cotton), yields were least affected by erosion on Mollisols and most on Ultisols. On the global level, there is no soil order that consistently shows small erosional impact. The impact of erosion and the relationship between erosion and productivity depends very much on the particular crop, soil and climate conditions. Averaging relative yield losses across crops and continents show that relative yield decline is generally smallest on Entisols (<0.01% Mg^{-1}) and highest on Spodosols (0.78% Mg^{-1}). The soils can be arranged in the following order of average relative erosion-induced yield loss: Entisols < Vertisols < Aridisols < Mollisols < Ultisols < Alfisols < Inceptisols < Spodosols.

Studies using management practices as their experimental method showed much greater absolute and relative yield losses. However, we cannot directly compare the results of studies investigating the effect of past and present erosion. In past erosion studies, management is the same across all experimental plots, where in present erosion studies management varies. Differences in crop yields between experimental plots may, therefore, be an artifact of the different management techniques being used, rather than (or in addition to) differences in erosion rates between the plots. The much greater yield losses in these studies illustrate the effect that different management practices can have on both erosion rates and crop yield losses. Productivity declines in these studies are a reflection of the combined effect of erosion and variable crop management practices. Studies using various TSD measures reflecting past soil erosion holding management constant provide a more realistic picture of the effect of erosion on productivity. Results of present erosion studies, however, are useful as well, as they indicate that inappropriate soil management may amplify the effect of erosion on productivity by one or several orders of magnitude beyond what can be expected from looking at studies investigating effects of past erosion. Good soil management for effective erosion control and maintaining productivity, therefore, is imperative to feed and cloth the world's present and future population.

REFERENCES

Abate, S. (1994). Land use dynamics, soil degradation and potential for sustainable use in Metu area, Illubabor, Ethiopia. Geographica Bernensia, African Studies Series No. A-13. University of Berne, Berne, Switzerland.

Adams, W. E. (1949). Loss of topsoil reduces crop yields. *J. Soil Water Conserv.* **4**(3), 130.

Afifi, M. Y., Genead, A. Y., Atta, S. Kh., and Aly, A. A. (1992). Impact of rainfall erosion and management practices on properties and productivity of Maryut soil. *Desert Inst. Bull. Egypt* **42**(2), 173–184.

Agnihotri, R. C., Bushan, L. S., and Singh, S. P. (1994). Productivity loss due to soil erosion and its restoration by conservation practices. Proceedings of the 8th ISCO Conference, December 4–8, 1994, pp. 202–103. New Delhi, India.

Alberts, E. E., and Spomer, R. G. (1987). Corn grain yield response to topsoil depth on deep loess soil. *Trans. ASAE* **30**(4), 977–981.

Albuquerque, J. A., Reinert, D. J., and Fiorin, J. E. (1996). Variabilidade de sole e planta em podzolico vermelho-amarelo. *Rev. Bras. Ci. Solo* **20**(1), 151–157.

Alderfer, R. B., and Fleming, H. (1948). Soil factors influencing grape production on well-drained lae terrace areas. *Pa. Agric. Exp. Stn. Bull.* 495.

Aune, J. B., Kullaya, I. K., Kilasara, M., Kaihura, F. S. B., Singh, B. R., and Lal, R. (1998). Consequences of soil erosion on soil productivity and its restoration by soil management in Tanzania. *In* "Soil Quality and Agricultural Sustainability" (R. Lal, Ed.), pp. 197–213. Ann Arbor Press, Ann Arbor, MI.

Azontonde, A. (1993). Degradation et restauration des terres de barren (sols ferralitiques fabilement desatures argilo-sableux) au Benin. *Cah. ORSTOM Sér. Pédol.* **23**(2), 217–226.

van Baren, J. H. V., and Oldeman, L. R. (1998). Human-induced soil degradation activities. *Int. Agrophysics* **12**, 37–42.

Barr, D. A. (1957). The effect of sheet erosion on wheat yield. *J. Soil Conserv. NSW* **13**(1), 27–32.

Barre, R. D. (1939). Effect of erosion on crop yields. Supplement to Muskingum Watershed, Ohio, survery report. Runoff and water retardation and soil erosion prevention for flood control. Appendix X. Cited in: J.H. Stalling, 1975, "Soil Conservation", pp. 195–220. Englewood Cliffs, Prentice Hall, Inc. NJ.

Battiston, L. A., McBride, R. A., Miller, M. H., and Brklacich, M. J. (1985). Soil erosion-productivity research in southern Ontario. Proceedings of the National Symposium on Erosion and Soil Productivity, December 10–11, 1984, Louisiana, pp. 28–38. ASEA Spec. Pub. 8-85. New Orleans.

Battiston, L. A., Miller, M. H., and Shelton, I. J. (1987). Soil erosion and corn yield on Ontario I. Field evaluation. *Can. J. Soil Sci.* **67**, 731–745.

Becher, H. H., Schwertmann, U., and Sturmer, H. (1985). Crop yield reduction due to reduced plant available water caused by water erosion. *In* "Soil Erosion and Conversation" (S. A. El-Swaify and W. C. Moldenhauer, Eds.), pp. 365–373. Soil Conserv. Soc. Am., Ankeny, IA.

Bhatti, A. U., Ali, R., Ullah, F., and Khan, M. J. (1998). Comparison of wheat yield under uniform and variable rates of fertilizer on spatially eroded land. *Commun. Soil Sci. Plant Anal.* **20**(19/20), 2855–2863.

den Biggelaar, C., Lal, R., Wiebe, K. D., and Breneman, V. (2001). Impact of soil erosion on crop yields in North America. *Adv. Agron.* **72**, 1–52.

Biot, Y. (1987). Forecasting productivity losses caused by sheet and rill erosion in semi-arid rangeland. A case study from the communal areas of Botswana. Ph.D. Dissertation, School of Development Studies, University of East Anglia, Norwich, England.

Biot, Y., and Lu, X. X. (1993). Assessing the severity of the problem and urgency for action. *In* "Topics in Applied Resource Management in the Tropics. Acceptance of Soil and Water Conservation". (E. Baum, P. Wolff, and M. A. Zobisch, Eds.), vol. 3, pp. 165–191. DITSL, Witzenhausen, Germany.

Biot, Y., and Lu, X. X. (1995). Loss of yield caused by soil erosion on sandy soils in the UK. *Soil Use Manage.* **11**, 157–162.

Bitzer, M. J, Blevins, R. L., Aswad, M., Deaton, P., Childers, J., Henry, D., and Amos, H. (1985). Effect of tillage on soil loss nad corn grain yield on slopping land. *In* "Proceedings of the 1985 Southern Region no-till conference" (W. L. Hargrove, F. C. Boswell, and G. W. Langdale, Eds.), July 16–17, 1985, pp. 163–164. Griffin, Georgia.

Blevins, R. L., Midkiff, D. V., and Frye, W. W. (1987). Interior low plateaus. *In* "Soil erosion and productivity". Southern Cooperative Series Bulletin 360 (J. W. Gilliam and G. D. Bubenzer, Eds.), Wisc. Agric. Exp. Stn., pp. 44–52. Madison, WI.

Boardman, J. (1998). An average soil erosion rate for Europe: Myth or reality? *J. Soil Water Conserv.* **53**(1), 46–50.

Boli Baboule, Z., and Roose, E. (1998). Degradation of a sandy Alfisol and restoration of its productivity under cotton/maize intensive cropping rotation in the west savannah of northern Cameroon. *Adv. Geoecology* **31**, 395–401.

Boli, B. Z., Roose, E., and Bep A Ziem, B. (1993). Effects des techniques culturales sur le ruisellement, l'érosion et la production de coton et maïs sur un sol ferrugineux tropical. Recherche de systèmes de culture intensifs et durables en région soudanienne du Nord Cameroun (Mbissiri, 1991-1992). *Cah. ORSTOM sér. Pédol.* **27**(2), 309–325.

Bramble-Brodahl, M., Fosberg, M. A., Walker, D. J., and Falen, A. L. (1985). Changes in soil productivity related to changing topsoil. Proceedings of the National Symposium on Erosion and

Soil Productivity, December 10–11, 1984, ASEA Special Publication 8-85, pp. 18–27. New Orleans, Louisiana.

Brown, L. R. (1984). The global loss of topsoil. *J. Soil Water Conserv.* **39**(3), 162–165.

Bruce, R. R., Langdale, G. W., West, L. T., and Miller, W. P. (1995). Surface soil degradation and soil productivity restoration and maintenance. *Soil Sci. Soc. Am. J.* **59**, 654–660.

Buerkert, A., and Lamers, J. P. A. (1999). Soil erosion and deposition effects on surface characteristics and pearl millet growth in the West African Sahel. *Plant Soil* **215**, 239–253.

Burnham, C. P., and Mutter, G. M. (1993). The depth and productivity of chalky soils. *Soil Use Manage.* **9**, 1–8.

Carlson, C. W., Grunes, D. L., Alessi, J., and Reichman, G. A. (1961). Corn growth on Gardena surface and subsoil as affected by applications of fertilizer and manure. *Soil Sci. Am. Proc.* **25**, 44–47.

Carter, D. L., Berg, R. D., and Sanders, B. J. (1985). The effect of furrow irrigation erosion on crop productivity. *Sci. Soc. Am. J.* **49**, 207–211.

Chengere, A., and Lal, R. (1995). Soil degradation by erosion of a Typic Hapludalf in central Ohio and its rehabilitation. *Land Degrad. Rehab.* **6**(4), 223–238.

CIAT, (1991). Erosion control and preservation of soil fertility: Trials in Asia and Latin America. CIAT Report 1991: Highlights for 1990 and early 1991. Cali, Colombia, CIAT.

Coelho Silva, J. R., Aguiar Coelho, M., Souza Moeira, E. G., and Olieira Neto, P. R. (1985). Efeitos da erosao na prodtividade de dois solos da classe latossolo vermelho-amarelo. *Cien. Agron. (Fortaleza)* **16**(1), 55–63.

Crosson, P. (1995). Future Supplies of Land and Water for World Agriculture. *In* "Population and Food in the Early Twenty-First Century: Meeting Future Food Demands of an Increasing Population" (N. Islam, Ed.), International Food Policy Research Institute, pp. 143–159. Washington, DC.

Davies, G., Jennings, J., Fawcett, R. G., Hughes, S., and Cichon, C. (1988). The effect of soil removal on wheat productivity at Mintaro, SA, 1986 and 1987. Working papers, Workshop on tillage systems, rotations, nitrogen and cereal root diseases, March 24, 1988, pp. T8–T9. Enterprise House, Adelaide.

Davis, D. S., and Browne, S. (1996). T12.9 Soil and resources. Natural History of Nova Scotia, vol. 1, pp. 355–359. Halifax, NS: Nova Scotia Museum of Natural History.

DeHaan, K. R., Vessey, G. T., Holmstrom, D. A., McLeod, J. A., Sanderson, J. B., and Carter, M. R. (1999). Relating potato yield to the level of soil degradation using a bulk yield monitor and differential global positioning systems. *Comp. Electr. Agric.* **23**, 133–143.

Delgado, F., and Lopez, R. (1998). Evaluation of soil degradation impact on the productivity of Venezuelan soils. *Adv. Geoecology* **31**, 113–142.

Delgado, F., Terrazas, R., and Lopez, R. (1998). Planificacion de la conservation de suelos en cuencas altas, utilizando relaciones erosion-productividad. *Agronomia Tropical (Maracay)* **48**(4), 395–411.

Djorovic, M. (1990). Experimental study of soil erosion and crop production on bench terraces on sloping land. *In* "Soil Erosion on Agricultural Land" (J. Boardman, I. D. L. Foster and J. A. Dearing, Eds.), pp. 531–536. Wiley, New York.

Dormaar, J. F., and Lindwall, C. W. (1984). Restoring productivity to an eroded dark brown chernozemic soil under dryland conditions. Proceedings of the National Symposium on Erosion and Soil Productivity, December 10–11, 1984, ASAE Special Publication 8-85, pp. 182–192. New Orleans, Louisana.

Dormaar, J. F., Lindwall, C. W., and Kozub, G. C. (1986). Restoring productivity to an artificially eroded dark brown chernozemic soil under dryland conditions. *Can. J. Soil Sci.* **66**, 273–285.

Dormaar, J. F., Lindwall, C. W., and Kozub, G. C. (1988). Effectiveness of manure and commercial fertilizer in restoring productivity of an artificially eroded dark brown chernozenmic soil under dryland conditions. *Can. J. Soil Sci.* **68**, 669–679.

Dregne, H. E. (1995). Erosion and soil productivity in Australia and New Zealand. *Land Degrad. Rehab.* **6**, 71–78.

Dregne, H. E. and Chou, N. T. (1992). Global desertification dimensions and costs. *In* "Degradation and Restoration of Arid Lands" (H. E. Dregne, Ed.), Texas Tech University, International Center for Arid and Semiarid Land Studies, pp. 249–282. Lubbock, TX.

Duck, T. (1974). Zusammenhang zwischen der Fruchtbarkeit des Bodens und dem Ausmass der Erosion auf Tschernosjomboden. *In* "Systems of soil protecting farming and soil erosion control. Transactions of the 10th International Congress of Soil Science" (N. K. Shikula, Ed.), vol. XI, pp. 105–111. Moscow, USSR.

Dzhadan, G. I., Demidenko, M. K., and Chabanov, G. N. (1975). Effect of the degree of erodibility of soils on their agrochemical properties and grain crop yield. *Soviet Soil Science*, **7**, 579–582, *translated from Pochvovedenye* **9**, 123–126.

Ebeid, M. M., Lal, R., Hall, G. F., and Miller, F. (1995). Erosion effects on soil properties and soybean yield of a Miamian soil in Western Ohio in a season with below normal rainfall. *Soil Technol.* **8**(2), 97–108.

Eck, H. V., Hauser, V. L., and Ford, R. H. (1965). Fertilizer needs for restoring productivity on Pullman silty clay loam after various degrees of soil removal. *Soil Sci, Soc. Am. Proc.* **29**, 209–213.

Eck, H. V. (1968). Effect of topsoil removal on nitrogen supplying ability of Pullman silty clay loam. *Soil Sci. Soc. Am. Proc.* **32**, 686–691.

Eck, H. V. (1987). Characteristics of exposed subsoil—At exposure and 23 years later. *Agron. J.* **79**, 1067–1073.

Economic Research Service (ERS), Natural Resources and Environment Division, (1997). ERS, Agricultural Resources and Environmental Indicators 1996–97. USDA Economic Research Service, pp. 41–49. Washington, DC.

Elliott, G. L., Campbell, B. L., Crouch, R. J., and Loughran, R. J. (1988). The effect of erosion on productivity of wheat grown on red-brown earths in the northern slopes of New South Wales. *In* "Land Conservation for Future Generations". "Proceedings of the 5th ISCO Conference" (S. Rimwanich, Ed.), January 1988. 18–29, pp. 299–304. Bangkok, Thailand.

Erenstein, O. C. A. (1999). The economics of soil conservation in developing countries: The case of crop residue mulching. Thesis. Wageningen, Wageningen University.

Evans, R. (1981). Assessments of soil erosion and peat wastage for parts of East Anglia, England—A field visit. *In* "Soil Conservation: Problems and Prospects" (R. P. C. Morgan, Ed.), pp. 521–530. John Wiley, Chichester.

Evans, R., and Nortcliff, S. (1978). Soil erosion in Norfolk. *J. Agric. Sci. (Cambridge)* **90**, 185–192.

Fahnestock, P., Lal, R., and Hall, G. F. (1995). Land use and erosional effects on two Ohio Alfisols: II: Crop yields. *J. Sust. Agric.* **7**(2/3), 85–100.

Fawcett, R., Malinda, D., Dubois, B., and Schubert, N. (1990). The effect of soil removal on crop nutrition and productivity. *In* "Working papers, workshop on tillage systems, rotations, nutrition and associated cereal root diseases" (S. A. Minatro, Ed.), Waite Agricultural Research Institute, March 29–30, 1990, pp. 29–30.

Felipe-Morales, F., Meyer, R., Alegre, C., and Vittorelli, C. (1979). Losses of water and soil under different cultivation systems in two Peruvian locations, Santa Ana (Central Highlands) and San Ramon, Central High Jungle), 1975–1976. *In* "Soil Physical Properties and Crop Production" (R. Lal and D. J. Greenland, Eds.), pp. 489–499. Wiley, New York.

Fernandez, N., and Flores, E. (1995). Effecto de la remocion superficial sobre la productividad de un suelo agricola en la faja maicera des Yaracuy. 13th Congreso Venezolano de la Ciencia del Suelo, Maracay, Venezuela, 15–20 Oct 1995. Maracay: Universidad Central de Venezuela.

Fournier, F. (1963). Soils of Africa. Fournier, Review of the natural resources of the African continent. pp. 223–248. UNESCO, Paris.

Frye, W. W., Murdock, L. W., and Blevins, R. L. (1983). Corn yield-fragipan depth relations on a Zanesville soil. *Soil Sci. Soc. Am. J.* **47**, 1043–1045.

Frye, W. W., Ebelhar, S. A., Murdock, L. W., and Blevins, R. L. (1982). Soil erosion effects on properties and productivity of two Kentucky soils. *Soils Sci. Soc. Am. J.* **46**, 1051–1055.

Frymire, W. L. (1980). Topsoil depth (mollic epipedon) and its effect on crop productivity in Latah County, Idaho. M.S. Thesis, Department of Soil Science, University of Idaho, Moscow, Idaho.

Gachene, C. K. K. (1995). Effects of soil erosion on soil properties and crop response in Central Kenya. Ph.D. Dissertation, Dept of Soil Sciences, University of Uppsala, Sweden.

Gantzer, C. J., and McCarthy, T. R. (1985). Corn yield prediction for a claypan soil using a productivity index. *In* Proceedings of the National Symposium on Erosion and Soil Productivity, December 10–11, 1984, pp. 170–181. ASEA Special Publication 8-85, New Orleans, Louisiana.

Getty Research Institute, (2000). Getty Theasurus of Geographic Names. Internet URL: http://shiva.pub.getty.edu/tgn_browser/.

Gilliam, J. W., Langdale, G. W., and Bruce, R. R. (1987). Southern Piedmont. *In* "Soil Erosion and Productivity. Southern Cooperative Series Bulletin 360" (J. W. Gilliam and G. D. Bubenzer, Eds.), Wisc. Agric. Exp. Stn., pp. 24–35. Madison, WI.

Gollany, H. T., Schumacher, T. E., Lindstrom, M. J., Evenson, P. D., and Lemme, G. D. (1992). Topsoil depth and desurfacing effects on properties and productivity of a Typic Argiustoll. *Soil Sci. Soc. Am. J.* **56**, 220–225.

Greb, B. W., and Smika, D. E. (1985). Topsoil removal effects on soil chemical and physical properties. *In* "Soil Erosion and Conservation" (S. A. Swaify, W. C. Moldenhauer, and A. Lo, Eds.), Soil Conserv. Soc. Am., pp. 316–327. Ankeny, IA.

Gumbs, F. A., Lindsay, J. I., Nasir, M., and Mohammed, A. (1985). Soil erosion studies in the nothern mountain range, Trinidad, under different crop and soil management. *In* "Soil Erosion and Conservation" (S. A. El-Swaify, W. C. Moldenhauer, and A. Lo, Eds.), Soil Cons. Soc. Am., pp. 90–98. Ankeny, IA.

Hariston, J. E., Sanford, J. O., Rhoton, F. E., Miller, J. G., and Gill, K. B. (1989). Effects of soil depth, organic matter and rainfall on soybean yield in the Missisippi Blackland Prairie. Technical Bulletin No. 163, Miss. Agric. For. Exp. Stn.

Hajek, B. F., and Collins, M. E. (1987). Results of experiments conducted on various land resource areas. *In* "Coastal Plain and Tennessee Valley regions. Soil Erosion and Productivity" (J. W. Gilliam and G. D. Bubenzer, Eds.), Southern Cooperative Series Bulletin 360. WI Agric. Exp. Stn., pp. 2–23. Madison, WI.

Hamilton, G. J. (1970). The effect of sheet erosion on wheat yield and quality. *J. Soil Cons. Serv. NSW* **26**, 116–123.

Henning, S. J., and Khalaf, J. A. (1985). Topsoil depth and management effects on crop productivity in north central Iowa. Proceedings of the National Symposium on Erosion and Soil Productivity, December 10–11, 1984, ASEA Publication 8-85, pp. 59–65. New Orleans, Louisiana.

Hepler, P. R., Long, L. H., and Ferwerda, J. A. (1983). Field appraisal of resource management systems FARMS. Crop yield and quality relationships with soil erosion-1980. Bull. No. 799 Maine Agric. Exp. Stn.

Hernani, L. C., Salton, J. C., Fabricio, A. C., Dedecek, R., and Alves, M. Jr. (1997). Perdas por erosao e rendimentos de soja e de triogo em diferentes sistemas de preparo de umlatossolo roxo de Dourados (MS). *Rev. Bras. Ci. Solo* **21**, 667–676.

Hoag, D. L. (1998). The intertemporal impact of soil erosion on non-uniform soil profiles: A new direction in analyzing erosion impacts. *Agric. Syst.* **56**(4), 415–429.

Hore, H. L., and Sims, H. J. (1954). Loss of topsoil-Effect on yield and quality of wheat. *J. Agric. (Victoria)* **52**, 241–250.

Horner, G. M. (1960). Effect of cropping systems on runoff, erosion and wheat yields. *Agron. J.* **52**(6), 342–344.

Hudson, N. W., and Jackson, D. C. (1959). Results achieved in the measurement of erosion and runoff in Southern Rhodesia", Third Interafrican Soil Conference, Djalaba, Central African Republic.

Hulugalle, N.R. (1986). Effect of topsoil removal on soil physical properties and grain yield of maize in the Sudan Savannah of Burkin Faso. Mimeo, IITA, Ibadan, Nigeria.

Ives, R. M., and Shaykewich, C. F. (1987). Effect of simulated soil erosion on wheat yields on the humid Canadian prairie. *Can J. Soil Sci.* **42**(3), 205–208.

Izaurralde, R. C., Solberg, E. D., Nyborg, M., and Malhi, S. S. (1998). Immediate effects of topsoil removal on crop productivity loss and its restoration with commercial fertilizers. *Soil Tillage Res.* **46**(3/4), 251–259.

Kilasara, M., Kulaya, I. K., Kaihura, F. B. S., Aune, J. B., Singh, B. R., and Lal, R. (1995). Impact of past soil erosion on land productivity in selected ecological regions in Tanzania. *Norwegian J. Agric. Sci., Suppl.* **21**, 71–79.

Krisztian, J., Hangyel, L., and Dornbach, L. (1987). Joint effect of erosion and fertilization on the yield of some field crops. *Novenytermeles* **36**(2), 97–103.

Krumov, V., and Tzvetkova, E. (1998). Effect of soil erosion and fertilization on the economic efficiency of some crops and the fertility of Chronic Luvisol. *Soil Sci. Agrochem. Ecol.* **33**(3), 55–56.

Lal, R. Response of maize and cassava to removal of surface soil from an Alfisol in Nigeria. Field Crops Research, unpublished report, IITA, Ibadan, Nigeria.

Lal, R. (1981). Soil erosion problems on Alfisols in western Nigeria VI. Effects of erosion on experimental plots. *Geoderma* **25**, 125–230.

Lal, R. (1985). Soil erosion and its relation to productivity in tropical soils. *In* "Soil Erosion and Conservation" (S. A. El-Swaify, W. C. Moldenhauer, and A. Lo, Eds.), Soil Conserv. Soc. Am., pp. 237. Ankeny, Iowa.

Lal, R. (1987a). Effects of soil erosion on crop productivity. *Crit. Rev. Plant Sci.* **5**(4), 303–367.

Lal, R. (1987b). Response of maize and cassava to removal of surface osil from an Alfisol in Nigeria. *Int. J. Trop. Agric.* **5**, 77–82.

Lal, R., and Stewart, B. A. (Eds.) (1995). *In* "Soil Management: Experimental Basis for Sustainability and Environmental Quality". CRC Press, Boca Raton.

Lamb, J. Jr., Andrews, J. S., and Gustafson, A. F. (1944). Experiments in the control of soil erosion in Southern New York. Cornell Agric. Exp. Stn. Bull. 811, Ithaca, NY.

Landon, J. R. (Ed.) (1984). *In* "Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics" Booker Agriculture International, Ltd./Longman, London/New York.

Langdale, G. W., Bruce, R. R., and Thomas, A. W. (1987). Restoration of eroded Southern Piedmont land in conservation tillage systems. *In* "The Role of Legumes in Conservation Tillage Systems". "Proceedings of the National Conference, University of Georgia, Athens, April 27–29, 1987" (J. F. Power, Ed.). Soil Cons. Soc. Am., Ankeny.

Langdale, G. W., Box, J. E. Jr., Leonard, R. A., Barnett, A. P., and Fleming, W. G. (1979). Corn yield reduction on eroded Southern Piedmont soils. *J. Soil Water Cons.* **34**(5), 226–228.

Larney, F. J., and Janzen, H. H. (1997). A simulated erosion approach to assess rates of cattle manure and phosphorus fertilizer for restoring productivity to eroded soils. *Agric. Ecosyst. Environ.* **65**, 113–126.

Larney, F. J., Janzen, H. H., Olson, B. M., and Lindwall, C. W. (1991). The impact of simulated erosion on soil productivity and methods for its amendment. Proceedings of the 28th Annual Alberta Soil Science Workshop, February 19–21, 1991, pp. 277–285. Lethbridge, Alberta.

Larney, F. J., Izaurralde, R. C., Janzen, H. H., Olson, B. M., Solberg, E. D., Lindwall, C. W., and Nyborg, M. (1995a). Soil erosion-crop productivity relationships for six Alberta soils. *J. Soil Water Cons.* **50**(1), 87–91.

Larney, F. J., Janzen, H. H., and Olson, B. M. (1995b). Efficacy of inorganic fertilizers in restoring wheat yields on artificially eroded soils. *Can. J. Soil Sci.* **75**, 369–377.

Larney, F. J., Bullock, M. S., Janzen, H. H., Ellert, B. H., and Olson, E. C. S. (1998). Wind erosion effects on nutrient redistribution and soil productivity. *J. Soil Water Cons.* **53**(2), 133–140.

Larson, W. E., Pierce, F. J., and Dowdy, R. H. (1983). The threat of soil-erosion to long-term crop production. *Science* **219**, 458–465.

Latham, E. E. (1940). Relative productivity of the A horizon of Cecil sandy loam and the B and C Horizons exposed by erosion. *J. Am. Soc. Agron.* **32**(12), 950–954.

Lindstrom, M. J., Schumacher, T. E., Lemme, G. D., and Gollany, H. M. (1986). Soil characteristics of a mollisol and corn (*Zea mays* L.) growth 20 years after topsoil removal. *Soil Tillage Res.* **7**, 51–62.

Lindstrom, M. J., Schumacher, T. E., Lemme, G. D., Swan, J. P., and Nelson, W. W. (1987). Erosion-productivity influence on three northwestern corn belt mollisols. Proceedings of the 1987 International Winter Meetings of the American Society of Agricultural Engineers, December 15–18, 1987, (paper No. 87-2599) Chicago, Illinois.

Littleboy, M., Coughlan, K. J., Silburn, D. M., and Boaler, L. J. (1992). Modelling erosion productivity relationships. *In* "Proceedings of the 5th Australian Soil Conservation Conference, Perth, Wa, 1990". "Erosion/productivity and erosion prediction workshop" (G. J. Hamilton, K. M. Howes, and R. Attwater, Eds.), vol. 3. Department of Agriculture, Perth, Australia.

Lowery, B., Andraski, B. J., and Paulson, W. H. (1990). Best management practices for an eroded soil. Transactions of the 14th International Congress of Soil Science, vol. VII, August 12–18, 1990, pp. 380–381. Kyoto, Japan.

Lu, X. X., and Biot, Y. (1994). Effect of soil erosion on spring barley growth in East Anglia, England: Preliminary results. *Pedosphere* **4**(1), 59–66.

Maetzold, J., and Alt, K. (1986). Forum on erosion productivity impact estimators. Asessment and Planning Report. Soil Conservation Service, Apprasial and Program Development Division, Washington, DC.

Massee, T. W. (1990). Simulated erosion and fertilizer effects on winter wheat cropping intermountain dryland area. *Soil Sci. Soc. Am. J.* **54**, 1720–1725.

Massee, T. W., and Waggoner, H. O. (1985). Productivity losses from soil erosion on dry cropland in the intermountain region. *J. Soil Water Conserv.* **40**, 447–450.

Mbagwu, J. S. C. (1981). Studies on soil loss-productivity relationships of alfisols and ultisols in southern Nigeria. Ph.D. dissertation, Dept. of Soil Science, Cornell University, Ithaca, NY.

Mbagwu, J. S. C., Lal, R., and Scott, T. W. (1984). Effects of desurfacing of Alfisols and Ultisols in souther Nigeria I. Crop performance. *Soil Sci. Soc. Am. J.* **48**, 828–833.

McDaniel, T. A., and Hajek, B. F. (1985). Soil erosion effects on crop productivity and soil properties in Alabama. Proceedings of the National Symposium on Erosion and Soil Productivity, pp. 48–58. December 10–11, 1984, New Orleans, Louisiana, ASEA Special Publication, 8-85.

McFarlane, D., Delroy, N., and van Vreeswyk, S. (1991). Water erosion of potato land in western Australia: I. Factors affecting soil loss and the effect of soil loss on productivity. *Austr. J. Soil Water Cons.* **4**(1), 33–40.

McFarlane, D. J., and Carter, D. J. (1992). The effect of erosion on soil productivity in southwestern Australia. *In* Proceedings of the 5th Australian Soil Conservation Conference, Perth, WA, 1990. Erosion/productivity and erosion prediction workshop (G. J. McFarlane, K. M. Howes, and R. Attwater, Eds.), vol. 3. Department of Agriculture, Perth, Australia.

Melo Filho, J. F., and Silva, J. R. C. (1993). Erosao, teor de agua no solo e productividade do milho em planto direto e preparo convencional de um podzolico vermelho-amarelo no Ceara. *Rev. Bras. Ci. Solo* **17**, 291–297.

Mensah-Bonsu, and Obeng, H. B. (1979). Effects of cultural practices on soil erosion and maize production in the semi-deciduous rainforest and forest savanna transitional zones of Ghana. *In* "Soil Properties and Crop Production in the Tropics" (R. Lal and D. J. Greenland, Eds.), pp. 509–520. Wiley, Chichester.

Mielke, L. N., and Schepers, J. S. (1986). Plant response to topsoil thickness on an eroded loess soil. *J. Soil Water Cons.* **41**, 59–63.

Miller, C. F. (1985). Effects of erosion on the productivity of two Ustolls. M.S. Thesis, Department of Agronomy, South Dakota State University, Brookings, SD.

Mokma, D. L., and Sietz, M. A. (1992). Effects of soil erosion on Corn Yields on Marlette soils in south-central Michigan. *J. Soil Water Cons.* **47**(4), 325–327.

Monreal, C. M., Zentner, R. P., and Robertson, J. A. (1995). The influence of management on soil loss and yield of wheat in Chernozemic and Luvisolic soils. *Can. J. Soil Sci.* **75**, 567–574.

Moyo, A. (1998). The effect of soil erosion on soil productivity as influenced by tillage: With special reference to clay and organic matter losses. *Adv. Geoecology* **31**, 363–368.

Murray, W. G., Englehorn, A. J., and Griffin, R. A. (1939). Yield tests and land valuation. *Iowa Agric. Exp. Stn. Res. Bull.*, 262.

Musgrave, R. unpublished data, Cornell University, Ithaca, NY. Cited in: R.F. Follett, B.A. Stewart, Eds., Soil Erosion and Crop Productivity, pp. 243. Madison, WI: ASA-CSSA-SA.

National Agricultural Statistics Service (NASS) (1999). 1997 Census of Agriculture. USDA National Agricultural Statistics Services, Washington, DC.

National Imagery and Mapping Agency (NIMA) (2000). GEOnet Names Server, Internet URL: http://164.214.2.59/gns/html/index.html.

National Soil Erosion-Soil Productivity Research Planning Committee (NSE-SPRPC), (1981). Soil erosion effects on soil productivity: A research perspective. *J. Soil Water Cons.* **36**(2), 82–90.

Natural Resources Canada, (1995). Geographical names of Canada. Internet URL: http://geonames.nrcan.gc.ca/english/cgndb.html.

Nieto, J. P., Haller, V. V., Menes, M. M., and Chuling, N. E. (1998). Erosion, productividad y rentabilidad de dos suelos del estado de Oaxaca. *Agrociencia* **32**(2), 113–118.

Nunes Filho, J., de Sousa, A. R., Mafra, R. C., and de Jacques, O. (1987). Efeito do preparo do solo sobre as perdas por erosao e producao de milho num podzolic vermelho-amarelo eutrofico de Serra Talhada (PE). *Rev. Bras. Ci Solo* **11**, 183–186.

Odell, R. T. (1950). Measurement of the productivity of soils under various environmental conditions. *Agron. J.* **42**, 282–292.

Oldeman, L. R. (1994). The global extent of soil degradation. *In* “Soil Resilience and Sustainable Land Use” (D. J. Greenland and T. Szablocs, Eds.), pp. 99–118. Commonwealth Agricultural Bureau International, Wallingford, UK.

Oldeman, L. R., Hakkeling, R. T. A., and Sombroek, W. G. (1991). “World Map of the Status of Human-Induced Soil Degradation: A Brief Explanatory Note”. International Soil Reference and Information Centre/United Nations Environmental Programme, Wageningen/Nairobi.

Olson, T. C. (1977). Restoring the productivity of a glacial till soil after topsoil removal. *J. Soil Water Cons.* **32**, 130–132.

Olson, K. R., and Carmer, S. G. (1990). Corn yield and plant population differences between eroded phases of Illinois soils. *J. Soil Water Cons.* **45**(5), 562–566.

Olson, K. R., and Nizeyimana, E. (1988). Maize yield response differences between moderately and severely eroded Illinosis soils. *Soil Survey Horizons* **29**(2), 57–62.

Olson, K. R., Mokma, D. L., Lal, R., Schumacher, T. E., and Lindstrom, M. J. (1999). Erosion impacts on crop yield for selected soils of the North Central United States. *In* “Soil Quality and Soil Erosion” (R. Lal, Ed.), pp. 259–284. CRC Press, Boca Raton, FL.

Oyedele, D. J., and Aina, P. O. (1998). A study of soil factors in relation to erosion and yield of maize on a Nigerian soil. *Toil Tillage Res.* **48**, 115–125.

Perrens S. J. and Trustum, N. A. (1984). Assessment and evaluation of soil conservation policy. Report, Workshop on Policies for Soil and Water Conservation, 25–27 January 1983, East West Center, Honolulu, Hawaii.

Pettry, D. E., Wood, C. W. Jr, and Soileau, J. M. (1985). “Effect of topsoil thickness and horizontation of a virgin coastal plain soil on soybean yields”. Proceedings of the National Symposium on Erosion and Soil Productivity, December 10–11, 1984, pp. 66–74, New Orleans, Louisiana, ESEA special publication, 8-85.

Power, J. F., Sandoval, F. M., Ries, R. E., and Merrill, S. D. (1981). Effects of topsoil and subsoil thickness on soil water content and crop production on a disturbed soil. *Soil Sci. Soc. Am. J.* **45**, 124–129.

Rabbinge, R., and van Ittersum, M. K. (1994). Tension between aggregation levels. *In* “The Further of the Land: Mobilising and Integrating Knowledge for Land Use Options” (L. O. Fresco, L. Stroosnijder, J. Bouma, and H. van Keulen, Eds.), pp. 31–40. Chichester, UK, Wiley.

Rasmussen, P. E., and Rohde, C. R. (1991). Tillage, soil depth and precipitation effects on wheat response to nitrogen. *Soil Sci. Soc. Am. J.* **55**(1), 121–124.

Reining, L. (1992). Erosion in Andean hillside farming. Characterization and reduction of soil erosion by water in small cassava cropping systems in the southern Central Cordillera of Colombia. Weikersheim, FRG, Margraf Verlag.

Rhoton, F. E. (1990). Soybean yield response to various depths of erosion on a fragipan soil. *Soil Sci. Soc. Am. J.* **54**, 1073–1079.

Rimwanich, S. Na-Thalang, R. (1978). Personal communication. Cited in: S.A. El-Swaify, E.W. Dangler, C.L. Armstrong, 1982, Soil Erosion by Water in the Tropics. Honolulu, Hawaii: College of Tropical Agriculture and Human Resources, University of Hawaii.

Ruppenthal, M. (1995). Soil Conservation in Andean Copyright Systems. “Soils Erosion and Crop Productivity in Traditional and Forage-based Cassava Cropping Systems in the South Colombian Andes”. Margraf Verlag, Weikersheim, FRG.

Salchow, E., and Lal, R. (1999). Crop yield variability due to erosion on a complex landscape in west central Ohio. *In* “Integrated Watershed Management in the Global Ecosystem” (R. Lal, Ed.), pp. 195–207. CRC Press, Boca Raton.

Salviano, A. A. C., Vieira, S. R., and Sparovek, G. (1998). Erosion intensity and *Crotolaria juncea* yield on a southeast Brazilian Ultisol. *Adv. Geoecology* **31**, 369–374.

Sandanam, S., and Rajasingham, C. C. (1981). Effects of mulching and cover crops on soil erosion and yield of young tea. *Tea Quarterly* **51**(1), 21–26.

Sanders, J.H., Southgate, D.D., Lee, J.G. (1995). The economics of soil degradation: Technological change and policy alternatives. Soil Management Support Services Technical Monograph No. 22. West Lafayette, IN: Purdue University.

Scherr, S. J. (1999). Soil Degradation. A Threat to Developing Country Food Security by 2020?. “Food, Agriculture, and the Environment Discussion Paper 27”. International Food Policy Research Institute, Washington, DC.

Schertz, D. L., Moldenhauer, W. C., Franzmeier, D. P., and Sinclair, H. R. Jr. (1985). Field evaluation of the effect of soil erosion on crop productivity. Proceedings of the National Symposium on Erosion and Soil Productivity, December 10–11, 1984, pp. 9–17. ASEA Special Publication 8-85. New Orleans, Louisiana.

Schertz, D. L., Moldenauer, W. C., Linvingston, S. J., Weesies, G. A., and Hintz, E. A. (1989). Effect of past soil erosion on crop productivity in Indiana. *J. Soil Water Cons.* **44**, 604–608.

Schumacher, T. E., Lindstrom, M. J., Mokma, D. L., and Nelson, W. W. (1994). Corn yield: erosion relationships of representative loess and till soils in the North Central United States. *J. Soil Water Cons.* **49**(1), 77–81.

Seather, A. H., Moen, K. L. E., Singh, B. R., Lal, R., and Kilasara, M. (1997). Soil management and topsoil thickness effects on maize for two Tanzanian soils. *J. Sust. Agric.* **10**(1), 43–61.

Sessay, M.F. (1991). The impact of soil erosion on the properties and productivity of an Oxisol in Sierra Leone. Ph.D. Dissertation, School of Development Studies, University of East Anglia, Norwich, England.

Shaffer, M. J., Schumacher, T. E., and Ego, C. L. (1994). Long-term effects of erosion and climate interactions on corn yield. *J. Soil Water Cons.* **49**(3), 272–275.

Shafiq, M., Zafar, M. I., Ikram, M. Z., and Ranjha, A. Y. (1988). The influence of simulated soil erosion and restorative fertilization on maize and wheat production. *Pakistan J. Sci. Ind. Res.* **31**(7), 502–505.

Shivaramu, H. S., Yadav, S. C., Chary, G. R., Kandpal, B. K., Gaikawad, S. T., and Thote, S. G. (1998). Soil requirements of Vertisols for soybean at varied management. *J. Indian Soc. Soil Sci.* **46**(1), 90–99.

da Silva, F. J., and Silva, J. R. C. (1997). Productivity of a Lithosol in association with control of erosion using stone barrier contours. *Rev. Bras. Ci. Solo* **21**, 435–440.

da Silva, A. B., Resende, M., de Sousa, A. R., and Margolis, E. (1999). Soil mobilization, erosion and corn and bean yields on a regosol in the Pernambuco State dry area. *Pesq. Agropec. Bras.* **34**(2), 299–307.

Singh, P., Alagarswamy, G., Pathak, P., Wani, S. P., Hoogenboom, G., and Virmani, S. M. (1999). Soybean–chickpea rotation on Vertic Inceptisols I. Effect of soil depth and land form on light interception, water balance and crop yields. *Field Crop Res.* **63**, 211–224.

Sinukaban, N., Pawitan, H., Arysad, S., Armstrong, J., and Nethery, M. (1994). Effect of soil conservation practices and slope lengths on runoff, soil loss and yield of vegetables in West Java. *Austr. J. Soil Water Cons.* **7**(3), 25–29.

Smith, D. D. (1946). The effect of contour planting on crop yield and erosion losses in Missouri. *J. Am. Soc. Agron* **38**(9), 811–819.

Soil Survey Staff, (1999). Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys, 2nd edn. USDA-NRCS Agricultural Handbook No. 436. USDA Natural Resources Conservation Service, Washington, DC.

Sojka, R. E., Westermann, D. T., Brown, M. J., and Meek, B. D. (1993). Zone-subsoiling effect on infiltration, runoff, erosion and yields of furrow-irrigated potatoes. *Soil Tillage Res.* **25**, 351–368.

Sparovek, G., Teramoto, E. R., Toreta, D. M., Rochele, T. C. P., and Shayer, E. P. M. (1991). Erosao simulade e productividade da cultura do milho. *Rev. Bras. Ci. Solo* **15**, 363–368.

Stallings, J. H. (1957). "Soil Conservation". Prentice-Hall, Englewood Cliffs, NJ, pp. 195–220.

Stocking, M. (1984). Erosion and Soil Productivity: A Review. Food and Agriculture Organization, Soil Conservation Programme, Land and Water Development Division, Rome.

Stocking, M. (1994). Soil erosion and conservation: A place for soil science?. *In* "Soil Science and Sustainable Land Management in The Tropics" (J. K. Syers and D. L. Rimmer, Eds.), pp. 40–58. CAB International, Wallingford, UK.

Stone, J. R., Gilliam, J. W., Cassel, D. K., Daniels, R. B., Nelson, L. A., and Kleiss, H. J. (1985). Effect of erosion and landscape position on the productivity of Piedmont soils. *Soil. Sci. Soc. Am. J.* **49**, 987–991.

Sturmer, H., Becher, H. H., and Schwertmann, U. (1982). Ertragsbildung bei Maiz auf erodierten Hangen. *Zeitschrift Acker und Pflanzenbau* **151**, 315–321.

Sudirman, N., Sinukaban, H., Suwardjo, and Arsyad, S. (1986). Effect of degree of soil loss and liming on soil productivity. *Pember. Pen Tanah dan Pupuk* **6**, 9–14.

Sur, S., Singh, R., and Malhi, S. S. (1998). Influence of simulated erosion on soil properties and maize yield in northwestern India. *Commun. Soil Sci. Plant Anal.* **29**(17/18), 2647–2658.

Swan, J. B., Shaffer, M. J., Paulson, W. H., and Peterson, A. E. (1987). Simulating effects of soil depth and climatic factors on corn yield. *Soil Sci. Soc. Am. J.* **51**, 1025–1032.

Tanaka, D. L. (1995). Spring wheat straw production and composition as influenced by topsoil removal. *Soil Sci, Soc. Am. J.* **59**, 649–654.

Tanaka, D. L., and Aase, J. K. (1989). Influence of topsoil removal and fertilizer application on spring wheat yields. *Soil Sci. Soc. Am. J.* **53**, 228–232.

Tegene, B. (1992). Erosion: Its effects on properties and productivity of Eutric Nitisols in Gununo area, southern Ethiopia, and some techniques of its control. Geographica Bernensia, African Studies Series No. A-9. University of Berne, Switzerland.

Tengberg, A., and Stocking, M. (1992). Erosion-induced loss in soil productivity and its impacts on agricultural production and food security. *Paper presented at the FAO/AGRITEX Expert Consultation on Integrated Soil Management for Sustainable Agriculture and Food Security in Southern and Eastern Africa, Harare, Zimbabwe* **8-12**, 1997.

Tengberg, A., Dechen, F. S. C., and Stocking, M. (1997a). The impact of erosion on soil productivity: An experimental design applied in Sao Paulo State, Brazil. *Geografiska Annaler* **79A**(1-2), 95–107.

Tengberg, A., Stocking, M., and da Veiga, M. (1997b). The impact of erosion on the productivity of a Ferralsol and a Cambisol in Santa Catarina, southern Brazil. *Soil Use Manage.* **13**, 90–96.

Tengberg, A., Stocking, M., and Dechen, S. C. F. (1998). Soil erosion and crop productivity research in South America. *Adv. Geoecology* **31**, 353–362.

Tenge, A. J., Kaihura, F. B. S., Lal, R., and Singh, B. R. (1998). Erosion effects on soil moisture and corn yield on two soils at Mlingano, Tanzania. *Am. J. Alternative Agric.* **13**(2), 83–89.

Thomas, H. L., Stephenson, R. E., Freese, C. R., Chapin, R. W., and Huggins, W. W. (1943). The economic effect of soil erosion on wheat yields in Eastern Oregon. *Oregon Ag. Exp. Stn. Circular*, 157.

Thompson, A. L., Gantzer, C. J., and Anderson, S. H. (1991a). Topsoil depth, fertility, water management and weather influences on Yield. *Soil Sci. Soc. Am. J.* **55**, 1085–1091.

Thompson, P. J., Simpson, T. W., and Baker, J. C. (1991b). Topsoil depth, fertility, water management, and weather influences on yield. *Soil Sci. Soc. Am. J.* **55**, 1085–1091.

Thompson, A. L., Gantzer, C. J., and Hammer, R. D. (1992). Productivity of a claypan soil under rainfed and irrigated conditions. *J. Soil Water Cons.* **47**(5), 405–410.

Tikhonov, A. V. (1960). Soil erosion and its effects on yield in areas of the Volga Upland. *Soviet Soil Sci.* **2**, 180–187.

Tiwari, R. J., and Jain, R. C. (1995). Effect of bunding methods on soil properties and yield of soybean in medium black soils of Madhya Pradesh. *Gujarat Agric. Univ. Res. J.* **21**(1), 176–178.

Tyler, D. D., Graveel, J. G., and Jones, J. R. (1987). Southern loess belt. *In* "Soil Erosion and Productivity". "Southern Cooperative Series Bulletin 360" (J. W. Gilliam and G. D. Bubenzer, Eds.), pp. 36–43. Wisc. Agric. Exp. Stn., Madison, WI.

United States Geological Survey (USGS) (2000). National Mapping Information. Geographic Names Information System, United States and Territories. Internet URL: http://mapping.usgs.gov/www/gnis/gnisform.html.

Vaje, P. I., Singh, B. R., and Lal, R. (1998). Erosional effects on soil properties and maize yield on a volcanic ash soil in Kilimajnaro region, Tanzania. *J. Sust. Agric.* **12**(4), 39–53.

da Veiga, M., Pandolfo, C. M., and do Prado Wildner, L. (1998). Aspectos tecnicos e economicos da erosao em um solo do Oeste Catarinense. *Agropecuaria Catarinense* **11**(3), 23–28.

Verity, G. E., and Anderson, D. W. (1990). Soil erosion effects on soil quality and yield. *Can. J. Soil Sci.* **70**, 471–484.

Vernander, N. B., Lan'ko, A. I., Marinich, A. M., Popov, V. P., Pomushkevich, V. I., Skorodumov, A. S., and Shcherban, M. I. (1964). Physical-geographic processes unfavorable for agricutlture and control measures against them. *Soviet Geography* **5**, 61–67.

Vesterby, M., and Krupa, K. S. (1993). Effects of urban land conversion on agriculture. *In* "Urbanization and Development Effects on the Use of Natural Resources". "SRDC No. 169" (E. Thunberg and J. Reynolds, Eds.), pp. 85–114. Southern Rural Development Center and Farm Foundation, Mississippi State, MS.

Vittal, K. P. R., Vijayalakshmi, K., and Bhaskara-Rao, U. M. (1991). Effects of topsoil, rainfall and fertilizer on finger millet on an Alfisol in India. *Soil Sci.* **152**(1), 3–6.

Wassif, M. M., Atta, S. Kh., and Tadros, S. F. (1995). Water erosion of calcareous soil and its productivity under rainfed agriculture of Egypt. *Egypt J. Soil Sci.* **35**(1), 15–31.

Weesies, G. A., Livingston, S. J., Hosteter, W. D., and Schertz, D. L. (1994). Effect of soil erosion on crop yield in Indiana: Results of a 10 year study. *J. Soil Water Cons.* **49**(6), 597–600.

Wetter, F. (1977). "The influence of topsoil depth on yield". "Tech. Note 10". USDA-SCS, Spokane, WA.

White, A. W. Jr., Bruce, R. R., Thomas, A. W., Langdale, G. W., and Perkins, H. F. (1985). Characterizing productivity of eroded soils in the southern Piedmont. Proceedings of the National Symposium on Erosion and Soil Productivity, December 10–11, 1984, New Orleans, Louisiana, pp. 83–95. ASEA Special Pub. 8-875.

Willet, I. R. (1994). Physical and chemical constraints to sustainable soil use under rainfed conditions in the humid tropics of Southeast Asia. *In* "Soil Science and Sustainable Land Management in the Tropics" (J. K. Syers and D. L. Rimmer, Eds.), pp. 235–247. CAB International, Wallingford, Oxford, UK.

World Soil Resources Staff, (1997). "Global soil regions map". USDA NRCS, Soil Survey, Division, World Soil Resources, Washington, DC.

Wright, R. J., Boyer, D. G., Winant, W. M., and Perry, H. D. (1990). The influence of soil factors on yield differences among landscape positions in an Appalachian cornfield. *Soil Sci.* **149**(6), 375–382.

Xu, L. L., and Biot, Y. (1994). Effect of soil erosion on spring barley growth in East Anglia. *England: Preliminary results. Pedosphere* **4**(1), 59–66.

Xu, Z., Fausey, N. R., Lal, R., and Hall, G. F. (1997). Erosional effects on soil properties and corn (*Zea mays* L.) yield on a Miamiam soil in Ohio. *J. Sust. Agric.* **10**(4), 21–35.

Yang, T., Blanchar, R. W., Hammer, R. D., and Thompson, A. L. (1996). Soybean growth and rhizosphere pH as influenced by A horizon thickness. *Soil Sci. Soc. Am. J.* **60**, 1901–1907.

Yost, R. S., el-Swaify, S. A., Dangler, E. W., and Lo, A. K. F (1985). The influence of simulated erosion and restorative fertilization on maize production on an Oxisol. *In* "Soil Erosion and Conservation" (S. A. El-Swaify, W. C. Moldenhauer, and A. Lo, Eds.), pp. 248–261. Soil Conserv. Soc. Am., Ankeny, IA.