THE GLOBAL IMPACT OF SOIL EROSION ON PRODUCTIVITY*

II: Effects On Crop Yields And Production Over Time

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Soil is one of the most important natural resources and a major factor in global food production. Soil erosion is widely considered the most serious

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form of soil degradation, posing a significant threat to world's food production capacity and global food security. In this report, we combine the estimates of absolute and relative yield declines per unit of soil erosion from the previous report with estimates, by soil order, of the extent of water-induced erosion, crop production areas and crop yields within a GIS. Analysis of six crops (maize, millet, potatoes, sorghum, soybeans and wheat) generates production loss estimates that vary across crops, soils, and regions but average 0.3%yr^{-1} at the global level, assuming that farmers' practices do not change. These losses correspond to an estimated economic value of \$523.1 million yr^{-1}. Reducing production losses by limiting soil erosion would, therefore, go a long way to attain food security, especially in the developing countries of the tropics and subtropics.

I. INTRODUCTION

As more than 99% of human food is coming from the land (Pimentel and Pimentel, 2000), soil is one of our important natural resources and a major factor in global food production. However, soil management has frequently had major impacts, both positive and negative, on the properties of the soil that govern its productivity. Erosion is widely considered to be the most serious form of soil degradation, undermining the long-term viability of agriculture in many parts of the world (Lal, 1994). Oldeman *et al*. (1991) estimated that erosion accounts for 84% of the total global area of degraded soils, ranging from 68% in South America to 99% in North America. Some researchers have argued that a significant area of land now being cultivated may be rendered biologically and/or economically unproductive if erosion continues unabated (Brown and Wolf, 1984; Lal, 1994; Pimental *et al*., 1995; Eaton, 1996). Although erosion is a very widespread phenomenon, it is generally neither assessed nor monitored. There are global and regional estimates of its magnitude. For example, Oldeman (1994), using the data of the Global Assessment of Soil Degradation (GLASOD) study, estimated that 1.6 billion ha of land is affected by erosion globally, 1.1 billion ha by water erosion, and 0.5 billion ha by wind erosion. Estimates of rates of soil loss are derived from few experiments around the world. Global soil loss due to erosion on agricultural land was estimated at 26 billion Mg yr^{-1} (an average of 16 Mg ha^{-1} yr^{-1}) by Brown (1984) and Brown and Wolf (1984). Pimental *et al*. (1995) estimated that the rate of soil erosion is three times higher (75 billion Mg yr^{-1}). However, what matters most from a policy standpoint is not how much land has already been lost, but productivity losses related to soil loss and vulnerability of the system to continued degradation (Young, 1999). A recent study by IFPRI (2000), using an overlay of cropland areas and GLASOD data, showed that soil degradation has already had significant impacts on the productivity of about 16% of the world's agricultural land. Lal and Stewart (1990) and Janargin and Smith (1993) estimated that erosion could cause a decline of 19–29% in food production from rain-fed cropland worldwide during the 25 years from 1985 to 2010 if allowed to continue unchecked. It must be pointed out that these estimates include the consequences of other forms of land degradation although soil loss is a major component.

While the literature on the extent and severity of erosion is voluminous, much less is known about the effects of erosion on soil productivity and on crop production (Lal, 1995). In the previous paper (den Biggelaar *et al*., this volume), we estimated crop yield losses (using crop yield as a proxy measure of soil productivity) per unit of soil erosion from an analysis of 329 records covering 161 soil subgroups from 37 countries from the soil science literature. In the present paper, we will combine those results with soil-based estimates of annual erosion rates, crop yields and production areas to determine annual crop yield, and production losses due to soil erosion by crop, soil order, and region.

A. Effect of Erosion on Food Production

Soil erosion poses a significant threat to the world's food production capacity to ensure food security in the context of an increasing global population. In addition, rates of soil loss are generally much greater than rates of soil formation. Lack of data has prevented econometric analysis of changes in crop productivity as a function of land degradation; as a result, national, regional, or global estimates of productivity changes are always speculative (van Baren and Oldeman, 1998; Boardman, 1998; Greenland *et al*., 1998). It is also difficult, if not impossible, to generalize the relationship between soil erosion and productivity because of the location-specific nature of soil erosion (Arifin, 1995). The multiple, location-specific factors affecting productivity (such as inherent soil physical, chemical, and biological properties; climate; management) (Rijsberman and Wolman, 1984; Power, 1990; Ponzi, 1993; Loch and Silburn, 1997; Sccones, 1998) interacting with technological advance may affect the relationship between erosion and productivity over time (Littleboy *et al*., 1996) and mask the negative impacts of erosion.

In general, erosion results in a decline in soil quality leading to a decrease in crop productivity. Crosson (1994) and Lindert (1999), however, argued that effects of soil erosion on productivity are overestimated. Crosson (1997), using data of Dregne and Chou (1982) and Oldeman *et al*. (1991), determined that the cumulative average degradation-induced loss of global soil productivity was roughly 0.1–0.2% yr^{-1} during the 1945–1990 period. In Crosson's opinion, these estimates support the conclusion that, despite widespread belief to the contrary, losses due to erosion and other forms of land degradation do not pose a serious threat to the capacity of the global agricultural systems to increase yields (Crosson, 1997). In some cases, people are able to adapt, cope and overcome severe resource degradation, as, for example, was shown by Tiffen *et al*. (1994) in Machakos District, Kenya. However, others argue that only some people in Machakos were able to do so using remittances from non-farm income from jobs and access to markets in nearby Nairobi (Rocheleau, 1995; Murton, 1999). In addition, as Young (1999) pointed out, the district was highly favored by foreign aid projects. According to Rocheleau, Murton, and Young, none of these factors were sufficiently taken into account by Tiffen *et al*. (1994). Further, none of these authors, particularly Crosson, have taken into consideration the fact that degradation–productivity relationships differ between soils. In addition, tropical soils in general have low resilience and a decline in productivity due to a change in soil quality is much greater in comparison to the organic matter and nutrient rich temperate soils. Farmers' response to changes in productivity has also national and regional differences.

B. Effect of Erosion on Food Security

Although soil erosion may not pose a threat to food production when looked at from a global perspective, it could still be a potentially serious threat to food security, rural incomes, and rural livelihoods in some parts of the world (Scherr and Yadav, 1996). Food security differs from food production. Food security means ensuring that all people have physical and economic access to the basic food they need to work and function normally (WRI, 1996). USDA's Economic Research Service (ERS) (1998) estimated that the food gap to maintain per capita consumption at 1995–1997 levels in 66 low-income developing countries was 11 million Mg; the gap to meet minimum nutritional requirements was estimated to be much higher at 17.6 million Mg (USDA, 1998). ERS estimates that the food gaps with respect to both consumption indicators would widen to 19.8 and 28.4 million Mg, respectively, by 2008. However, the threat is not uniform, and depends upon a variety of land, environmental, social, economic, demographic, and political circumstances (Tengberg and Stocking, 1997).

C. Erosion–Productivity Estimates

Globally, there are few studies on the impact of soil erosion on agricultural production. Soil based estimates of production losses due to water and wind erosion in North America revealed potential losses of 235,000 Mg yr^{-1} of maize

(*Zea mays* L), 60,000 Mg yr^{-1} of soybeans [*Glycine max* (L). Merr.], 75,000 Mg yr^{-1} of wheat (*Triticum aestivum* L.), and 2,000 Mg yr^{-1} of cotton (*Gossypium hirsutum* L.) (den Biggelaar *et al*., 2001). The annual economic value of these production losses were estimated at US$ 56 million in the United States and US$ 3 million in Canada (additional costs for fertilizers, irrigation, etc. and the off-farm costs of erosion may be much higher, but are not included in these estimates). UNEP (1986) estimated the global costs of soil erosion at US$ 26 billion yr^{-1}, of which US$ 12 billion occurred in developing countries. A joint UNDP, FAO and UNEP (1993) study estimated the costs of all forms of land degradation in South Asia alone at between US$ 9.8 and 11 billion yr^{-1}. According to Eswaran *et al*. (2001) the productivity of some lands has declined by 50% due to soil erosion and desertification. Yield reduction in Africa due to past soil erosion may range from 2 to 40%, with a mean loss of 8.2% for the continent. In South Asia, annual loss in productivity is estimated at 36 million tons of cereal equivalent valued at US$ 5,400 million by water erosion, and US$ 1,800 million due to wind erosion. It is estimated that the total annual cost of erosion from agriculture in the USA is about US$ 44 billion per year, i.e., about US$ 247 ha^{-1} of cropland and pasture. On a global scale the annual loss of 75 billion Mg of soil costs the world about US$ 400 billion yr^{-1}, or approximately US$ 70 per person per year.

Young (1999) concluded that it may not be unreasonable to say that land degradation (which is more inclusive than just soil erosion, although the latter makes up the largest share of it) that has taken place until now is costing developing countries between 5 and 10% of their total agricultural sector production. Tentatively, Young estimated that this rate may be rising by 1% every 5–10 years. Compared to the total value of global agricultural GDP, estimated at $1.25 trillion in 1997 (World Bank, 2000), the economic value of production lost as a result of erosion is fairly small ($26 billion is about 2% of $ 1.25 trillion).

II. OBJECTIVES OF THE PRESENT STUDY

In the previous paper (den Biggelaar *et al*., this volume), we compiled and synthesized data from published erosion–productivity studies from around the world to estimate absolute and relative crop yield declines per unit of soil erosion. The objective of this report, which compliments the previous one, is to combine the results of the previous paper with estimates of soil erosion rates and crop production areas to make continent-level assessments of the impact of soil erosion on crop yields and production over time.

III. METHODS

A. Data Sources

To determine the effect of erosion-induced soil productivity loss on global crop production, food security and national economies, multiple types of data are necessary. We used the relative yield losses per Mg of soil erosion from den Biggelaar *et al*. (this volume) as the basis for our calculations of annual yield and production losses for the selected crops. These relative yield loss estimates assumed that (1) erosion is uniform across a field or landscape; (2) erosion-induced yield declines are constant in percentage terms over time corresponding to a logistic decline in yields, consistent with numerous studies of tropical soils (e.g., Tengberg and Stocking, 1997, 1999); and (3) the impact of erosion on productivity remains constant across differential levels of inputs and management practices. In addition, two additional assumptions (adapted from Lal, 1995) are critical to the estimates generated and their interpretation, namely, that (1) the erosion-induced productivity declines observed at a few sites are applicable across wide geographical and ecological regions within one continent; and (2) the impact of erosion on productivity is identical for different land uses and farming systems.

We will estimate the yield loss due to erosion for six crops: maize, wheat, soybeans, potatoes (*Solanum tuberosum* L.), and sorghum (*Sorghum bicolor* L.) (in North Americal) or millet (*Panicum milicaceum* L. and/or *Pennisetum glaucum* L.) (in Asia and Europe). For these estimations, we will only use the relative yield declines from past erosion studies. Studies that involved yield comparisons across management practices associated with differential rates of erosion (e.g., fertilizer rates, irrigation, tillage, terracing, and contour plowing) are excluded from the analysis in order to avoid confusing the effects of different management practices with the effect of erosion per se. The yield loss estimations for the six selected crops are based on the analysis of 292 soil based erosion–productivity records with 362 nested crop-input combination entries (out of a total 329 records and 576 entries in the entire database, 37 records are based on management practices studies, while 122 and 92 entries involve crop-input combinations in past erosion studies for other crops investigated and in management practices studies, respectively).

In the absence of global datasets on soil-specific erosion rates and crop production areas, we estimated this information from existing climate and soil databases within a geographic information system (GIS). We then used the derived potential soil-based erosion rates and crop area data, together with the relative yield losses per Mg of soil erosion from the synthesis of global erosion–productivity studies (den Biggelaar *et al*., this volume) and FAO production statistics to estimate the impact of erosion on the production of the six selected crops. Applying projected 2000/01 crop prices from the USDA Agricultural Baseline Projections to 2010 (USDA, 2001), we then estimate the value of lost production allowing comparisons of the magnitude of the estimated losses across commodities and soil orders within and between continents. There are, however, additional effects of erosion besides losses in production, such as increased sedimentation downstream, water pollution, extra expenses for fertilizer, irrigation, soil preparation, which will increase both societal and producer costs of erosion significantly. These additional effects will not be considered in this paper.

From the review of the impact of erosion on productivity in North America, den Biggelaar *et al*. (2001) reported that, for the United States, using soil-based extrapolations of productivity declines to determine production and economic losses reduced aggregate estimated losses by 25% compared to using an average national erosion rate that disregards soil-based differences in erosion and crop yield impacts. In the hope that such greater precision can be obtained at the global level as well, we estimated the impact of erosion on soil-based extrapolations of productivity declines at the global level. However, doing so requires global data on erosion rates for each soil order, and on the area of selected major crops produced on each soil order. At present, no global database with this type of data exist. For example, FAO agricultural statistics databases contain information on total land area, agricultural area, arable area, and on area and yield of various crops at country, region or continent levels, but none of the information is disaggregated by soil order (FAO, 2000). To obtain soil-based information on erosion rates, crop production areas and crop yields, we used a multi-step process within GIS to estimate potential average erosion rates, potential crop growing areas, and potential crop yields by soil order and continent. The potential crop growing areas and potential yields are then adjusted using published FAO area and production statistics to better reflect actual crop production areas and yields on the various continents. These procedures are described in Sections II.B, II.C, and II.D, respectively.

B. Potential Erosion Rate Estimates

Information on the global extent of erosion was obtained in a two-step process; details of the procedures and their results can be found in Eswaran *et al*. (1999) and Reich *et al*. (2000). First, each soil unit of the Global Soil Regions map (World Soil Resources Staff, 1997) was assigned a vulnerability class to water and wind erosion (Eswaran *et al*., 1999; Reich *et al*., 2000). The Global Soil Regions Map is based on a reclassification of soil units of the FAO-UNESCO (1971–81) Soil Map of the World. Soil data from the digitized version of this map was combined with soil climate data to reclassify the soils according to the US Soil Taxonomy suborders on a 2-min grid cell (Soil Survey Staff, 1998). In the Global Soil Regions map, soils are grouped according to the 12 soil orders of the US Soil Taxonomy.

Research by Fournier (1960), Charreau (1969), Delwaulle (1973), Wishmeier and Smith (1978), and E1-Swaify and Cooley (1981) has shown that soil loss can be estimated from rainfall induced erosivity. Available data on erosivity was estimated based on published data for specific locations and extrapolating the value to similar soil units. Based on the knowledge of soil behavior under the prevailing climatic conditions, soils were assigned an erosion vulnerability class; catastrophic events were excluded in this assessment (Eswaran *et al*., 1999). Second, the combination of soil and climate information was used to assign polygons derived from an overlay of the soil map and climate data to one of 25 major land resource stress classes. Knowing the properties of the soils (i.e. soil performance criteria) and the major stresses they experience (expressed as soil resilience), nine inherent land quality classes were created (Eswaran *et al*., 1999). A matrix was used to estimate magnitudes of potential rates of soil loss due to water and wind erosion as a function of the inherent land quality (ILQ) classes. Due to the paucity of data, values for most of the classes in this matrix were interpolated to represent relative magnitudes. GIS analysis was used to make global estimates of the area occupied by each class; average annual soil losses were then computed from this information. The results were verified by comparing computed values for the US and India with maps based on field measurements of erosion in these countries, the only ones for which national level erosion rate data were available.

Reich *et al*. (2000) calculated the area vulnerable to erosion and total amount of erosion for the African continent using four vulnerability classes, each corresponding to a range of erosion rates: low, medium, high, and very high. For purposes of our analysis, we assumed that erosion occurred at the midpoints of each range. According to Reich *et al*., most arable land is found in ILQ classes I–VI. Based on the total area vulnerable to water erosion and the total amount of soil erosion in these six ILQ classes, we estimate average annual cropland erosion rates of 9.32, 14.25, 17.20, and 25.78 Mg ha^{-1} for the low, medium, high, and very high vulnerability classes, respectively. For land in the depositional class, we assumed an erosion rate of 0 Mg ha^{-1}. From an overlay of the water erosion vulnerability map created by Reich *et al*. (2000), the map of cropland areas according to the land cover classification of the International Geosphere Biosphere Programme (IGBP) (Belward, 1996), and the Global Soil Regions map, we then estimated the cropland area within each soil order assigned to each vulnerability class. From the soil order areas assigned to the different vulnerability classes and the average erosion rates for these classes, we then calculated average weighted potential cropland water erosion rates for each soil order as follows:

$$\overline{E_{wp}} = \frac{\sum_{c=1}^{n} A_c \times \overline{E_c}}{A_t} \tag{1}$$

where $\overline{E_{wp}}$ is the weighted potential mn erosion rate (Mg ha^{-1} yr^{-1}); A_c is cropland area in the erosion class (ha); $\overline{E_c}$ is the mean erosion rate in the erosion class (Mg ha^{-1} yr^{-1}), and A_t the total cropland area (ha).

Crop specific soil erosion rates were estimated by selecting only those polygons that were classified as both IGBP cropland and potentially suitable for the selected crops. The estimated average crop specific erosion rates by soil order and continent resulting form these calculations are given in Table I.

C. Estimates of Potential Crop Growing Areas

Information on potential arable land by soil order was obtained from global land cover, climate, and soil data. We used global land cover data on a continent-by-continent basis, derived from 1-km Advanced Very High Resolution Radiometer (AVHRR) data spanning the 12-month period of April 1992–March 1993 (Eidenshink and Faudeen, 1994). In particular, we used land cover classes 12 (cropland) and 14 (cropland-natural vegetation mosaic) of the IGBP Land Cover Classification (Belward, 1996). The World Soil Resources Staff maintains a database of climate with average monthly temperature and precipitation data for about 20,000 stations. A soil water balance model that estimates soil moisture and temperature regimes (Newhall, 1972) was used to obtain soil property information from atmospheric data. The point data was interpolated using a kriging method to create a raster map on a 2-min grid cell. Soil data were derived from the Global Soil Regions map (World Soil Resources Staff, 1997).

From the climate and global land cover data, combined with information on growth requirements of the selected crops (maize, wheat, potatoes, soybeans, and millet/sorghum), a determination of areas suitable for these crops was made. Production suitability was classified on a four-point scale (low, moderate, high, and very high) corresponding to the yield ranges for each crop as specified in Table II. This layer was then projected over the Global Soil Regions map to estimate potential arable land for each selected crop by soil order and country. The total area of potential arable land for these crops by soil order at the level of each continent was determined by adding the potential production areas of each crop within each soil order and country.

The potential arable land for the selected crops differs from the actual area in those crops, since some land is suitable for the production of a variety of crops or the crops may not be grown for cultural or economic reasons. Accordingly, we

Table I

Crop-Specific Potential Mean Weighted Erosion Rates (Mg ha^{-1} yr^{-1}) for Selected Crops by Continent and Soil Order

		Erosion rate (Mg ha^{-1} yr^{-1})											
		Alfisols	Andisols	Aridisols	Entisols	Histosols	Inceptisols	Mollisols	Oxisols	Spodosols	Ultisols	Vertisols	Mean
Africa	Maize	14.10	13.77	17.17	2.46	12.52	18.75	16.58	12.21	n/a	11.97	18.62	13.68
Asia	Maize	12.58	13.21	11.50	1.80	16.45	18.87	13.67	15.77	14.46	15.09	18.55	15.10
	Millet	14.12	12.20	19.21	1.03	10.19	11.44	17.17	17.75	n/a	14.45	18.75	14.45
	Soybean	12.17	13.83	19.49	1.60	10.62	13.48	12.48	14.33	n/a	16.77	16.69	14.91
	Wheat	10.97	14.34	9.75	1.52	13.71	18.38	13.33	20.92	n/a	15.25	18.26	14.33
Australia	Potatoes	12.07	14.25	10.58	8.12	n/a	22.37	15.62	12.83	0.38	6.98	14.07	12.47
	Wheat	12.34	14.25	13.54	11.84	n/a	22.55	15.71	12.99	14.48	14.01	17.75	15.13
Europe	Potatoes	10.66	11.12	12.60	0.95	3.61	18.13	10.61	9.32	0.04	0.68	21.03	8.89
	Millet	13.58	n/a	11.86	0.89	18.09	10.98	14.25	11.13	n/a	12.06	15.87	10.81
	Soybean	12.26	14.29	n/a	0.79	5.64	10.56	11.99	13.29	7.64	16.66	16.75	11.47
	Wheat	5.35	11.16	12.07	0.91	3.72	19.22	10.61	n/a	8.88	8.09	21.30	9.09
North America	Maize	11.44	12.75	12.55	1.97	10.61	24.00	13.87	n/a	15.85	16.73	17.31	14.95
	Potatoes	11.14	5.76	11.13	2.26	5.57	11.62	13.27	n/a	0.02	14.96	17.04	8.73
	Sorghum	13.48	11.97	11.50	0.57	0.00	13.97	12.92	n/a	n/a	14.27	17.12	13.05
	Soybean	10.66	14.06	11.54	12.64	9.32	14.50	14.53	n/a	10.80	16.80	16.80	14.32
	Wheat	10.74	5.75	11.65	2.28	8.15	14.30	13.21	n/a	10.81	15.00	17.26	12.08
South + Central America	Maize	14.36	14.01	19.50	1.74	14.66	19.21	14.26	12.86	25.78	13.06	17.85	13.99
	Potatoes	10.29	7.61	9.56	1.76	9.32	19.90	14.45	9.60	0.62	14.26	16.42	12.36
	Soybean	14.36	14.46	23.35	2.09	11.82	14.09	14.39	11.96	n/a	15.72	15.25	13.83
	Wheat	10.95	11.36	7.28	1.68	9.32	21.27	14.27	9.77	17.42	15.37	17.23	13.22

Table II
Yield Classes for the Selected Crops and Their Mid-Points (in parentheses) Used to Calculate Mean Weighted Potential Yields (in Mg ha^{-1})

	Maize	Millet	Potatoes	Sorghum	Soybeans	Wheat
Low	0.5–1.0 (0.75)	0.5–1.0 (0.75)	5.0–20.0 (12.5)	0.5–1.0 (0.75)	$<$0.5 (0.25)	0.5–1.5 (1.0)
Medium	1.0–3.0 (2.0)	1.0–2.0 (1.5)	20.0–40.0 (30.0)	1.0–2.0 (1.5)	0.5–2.0 (1.25)	1.5–2.5 (2.0)
High	3.0–6.0 (4.5)	2.0–3.0 (2.5)	40.0–60.0 (50.0)	2.0–4.0 (3.0)	2.0–4.0 (3.0)	2.5–4.0 (3.25)
Very high	$>$6.0 (6.0)	$>$3.0 (3.0)	$>$60.0 (60.0)	$>$4.0 (4.0)	$>$4.0 (4.0)	$>$4.0 (4.0)

adjusted the potential area of each crop to the 1998–2000 average harvested area of that crop within each continent as reported in FAO (2000). Furthermore, since FAO statistics do not disaggregate production data by soil order, it was necessary also to devise a way to estimate how actual production areas for the selected crops are distributed across soil orders. This was done as follows. We assumed that there would be a close correlation between the amount of land within a soil order potentially suitable for the selected crops and the actual amount of land devoted to these crops. Using the relative distribution of land potentially suitable for the selected crops across the 11 soil orders (Gelisols were omitted from all our analyses, as they are not suitable for crop production), we estimated the areas of these crops in each soil order and continent by multiplying the percentage of potential cropland in each soil order with the 1998–2000 mean harvested areas of these crops (FAO, 2000). The area of land in all four yield classes for each crop was added together, regardless of the potential yields. The results of these calculations are given in Table III; some soil orders are not found on some continents, as indicated by the 'not applicable' (n/a) in the table. Non-potential for a particular crop on a specific soil order is indicated by n/p in Table III. The estimated areas of the selected crops in each order in Table III will be used for our calculations of crop losses and their economic value.

D. Crop Yield Estimation

Similar to production areas for various crops, global production statistics (e.g. FAO, World Bank) do not disaggregate crop yields by soil order. In Section II.C, we described how potential crop production areas were determined, and explained how we adjusted the potential area to estimate production areas for each crop within each soil order. Using the potential production areas in each soil order and the midpoints of the yields classes (number in parentheses in Table II) we determined the weighted potential mean yield for each crop in each soil order and continent as follows:

$$\overline{Y_{wp}} = \frac{\sum_{c=1}^{n} A_{pc} \times \overline{Y_c}}{A_{tp}} \tag{2}$$

where $\overline{Y_{wp}}$ is the weighted potential mean yield (Mg ha^{-1}); A_{pc} is potential production area in the yield class (ha); $\overline{Y_c}$ is the mean yield in the yield class (Mg ha^{-1}); and A_{tp} is the total potential production area (ha).

We also calculated the aggregate weighted potential mean yields across soil orders for each continent, and compared these yields with the 1998–2000 mean yields (FAO, 2000) for the selected crops. Since the actual mean yields reported in FAO (2000) differed substantially from the potential mean yields obtained through our calculations, we decided to normalize the potential weighted mean

Table III

Areas in Selected Crops by Soil Order and Continent (10^3 ha) Estimated from FAO (2000) Harvested Areas and the Relative Distribution of Land Potentially Suitable for the Production of those Crops (= Potential Area). Total Cropland Area (10^3 ha) According to IGBP Listed for Comparative Purposes

			Alfisols	Andisols	Aridisols	Entisols	Histosols	Inceptisols	Mollisols	Oxisols	Spodosols	Ultisols	Vertisols	Total[a]
Africa	IGBP cropland		45,248.1	1,657.1	742.8	36,920.0	276.1	38,737.2	3,097.5	36,909.4	n/a	35,994.6	11,476.5	211,059.3
	Maize	Pot. Area[b] (%)	33.70%	0.74%	0.17%	5,66%	0.00%	15.41%	0.72%	0.88%	n/a	36.27%	6.45%	100.0%
		Est. Area[b] (ha)	8,567.4	187.3	42.5	1,438.8	0.4	3,917.3	182.1	223.9		9,220.6	1,639.4	25,419.7
Asia	IGBP cropland		94,652.0	7,985.1	8,702.5	109,400.7	6,657.9	230,374.1	42,052.4	5,311.2	2,401.7	191,227.5	59,675.1	758,440.3
	Maize	Pot. Area (%)	14.03%	0.62%	0.03%	4.52%	0.05%	20.70%	5.62%	0.04%	0.00%	46.37%	8.02%	100.0%
		Est. Area (ha)	6,056.8	266.5	11.4	1,952.4	22.3	8,937.3	2,425.6	19.2	1.4	20,021.3	3,462.5	43,176.8
	Millet	Pot. Area (%)	35.07%	0.05%	0.04%	3.29%	0.02%	19.20%	0.02%	0.01%	n/p	15.88%	26.42%	100.0%
		Est. Area (ha)	5,164.4	7.7	5.3	484.6	3.4	2,827.2	3.6	2.1		2,338.2	3,891.0	14727.4
	Soybeans	Pot. Area (%)	25.41%	1.67%	0.01%	3.47%	0.01%	0.79%	1.69%	0.00%	n/p	56.37%	10.57%	100.0%
		Est. Area (ha)	4,251.3	279.0	1.9	581.1	1.6	132.0	283.5	0.7		9,429.1	1,768.3	16,728.5
	Wheat	Pot. Area (%)	21.58%	2.27%	0.06%	6.78%	0.01%	33.59%	20.02%	0.01%	n/p	6.16%	9.54%	100.0%
		Est. Area (ha)	21,304.9	2,236.0	58.6	6,692.9	10.1	33,152.8	19,757.6	9.6		6,076.3	9,412.7	98,711.7
Australia	IGBP cropland		37,109.5	13.5	5,092.3	3,563.0	24.6	1,951.2	3,400.9	160.5	1,411.0	722.6	6,423.9	59,872.9
	Potatoes	Pot. Area (%)	66.13%	0.62%	1.05%	0.94%	n/p	10.65%	6.90%	0.21%	5.62%	5.65%	2.23%	100.0%
		Est. Area (ha)	36.8	0.3	0.6	0.5		5.9	3.8	0.1	3.1	3.1	1.2	55.7
	Wheat	Pot. Area (%)	49.54%	0.46%	1.23%	0.71%	n/p	7.74%	5.19%	0.15%	0.12%	2.21%	32.65%	100.0%
		Est. Area (ha)	5,698.0	52.8	141.8	81.8		889.8	597.5	17.4	13.4	253.9	3,755.9	11,502.3

(*continued*)

Table III (*continued*)

			Alfisols	Andisols	Aridisols	Entisols	Histosols	Inceptisols	Mollisols	Oxisols	Spodosols	Ultisols	Vertisols	Total[a]
Europe	IGBP cropland		203,776.1	653.7	3,015.0	43,757.1	11,744.3	136,211.9	127,566.5	650.9	24,398.7	630.1	4,894.4	557,298.7
	Potatoes	Pot. Area (%)	23.58%	1.38%	0.01%	5.25%	0.10%	16.38%	28.42%	0.00%	24.00%	0.05%	0.82%	100.0%
		Est. Area (ha)	2,162.1	126.7	1.3	481.3	9.6	1,501.2	2,605.0	0.2	2,199.8	4.8	75.5	9,167.3
	Millet	Pot. Area (%)	47.82%	n/p	0.23%	15.11%	0.07%	33.35%	0.02%	0.97%	n/p	0.40%	2.04%	100.0%
		Est. Area (ha)	617.3		3.0	195.0	0.9	430.5	0.2	12.5		5.2	26.3	1,290.7
	Soybeans	Pot. Area (%)	51.63%	0.24%	n/p	6.93%	0.05%	0.78%	37.41%	0.04%	0.14%	0.59%	2.19%	100.0%
		Est. Area (ha)	631.1	3.0		84.7	0.6	9.5	457.3	0.5	1.7	7.2	26.8	1,222.4
	Wheat	Pot. Area (%)	47.13%	1.39%	0.01%	5.59%	0.10%	15.54%	28.62%	n/p	0.10%	0.00%	1.50%	100.0%
		Est. Area (ha)	27,229.8	800.6	8.2	3,230.4	59.0	8,980.3	16,536.9		57.2	1.1	868.6	57,772.0
	IGBP cropland		54,168.6	282.9	896.1	9,182.0	2,311.1	12,594.0	86,023.9	n/a	10,446.2	18,832.7	4,000.7	198,738.2
North America	Maize	Pot. Area (%)	26.15%	0.04%	0.03%	0.86%	0.00%	11.73%	39.39%	n/a	0.05%	20.74%	1.01%	100.0%
		Est. Area (ha)	7,832.5	13.1	10.1	258.5	0.4	3,513.5	11,799.3		14.1	6,212.3	301.6	29,955.5
	Potatoes	Pot. Area (%)	28.34%	2.93%	0.07%	0.62%	0.04%	5.13%	30.69%	n/a	27.57%	4.05%	0.56%	100.0%
		Est. Area (ha)	200.1	20.7	0.5	4.4	0.3	36.2	216.7		194.7	28.6	3.9	706.1
	Sorghum	Pot. Area (%)	32.23%	0.08%	0.06%	3.65%	0.00%	2.06%	44.07%	n/a	n/p	12.92%	4.94%	100.0%
		Est. Area (ha)	1,068.7	2.7	1.9	121.0	0.1	68.2	1,461.2			428.4	163.9	3,315.9
	Soybeans	Pot. Area (%)	26.05%	0.04%	0.02%	0.10%	0.00%	0.27%	38.07%	n/a	0.02%	32.65%	2.77%	100.0%
		Est. Area (ha)	7,871.0	13.6	6.2	28.8	0.2	80.9	11,502.7		6.9	9,863.9	836.8	30,211.1

	Wheat	Pot. Area (%)	40.16%	3.99%	0.09%	0.84%	0.04%	5.69%	41.93%	n/a	0.08%	5.52%	1.66%	100.0%
		Est. Area (ha)	13,223.0	1,313.3	29.7	276.3	12.7	1,874.9	13,804.8		26.5	1,818.2	545.2	32,924.6
	IGBP cropland		87,582.1	7,673.0	846.3	59,456.9	957.2	69,506.6	50,264.1	151,113.0	1.1	76,620.2	11,659.4	515,680.0
South+ Central America	Maize	Pot. Area (%)	25.28%	2.04%	0.17%	5.07%	0.02%	12.35%	18.48%	1.08%	0.00%	32.15%	3.36%	100.0%
		Est. Area (ha)	6,793.5	549.4	46.8	1,362.1	4.5	3,317.5	4,964.2	289.0	0.2	8,637.7	903.5	26,868.4
	Potatoes	Pot. Area (%)	24.37%	11.81%	0.15%	6.50%	0.00%	12.73%	42.12%	0.47%	0.82%	0.58%	0.45%	100.0%
		Est. Area (ha)	268.7	130.2	1.6	71.7	0.0	140.4	464.3	5.2	9.0	6.4	5.0	1,102.5
	Soybeans	Pot. Area (%)	47.53%	2.40%	0.24%	5.17%	0.00%	0.98%	33.66%	0.79%	n/p	2.38%	6.84%	100.0%
		Est. Area (ha)	10,923.2	551.9	55.2	1,189.2	0.3	225.3	7,735.4	180.8		547.7	1,571.6	22,980.4
	Wheat	Pot. Area (%)	18.69%	9.48%	0.16%	8.22%	0.00%	10.34%	49.62%	0.36%	0.04%	0.60%	2.48%	100.0%
		Est. Area (ha)	1,632.9	828.3	14.4	718.3	0.1	903.6	4,336.0	31.5	3.3	52.4	217.0	8,737.6

n/a, Soil order not represented on a continent; n/p, Soil order without potential for production of the selected crop.
[a]For the selected crops total areas are equal to the 1998–2000 mean harvested areas reported in FAO (2000).
Pot. Area = Potential Area; Est. Area = Estimated Area.

yields around the actual mean yield reported by FAO in order to make better estimations of crop losses and their value. We assumed that if the potential yield of a crop is high on a particular soil order, actual yield will in all likelihood also be high and contribute a greater share to the actual overall continental mean yield than soil orders with low potential mean yields. The normalization was done as shown in Equation (3):

$$Y_{no} = \frac{Y_{po}}{\overline{Y_{wp}}} \times \overline{Y_{FAO}} \qquad (3)$$

where Y_{po} and Y_{no} are the potential and normalized yield (Mg ha^{-1}) in a soil order, respectively. The calculated weighted potential mean yields and the normalized yields are given in Table IV; the normalized yields will be used in our calculations of crop losses below.

In order to verify the accuracy of the estimated crop areas by soil order and normalized yields obtained in the procedures outlined in Sections II.C and II.D above, we multiplied estimated area data with the normalized mean yields to determine total production of the selected crops by soil order and continent. We then compared the results with the 1998–2000 average total production reported in FAO (2000). The deviation between estimated and actual production amounts is given as a percentage (plus or minus) in Table V. With the exception of millet in Africa, Asia and Europe, and wheat in North America, the deviations between actual (FAO) and estimated production were $\leq 1.0\%$. This may not be surprising given that the potential yield and area data were adjusted to FAO statistics. Nevertheless, using the adjusted numbers led to an overestimation of millet production of 7.07, 13.36, and 10.45% in Africa, Asia, and Europe, respectively, and an underestimation of 13.11% for wheat production in North America. The reasons for these deviations is not clear, but we speculate it may be due to disproportionate allocation of land in soil orders of lower or higher yielding potential to those crops using the above outlined procedure. Nevertheless, given the absence of any soil-based data on crop areas and yields outside the United States and the small deviations in production estimated form derived data for most crops and continents, we feel that the procedure enables one to obtain reasonably accurate estimations of yields and crop area by soil order.

E. Data Analysis

To estimate the annual amount of production loss due to water-induced soil erosion, we used four types of data:

1. average relative yield declines for the respective crops and soil orders across experimental methods calculated form the review of soil erosion–soil

Table IV
Potential and Normalized Crop Yields (Mg ha^{-1}) by Soil Order and Continent

			Alfisols	Andisols	Aridisols	Entisols	Histosols	Inceptisols	Mollisols	Oxisols	Spodosols	Ultisols	Vertisols	Mean
Africa	Maize	Potential yield	4.64	2.62	4.18	2.74	1.48	1.68	4.49	1.90	n/a	0.79	1.00	2.40
		Normalized yield	3.13	1.77	2.82	1.85	1.00	1.13	3.03	1.28		0.53	0.68	1.62
Asia	Maize	Potential yield	5.18	2.93	4.09	3.93	1.09	2.11	4.64	0.80	0.75	1.42	1.34	2.39
		Normalized yield	8.12	4.59	6.42	6.17	1.71	3.30	7.29	1.25	1.18	2.22	2.10	3.75
	Millet	Potential yield	1.91	1.95	2.09	2.76	2.64	0.98	2.20	2.27	n/p	2.53	1.62	1.78
		Normalized yield	0.92	0.94	1.01	1.33	1.28	0.47	1.06	1.10		1.22	0.78	0.86
	Soybeans	Potential yield	0.75	1.56	0.51	2.57	0.93	1.41	1.87	0.38	n/p	2.17	1.90	1.77
		Normalized yield	0.59	1.23	0.40	2.03	0.74	1.12	1.48	0.30		1.71	1.50	1.40
	Wheat	Potential yield	1.99	1.03	2.81	3.27	1.64	3.08	3.48	2.35	n/p	2.26	3.08	2.84
		Normalized yield	1.81	0.94	2.55	2.97	1.49	2.80	3.16	2.13		2.06	2.80	2.58
Australia	Potatoes	Potential yield	51.03	12.50	53.19	48.07	n/a	49.60	50.85	47.37	49.99	27.80	41.88	49.04
		Normalized yield	34.96	8.56	36.44	32.94		33.99	34.84	32.46	34.25	19.05	28.69	33.60
	Wheat	Potential yield	2.58	1.00	3.11	2.73	n/a	3.19	3.32	1.86	3.01	2.33	3.19	2.86
		Normalized yield	1.78	0.69	2.15	1.89		2.21	2.30	1.29	2.09	1.61	2.21	1.98
Europe	Potatoes	Potential yield	51.96	28.00	40.04	49.04	48.66	43.34	52.36	12.50	50.00	30.15	46.69	49.65
		Normalized yield	15.63	8.42	12.04	14.75	14.63	13.03	15.74	3.76	15.03	9.07	14.04	14.93
	Millet	Potential yield	2.32	n/p	1.02	2.88	2.83	1.02	2.50	2.63	n/p	2.00	2.24	1.78
		Normalized yield	1.07		0.47	1.33	1.30	0.47	1.15	1.21		0.92	1.03	0.82
	Soybeans	Potential yield	2.79	1.85	n/p	2.92	3.08	2.88	1.77	0.79	2.98	2.24	1.44	2.38
		Normalized yield	2.22	1.47		2.32	2.45	2.29	1.41	0.63	2.37	1.78	1.14	1.89
	Wheat	Potential yield	2.02	2.16	2.75	3.24	2.01	2.80	3.62	n/p	2.68	2.12	3.12	2.69
		Normalized yield	2.36	2.52	3.21	3.78	2.35	3.26	4.23		3.12	2.48	3.65	3.14

(continued)

Table IV (*continued*)

			Alfisols	Andisols	Aridisols	Entisols	Histosols	Inceptisols	Mollisols	Oxisols	Spodosols	Ultisols	Vertisols	Mean
North America	Maize	Potential yield	5.39	3.30	4.82	4.63	5.10	2.14	5.58	n/a	4.07	1.98	2.08	4.34
		Normalized yield	10.74	6.57	9.60	9.23	10.16	4.27	11.13		8.10	3.95	4.15	8.65
	Potatoes	Potential yield	50.09	33.72	55.94	38.51	51.89	41.88	52.87	n/a	49.98	21.92	31.32	48.70
		Normalized yield	37.74	25.40	42.14	29.01	39.09	31.55	39.83		37.65	16.51	23.60	36.69
	Sorghum	Potential yield	3.62	3.00	3.51	3.11	3.00	1.72	3.94	n/a	n/a	1.50	1.56	3.32
		Normalized yield	4.53	3.76	4.39	3.90	3.76	2.15	4.93			1.88	1.96	4.16
	Soybeans	Potential yield	3.28	0.72	1.37	2.11	3.00	2.71	2.47	n/a	3.60	2.52	1.62	2.67
		Normalized yield	3.17	0.69	1.32	2.04	2.90	2.62	2.39		3.48	2.44	1.56	2.58
	Wheat	Potential yield	2.32	2.45	2.53	2.47	1.59	2.97	3.61	n/a	2.62	2.00	2.25	3.32
		Normalized yield	1.92	2.02	2.09	2.04	1.31	2.45	2.98		2.16	1.65	1.85	2.74
Central + South America	Maize	Potential yield	4.61	2.78	4.30	4.00	0.89	1.74	5.66	2.17	0.75	0.84	1.14	3.02
		Normalized yield	4.24	2.56	3.96	3.68	0.82	1.60	5.21	2.00	0.69	0.77	1.05	2.78
	Potatoes	Potential yield	27.22	20.62	48.62	53.38	12.50	45.89	52.50	14.20	50.03	26.23	35.46	41.35
		Normalized yield	9.72	7.37	17.37	19.07	4.46	16.39	18.75	5.07	17.87	9.37	12.67	14.77
	Soybeans	Potential yield	0.89	2.30	0.52	1.99	0.74	1.00	2.66	0.94	n/p	1.30	2.48	1.70
		Normalized yield	1.25	3.24	0.73	2.80	1.04	1.40	3.74	1.32		1.83	3.49	2.39
	Wheat	Potential yield	1.99	1.81	3.23	3.53	1.00	3.18	3.45	1.16	3.32	2.16	2.93	2.97
		Normalized yield	1.67	1.51	2.71	2.96	0.84	2.67	2.89	0.98	2.78	1.81	2.46	2.49

n/a, not applicable (soil order not found on a continent); n/p, no potential for that crop on a soil order. Potential yield is the weighted average potential yield calculated from yield classes and potential crop production areas. Normalized yield is the potential yield adjusted around the 1998–2000 average mean yield reported in FAO (2000).

Table V
Deviation Between Actual Production Statistics from FAO (2000) and Calculated Production Using Normalized Yields and Estimated Production Area by Soil Order

		Actual Production (10^3 Mg)	Calculated production (10^3 Mg)	Deviation (%)
Maize	Africa	41,198.1	41,227.5	0.07%
	Asia	162,288.9	161,585.7	−0.43%
	North America	259,121.8	258,939.8	−0.07%
	Central + South America	74,608.3	74,762.5	0.21%
Potatoes	Australia	1,872.0	1,871.5	−0.03%
	Europe	136,831.9	136,858.4	0.02%
	North America	25,903.0	25,906.3	0.01%
	Central + South America	16,281.4	16,328.2	0.29%
Sorghum/millet	Asia	12,692.7	14,387.9	13.36%
	Europe	1,059.8	1,170.5	10.45%
	North America	13,810.9	13,809.7	−0.01%
Soybeans	Asia	23,492.6	23,430.7	−0.26%
	Europe	2,313.8	2,313.9	0.00%
	North America	77,878.5	78,058.8	0.23%
	Central + South America	55,425.5	54,784.8	−1.16%
Wheat	Asia	254,338.3	254,983.3	0.25%
	Australia	22,739.0	22,746.1	0.03%
	Europe	181,517.3	181,288.9	−0.13%
	North America	90,360.1	78,510.9	−13.11%
	Central + South America	21,719.9	21,768.3	0.22%

Table VI

Summary of the Relative Water Erosion Induced Yield Declines of the Selected Crops by Continent and Soil Order, (the Number in Parentheses Refers to the Number of Records on Which the Yield Declines are Based (for details, see Tables III–V in den Biggelaar *et al*. (this volume)

		Alfisols	Aridisols	Entisols	Inceptisols	Mollisols	Oxisols	Spodosols	Ultisols	Vertisols	Weighted mean
Africa	Maize	0.04% (24)	n/a	n/a	0.01% (3)	n/a	0.01% (5)	n/a	0.05% (9)	n/a	0.03%
Asia	Maize	n/a	0.04% (2)	n/a	0.05% (2)	n/a	n/a	n/a	n/a	n/a	0.04%
	Millet	0.03% (2)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.03%
	Soybeans	n/a	n/a	n/a	0% (1)	n/a	0.04% (2)	n/a	n/a	−0.22% (1)	−0.05%
	Wheat	n/a	0.02% (2)	n/a	0.02% (2)	n/a	n/a	n/a	n/a	n/a	0.02%
Australia	Potatoes	n/a	0.01% (1)	n/a	n/a	n/a	n/a	n/a	0% (1)	n/a	0.01%
	Wheat	0.05% (8)	0.02% (3)	n/a	n/a	n/a	n/a	n/a	n/a	0.04% (5)	0.04%
Europe	Potatoes	0.001% (1)	n/a	n/a	n/a	0.01% (1)	n/a	n/a	n/a	n/a	0.00%
	Millet	n/a	n/a	n/a	n/a	0.02% (2)	n/a	n/a	n/a	n/a	0.02%
	Soybeans	n/a	n/a	n/a	n/a	0.02% (1)	n/a	n/a	n/a	n/a	0.02%
	Wheat	0% (1)	n/a	0% (1)	n/a	0.01% (6)	n/a	n/a	n/a	n/a	0.00%
North America	Maize	0.01% (66)	n/a	0.005% (1)	n/a	0.01% (50)	0.02% (2)	n/a	0.02% (12)	n/a	0.01%
	Potatoes	n/a	0% (1)	n/a	1.09% (1)	n/a	n/a	0.78% (1)	n/a	n/a	0.42%
	Sorghum	n/a	n/a	n/a	n/a	0.01% (13)	n/a	n/a	−0.01% (4)	n/a	0.00%
	Soybeans	0.01% (21)	n/a	0.03% (1)	0.02% (1)	0.01% (6)	n/a	n/a	0.03% (13)	n/a	0.01%
	Wheat	0.01% (4)	0.01% (2)	n/a	n/a	0.01% (56)	n/a	n/a	n/a	n/a	0.01%
Central + South America	Maize	0.01% (2)	n/a	0.01% (2)	0.33% (1)	0.07% (1)	0.03% (9)	n/a	n/a	n/a	0.05%
	Potatoes	n/a	n/a	0.001% (1)	n/a	n/a	n/a	n/a	n/a	n/a	0.001%
	Soybeans	n/a	n/a	n/a	n/a	0.02% (1)	0.03% (3)	n/a	n/a	n/a	0.03%
	Wheat	n/a	n/a	n/a	n/a	0.02% (1)	n/a	n/a	n/a	n/a	0.02%

productivity studies (see den Biggelaar *et al*., this volume). Table VI summarizes the relative yield declines for the selected crops by soil order and continent;
2. the crop specific estimated mean annual erosion rates for various soil orders by continent (see II.B);
3. the estimated area of various crops by soil order and continent (see II.C); and
4. the normalized mean crop yields by soil order and continent (see II.D).

To estimate soil-based production losses due to erosion-induced productivity declines, soil orders for which there are no crop-specific soil erosion productivity studies within a continent are assigned the weighted mean relative yield decline of the studies reviewed in Part I (den Biggelaar *et al*., this volume). However, if there were no studies for a selected crop in a continent, no production loss estimates were attempted. The mean relative yield declines used in our production loss calculations for soil orders for which there were no specific studies are listed in the last column in Table VI.

The following equations (Equations 4–7) show the calculations made to determine annual production losses for each soil order:

$$L_a = L \times \overline{E_{wp}} \tag{4}$$

where L_a is the relative annual yield loss (% yr^{-1}) and L is the relative yield loss per Mg of soil erosion (% Mg^{-1}). We will use the crop-specific mean annual erosion rates by soil order provided in Table I in our calculations.

$$C = L_a \times \overline{Y_n} \tag{5}$$

where C is crop loss (Mg ha^{-1} yr^{-1}), the normalized mean yield (Mg ha^{-1}), T the total production loss (Mg yr^{-1}); and A_e the estimated crop area (ha).

$$T = C \times A_e \tag{6}$$

To aggregate production losses across crops, we multiplied the annual production loss estimates for each crop, soil order, and continent by the 2000/01 crop prices from the USDA Agricultural Baseline Projections to 2010 (USDA, 2001).

$$V = T \times P \tag{7}$$

Where V is the value of production lost (\$ yr^{-1}), and P the price (\$ Mg^{-1}).

IV. RESULTS

A. Maize

The mean relative yield losses of maize range from 0.15% yr^{-1} in North America to 0.94% yr^{-1} in Central and South America. Losses in Africa and Asia are intermediate at 0.49 and 0.59% yr^{-1}, respectively. In Africa, the highest relative yield losses occur on Alfisols, Vertisols and Ultisols at 0.56. 0.56 and 0.60% yr^{-1}, respectively (Table VII). Relative yield losses are lowest on Entisols (0.07% yr^{-1}) due to the low erosion rate of these soils (estimated at 2.46 Mg ha^{-1} yr^{-1}). Many of the Entisols are on valley floors and instead of soil loss, there is soil gain through sedimentation. Despite low erosion induced yield losses on Inceptisols and Oxisols in Africa (0.01% ha^{-1} yr^{-1}), relative annual yield losses are somewhat greater (0.19 and 0.12% yr^{-1}, respectively) as a result of higher erosion rates. The loss in maize production in Africa is estimated at about 200,000 Mg yr^{-1}, with about two-thirds of these losses being realized on Alfisols and about 14.5% on Ultisols.

Relative yield losses for maize in Asia were estimated to be $\geq$0.5% yr^{-1} on all soil orders except Entisols (Table VII). On Entisols, relative yield losses were estimated at 0.07% yr^{-1} as a result of its low estimated erosion rate of 1.80 Mg ha^{-1} yr^{-1}. The highest yield loss occurred on Inceptisols (0.94% yr^{-1}). Relative annual yield losses were also high on Vertisols (0.74% yr^{-1}), Histosols (0.66% yr^{-1}), Oxisols (0.63% yr^{-1}), and Ultisols (0.60% yr^{-1}). Total production losses of maize in Asia were estimated to be about 960,000 Mg yr^{-1}, about 57% of which were lost on Inceptisols and Ultisols, and 25% on Alfisols (Table VII).

Although the mean relative annual production losses in North America were fairly low at 0.15% yr^{-1} (Table XII), losses were significant in several soil orders. Relative annual production losses were at or below the average on Alfisols, Andisols, Aridisols, Entisols, Histosols, and Mollisols, but were greater than average on Inceptisols, Spodosols, Ultisols, and Vertisols at 0.24, 0.16, 0.33, and 0.17% yr^{-1}, respectively. The total loss of maize production in North America was estimated at 400,000 Mg yr^{-1}, comprising 46% on Mollisols (200×10^3 Mg yr^{-1}) and 24% on Alfisols (100×10^3 Mg yr^{-1}) (Table VII).

The relative annual yield losses for maize in Central and South America were more than 0.5% per year on almost all soil orders. The exceptions are Entisols, Alfisols, and Oxisols at 0.02, 0.14, and 0.39% yr^{-1}, respectively (Table VII). Relative annual yield losses of >1% yr^{-1} were found for Aridisols, Mollisols, Spodosols, and Inceptisols at 0.98, 1.0, 1.29, and 6.34% yr^{-1}, respectively (Table VII). The very high relative production losses on Inceptisols (6.34% yr^{-1}) are a result of both the high erosion rates on these soils (estimated at 19.21 Mg ha^{-1} yr^{-1}), and the high erosion-induced yield declines reported in erosion–productivity studies on these soils. Although only about 12% of total maize area in Central and South America is grown on Inceptisols, erosion on these soils contribute 48% of total crop loss of maize about 700,000 Mg yr^{-1} in this continent. The 1.29% yr^{-1} production loss of maize on Spodosols is less problematic, since only about 200 ha of these soils is estimated to being used for maize production. Relative and absolute production losses of maize on Mollisols are 1.0% yr^{-1} and 258 Mg yr^{-1}, respectively; the absolute production loss is

TableVII
Estimated Absolute and Relative Annual Losses in Maize Production by Continent and Soil Order

		Erosion-induced yield loss (% Mg^{-1})	Crop-specific estimated erosion rate (Mg ha^{-1} yr^{-1})	Relative annual yield loss (% yr^{-1})	Normalized yield (Mg ha^{-1})	Estimated production area (10^3 ha)	Total Production (10^3 Mg)	Production loss (10^3 Mg yr^{-1})
Africa	Alfisols	0.04%	14.10	0.56%	3.13	8,567.4	26,812.0	151.3
	Andisols	0.03%	13.77	0.41%	1.77	187.3	331.4	1.4
	Aridisols	0.03%	17.17	0.52%	2.82	42.5	119.9	0.6
	Entisols	0.03%	2.46	0.07%	1.85	1,438.8	2,657.2	2.0
	Histosols	0.03%	12.52	0.38%	1.00	0.4	0.4	0.0
	Inceptisols	0.01%	18.75	0.19%	1.13	3,917.3	4,441.7	8.3
	Mollisols	0.03%	16.58	0.50%	3.03	182.1	552.4	2.7
	Oxisols	0.01%	12.21	0.12%	1.28	223.9	287.3	0.4
	Ultisols	0.05%	11.97	0.60%	0.53	9,220.6	4,915.9	29.4
	Vertisols	0.03%	18.62	0.56%	0.68	1,639.4	1,109.3	6.2
	Total					25,419.7	41,227.5	202.2
Asia	Alfisols	0.04%	12.58	0.50%	8.12	6,056.8	49,180.4	247.5
	Andisols	0.04%	13.21	0.53%	4.59	266.5	1,223.2	6.5
	Aridisols	0.04%	11.50	0.46%	6.42	11.4	73.2	0.3
	Entisols	0.04%	1.80	0.07%	6.17	1,952.4	12,053.6	8.7
	Histosols	0.04%	16.45	0.66%	1.71	22.3	38.1	0.3
	Inceptisols	0.05%	18.87	0.94%	3.30	8,937.3	29,521.8	278.5
	Mollisols	0.04%	13.67	0.55%	7.29	2,425.6	17,672.5	96.6
	Oxisols	0.04%	15.77	0.63%	1.25	19.2	24.0	0.2
	Spodosols	0.04%	14.46	0.58%	1.18	1.4	1.7	0.0
	Ultisols	0.04%	15.09	0.60%	2.22	20,021.3	44,511.7	268.7
	Vertisols	0.04%	18.55	0.74%	2.10	3,462.5	7,285.5	54.0
	Total					43,176.8	161,585.7	961.2

(*continued*)

TableVII (*continued*)

		Erosion-induced yield loss (% Mg^{-1})	Crop-specific estimated erosion rate ($Mg\ ha^{-1}\ yr^{-1}$)	Relative annual yield loss (% yr^{-1})	Normalized yield ($Mg\ ha^{-1}$)	Estimated production area (10^3 ha)	Total Production (10^3 Mg)	Production loss ($10^3\ Mg\ yr^{-1}$)
North America	Alfisols	0.01%	11.44	0.11%	10.74	7,832.5	84,133.4	96.2
	Andisols	0.01%	12.75	0.13%	6.57	13.1	86.1	0.1
	Aridisols	0.01%	12.55	0.13%	9.60	10.1	96.8	0.1
	Entisols	0.01%	1.97	0.01%	9.23	258.5	2,387.0	0.2
	Histosols	0.01%	10.61	0.11%	10.16	0.4	4.5	0.0
	Inceptisols	0.01%	24.00	0.24%	4.27	3,513.5	15,008.4	36.0
	Mollisols	0.01%	13.87	0.14%	11.13	11,799.3	131,327.1	182.2
	Spodosols	0.01%	15.85	0.16%	8.10	14.1	114.4	0.2
	Ultisols	0.02%	16.73	0.33%	3.95	6,212.3	24,530.5	82.1
	Vertisols	0.01%	17.31	0.17%	4.15	301.6	1,251.5	2.2
	Total					29,955.5	258,939.8	399.3
Central + South America	Alfisols	0.01%	14.36	0.14%	4.24	6,793.5	28,801.5	41.4
	Andisols	0.05%	14.01	0.70%	2.56	549.4	1,405.9	9.8
	Aridisols	0.05%	19.50	0.98%	3.96	46.8	185.1	1.8
	Entisols	0.01%	1.74	0.02%	3.68	1,362.1	5,018.7	0.9
	Histosols	0.05%	14.66	0.73%	0.82	4.5	3.7	0.0
	Inceptisols	0.33%	19.21	6.34%	1.60	3,317.5	5,323.2	337.5
	Mollisols	0.07%	14.26	1.00%	5.21	4,964.2	25,851.9	258.1
	Oxisols	0.03%	12.86	0.39%	2.00	289.0	577.4	2.2
	Spodosols	0.05%	25.78	1.29%	0.69	0.2	0.1	0.0
	Ultisols	0.05%	13.06	0.65%	0.77	8,637.7	6,648.2	43.4
	Vertisols	0.05%	17.85	0.89%	1.05	903.5	946.8	8.4
	Total					26,868.4	74,762.5	703.6

about 37% of the total maize production loss due to erosion in Central and South America (Table VII).

B. Millet and Sorghum

Studies on the effect erosion on millet yields were carried out in Asia and Europe, whereas studies using sorghum were undertaken only in the United States. It should be noted, though, that very few studies on erosion-induced soil productivity declines have been undertaken using millet (two each in Europe and Asia) or sorghum (17 records in the US) as an indicator crop, the results presented below should therefore be interpreted with caution and not taken as absolutes. However, they do provide an indication of the seriousness of the problem and, especially for millet, should be used only to identify the primary soil orders used for its production as priority areas to reduce erosion.

Mean relative annual yield losses on millet were estimated at 0.51 and 0.23% yr^{-1} in Asia and Europe, respectively. The relative annual yield loss of millet in Asia ranges from 0.03% yr^{-1} on Entisols to 0.58% yr^{-1} on Aridisols. Millet in Asia is grown primarily on, in order of importance, Inceptisols, Ultisols, Entisols, Alfisols, and Vertisols. Relative production losses on the these soils were estimated at 0.34, 0.43, 0.03, 0.42, and 0.56% yr^{-1}, respectively (Table VIII). Total production losses were estimated at about 64,000 Mg yr^{-1}, with most of the losses (42%) incurred on Vertisols. In spite of a much greater area of cropland in millet on Alfisols than on Vertisols, production losses on these soils (20.2 Mg yr^{-1} or 31% of the total losses) are lower due to the lower erosion rate (14.12 and 18.75 Mg ha^{-1} yr^{-1} on Alfisols and Vertisols, respectively) (Table VIII).

Millet is only a small crop in Europe, primarily produced in southern and Eastern Europe on about 1.3 Mha. Nearly half the millet area in Europe is grown on Alfisols, with about one-third of the area being on Inceptisols. The estimated average annual relative yield loss ranged from at 0.02% yr^{-1}on Entisols to 0.36% yr^{-1} on Histosols (Table VIII). Production loss of millet on this continent was estimates at 2,400 Mg yr^{-}, almost all of it due to erosion-induced production losses on Alfisols (75%) and a much smaller amount (17%) being contributed by losses on Inceptisols.

A review of erosion–productivity studies conducted on sorghum in North America showed relative erosion-induced yield declines of 0.01% Mg^{-1} on Mollisols. However, on Ultisols, yield increased by a similar percentage with increasing erosion. The mean relative yield loss in sorghum in North America was 0.06, 0.13% yr^{-1} on Millisols and −0.13% on Ultisols, with losses of less than 0.00% yr^{-1} for sorghum grown on other soil orders (Table VIII). The apparent beneficial effect of soil erosion on Ultisols is interesting and perhaps suggests the sensitivity of the model. The organic-rich surface layers are more

TableVIII
Estimated Absolute and Relative Annual Losses in the Production of Millet (Asia and Europe) and Sorghum (North America) by Continent and Soil Order

		Erosion-induced yield loss (% Mg^{-1})	Crop-specific estimated erosion rate ($Mg\ ha^{-1}\ yr^{-1}$)	Relative annual yield loss (% yr^{-1})	Normalized yield ($Mg\ ha^{-1}$)	Estimated production area (10^3 ha)	Total Production (10^3 Mg)	Production loss ($10^3\ Mg\ yr^{-1}$)
Asia	Alfisols	0.03%	14.12	0.42%	0.92	5,164.4	4,765.7	20.2
	Andisols	0.03%	12.20	0.37%	0.94	7.7	7.2	0.0
	Aridisols	0.03%	19.21	0.58%	1.01	5.3	5.4	0.0
	Entisols	0.03%	1.03	0.03%	1.33	484.6	646.2	0.2
	Histosols	0.03%	10.19	0.31%	1.28	3.4	4.3	0.0
	Inceptisols	0.03%	11.44	0.34%	0.47	2,827.2	1,338.6	4.6
	Mollisols	0.03%	17.17	0.52%	1.06	3.6	3.8	0.0
	Oxisols	0.03%	17.75	0.53%	1.10	2.1	2.3	0.0
	Ultisols	0.03%	14.45	0.43%	1.22	2,338.2	2,858.1	12.4
	Vertisols	0.03%	18.75	0.56%	0.78	3,891.0	4,756.2	26.8
	Total					14,727.4	14,387.9	64.2
Europe	Alfisols	0.02%	13.58	0.27%	1.07	617.3	659.7	1.8
	Aridisols	0.02%	11.86	0.24%	0.47	3.0	1.4	0.0
	Entisols	0.02%	0.89	0.02%	1.33	195.0	258.7	0.0
	Histosols	0.02%	18.09	0.36%	1.30	0.9	1.1	0.0

	Inceptisols	0.02%	10.98	0.22%	0.47	430.5	202.3	0.4
	Mollisols	0.02%	14.25	0.29%	1.15	0.2	0.3	0.0
	Oxisols	0.02%	11.13	0.22%	1.21	12.5	15.1	0.0
	Ultisols	0.02%	12.06	0.24%	0.92	5.2	4.8	0.0
	Vertisols	0.02%	15.87	0.32%	1.03	26.3	27.1	0.1
	Total					1,290.7	1,170.5	2.4
North America	Alfisols	0.00%	13.48	0.00%	4.53	1,068.7	4,841.6	0.0
	Andisols	0.00%	11.97	0.00%	3.76	2.7	10.2	0.0
	Aridisols	0.00%	11.50	0.00%	4.39	1.9	8.2	0.0
	Entisols	0.00%	0.57	0.00%	3.90	121.0	471.9	0.0
	Histosols	0.00%	0.00	0.00%	3.76	0.1	0.2	0.0
	Inceptisols	0.00%	13.97	0.00%	2.15	68.2	146.5	0.0
	Mollisols	0.01%	12.92	0.13%	4.93	1,461.2	7,205.8	9.3
	Ultisols	−0.01%	14.27	−0.14%	1.88	428.4	804.9	−1.1
	Vertisols	0.00%	17.12	0.00%	1.96	163.9	320.4	0.0
	Total					3,315.9	13,809.7	8.2

acid than sub-surface layers in Ultisols. Removal of the acid surface layers is beneficial to sorghum, which responds better. Similar site-specific processes also operate in other soils and crops respond differently. In Alfisols of the semi-arid regions, for example, the subsoil retains more moisture and nutrients than the lighter-textured surface soil. In some of these Alfisols, removal of the topsoil may have beneficial effects with respect to crop performance. The specific soil–crop relationships cannot be included in this global generalization, but must be considered in more detailed analysis. In North America, we estimate that about half the total area in sorghum is grown in Mollisols and about one-third on Alfisols. Although the production of sorghum increases by 1,100Mg yr^{-1} on Ultisols in spite of erosion, North America experiences a net decline in production of 8 200 Mg yr^{-1} due to the production losses of 9,300 Mg yr^{-1} incurred on Mollisols (Table VIII).

C. Potatoes

Erosion–productivity studies using potatoes were conducted in Australia, Europe, North America, and Central and South America. As shown in Part I of this review (den Biggelaar *et al*., this volume), observed erosion-induced yield losses for potatoes were very small in Australia, Europe, and Central and South America ($\leq$0.01% Mg^{-1} soil loss), but much larger in North America, especially on the Inceptisols on this continent. Mean relative annual yield losses of potatoes were small in Australia, Europe and Central and South America at 0.12, 0.04, and 0.01% yr^{-1}, respectively, but very large in North America at 3.98% yr^{-1}. Given that the number of studies having investigated the effect of erosion using potatoes is small (eight worldwide), these results may, therefore, not be an accurate reflection of the real impact of erosion on this crop.

The relative yield loss of potatoes in Australia ranged from 0.00% yr^{-1} on Spodosols and Ultisols to 0.22% yr^{-1} on Inceptisols (Table IX). On Alfisols, which make up 62% of Australia's cropland and 69% of the area in potatoes, the relative yield loss for potatoes was 0.12% yr^{-1}. The loss of potato production as a result of erosion amounts to about 2,300 Mg yr^{-1}, 69% of which is due to erosion-induced yield losses on Alfisols (Table IX). In Europe, we estimate that there are no relative production losses for potatoes on Entisols, Histosols, Spodosols and Ultisols, and very small losses of 0.01% yr^{-1} on Alfisols, Andisols, Aridisols and Mollisols and of 0.02% yr^{-1} on Inceptisols and Vertisols (Table IX). We calculated that the largest losses would occur on Mollisols at 0.11% yr^{-1}. Production losses on Mollisols contribute about 85% of the total annual production loss of 51,100 Mg yr^{-1} of potatoes in Europe (Table IX).

The mean relative yield losses of potatoes in North America are estimated to be high, ranging from 0.00% yr^{-1} on Aridisols to 12.66% yr^{-1} on Inceptisols. Most potatoes in North America are grown on Alfisols, Mollisols and Spodosols, with estimated yield declines of 4.68, 5.57, and 0.02% yr^{-1}, respectively. The low

Table IX
Estimated Absolute and Relative Annual Losses in Potato Production by Continent and Soil Order

		Erosion-induced yield loss (% Mg^{-1})	Crop-specific estimated erosion rate (Mg ha^{-1} yr^{-1})	Relative annual yield loss (% yr^{-1})	Normalized yield (Mg ha^{-1})	Estimated production area (10^3 ha)	Total Production (10^3 Mg)	Production loss (10^3 Mg yr^{-1})
Australia	Alfisols	0.01%	12.07	0.12%	34.96	36.8	1,287.9	1.6
	Andisols	0.01%	14.25	0.14%	8.56	0.3	3.0	0.0
	Aridisols	0.01%	10.58	0.11%	36.44	0.6	21.2	0.0
	Entisols	0.01%	8.12	0.08%	32.94	0.5	17.2	0.0
	Inceptisols	0.01%	22.37	0.22%	33.99	5.9	201.7	0.5
	Mollisols	0.01%	15.62	0.16%	34.84	3.8	133.9	0.2
	Oxisols	0.01%	12.83	0.13%	32.46	0.1	3.9	0.0
	Spodosols	0.01%	0.38	0.00%	34.25	3.1	107.2	0.0
	Ultisols	0.00%	6.98	0.00%	19.05	3.1	60.0	0.0
	Vertisols	0.01%	14.07	0.14%	28.69	1.2	35.7	0.1
	Total					55.7	1,871.5	2.3
Europe	Alfisols	0.00%	10.66	0.01%	15.63	2,162.1	33,783.3	3.6
	Andisols	0.00%	11.12	0.01%	8.42	126.7	1,066.2	0.1
	Aridisols	0.00%	12.60	0.01%	12.04	1.3	15.4	0.0
	Entisols	0.00%	0.95	0.00%	14.75	481.3	7,096.8	0.1
	Histosols	0.00%	3.61	0.00%	14.63	9.6	140.2	0.0
	Inceptisols	0.00%	18.13	0.02%	13.03	1,501.2	19,565.8	3.5
	Mollisols	0.01%	10.61	0.11%	15.74	2,605.0	41,012.9	43.5
	Oxisols	0.00%	9.32	0.01%	3.76	0.2	0.6	0.0
	Spodosols	0.00%	0.04	0.00%	15.03	2,199.8	33,074.1	0.0
	Ultisols	0.00%	0.68	0.00%	9.07	4.8	43.2	0.0
	Vertisols	0.00%	21.03	0.02%	14.04	75.5	1,060.0	0.2
	Total					9,167.3	136,858.4	51.1

(*continued*)

Table IX (*continued*)

		Erosion-induced yield loss (% Mg^{-1})	Crop-specific estimated erosion rate (Mg ha^{-1} yr^{-1})	Relative annual yield loss (% yr^{-1})	Normalized yield (Mg ha^{-1})	Estimated production area (10^3 ha)	Total Production (10^3 Mg)	Production loss (10^3 Mg yr^{-1})
North America	Alfisols	0.42%	11.14	4.68%	37.74	200.1	7,552.2	353.4
	Andisols	0.42%	5.76	2.42%	25.40	20.7	524.8	12.7
	Aridisols	0.00%	11.13	0.00%	42.14	0.5	20.6	0.0
	Entisols	0.42%	2.26	0.95%	29.01	4.4	126.9	1.2
	Histosols	0.42%	5.57	2.34%	39.09	0.3	11.4	0.3
	Inceptisols	1.09%	11.62	12.66%	31.55	36.2	1,143.3	144.8
	Mollisols	0.42%	13.27	5.57%	39.83	216.7	8,630.5	480.9
	Spodosols	0.78%	0.02	0.02%	37.65	194.7	7,330.9	1.3
	Ultisols	0.42%	14.96	6.28%	16.51	28.6	472.6	29.7
	Vertisols	0.42%	17.04	7.16%	23.60	3.9	93.2	6.7
	Total					706.1	25,906.3	1,030.9
Central +South America	Alfisols	0.00%	10.29	0.01%	9.72	268.7	2,611.9	0.3
	Andisols	0.00%	7.61	0.01%	7.37	130.2	959.1	0.1
	Aridisols	0.00%	9.56	0.01%	17.37	1.6	28.6	0.0
	Entisols	0.00%	1.76	0.00%	19.07	71.7	1,367.1	0.0
	Histosols	0.00%	9.32	0.01%	4.46	0.0	0.0	0.0
	Inceptisols	0.00%	19.90	0.02%	16.39	140.4	2,301.2	0.5
	Mollisols	0.00%	14.45	0.01%	18.75	464.3	8,707.4	1.3
	Oxisols	0.00%	9.60	0.01%	5.07	5.2	26.1	0.0
	Spodosols	0.00%	0.62	0.00%	17.87	9.0	161.1	0.0
	Ultisols	0.00%	14.26	0.01%	9.37	6.4	84.4	0.0
	Vertisols	0.00%	16.42	0.02%	12.67	5.0	81.2	0.0
	Total					1,102.5	16,328.2	2.1

annual yield loss on Spodosol is due to the very low estimated erosion rate of Spodosols in potatoes (0.02 Mg ha^{-1} yr^{-1}), as these are sandy soils. The total production loss of potatoes was estimated at about 1.0 million Mg yr^{-1}, 35% coming from losses on Alfisols and 48% on Mollisols. Mechanized land preparation and harvesting perhaps contributed to the larger losses in North America.

In Central and South America, potatoes were used only in one erosion–productivity study on an Entisol. The mean yield decline in this study was 0.001% Mg^{-1} of erosion. If we accept that this study is representative for soils in all soil orders on which potatoes are grown in this continent, relative annual yield losses of potatoes are small, ranging from 0.00 to 0.02% yr^{-1}. The higher rates of yield decline were found on Inceptisols and Vertisols, resulting from the high erosion estimates for land under potatoes on these soils. Based on the relative annual yield losses on the various soil orders, we estimate that farmers lose about 2,100 Mg $yr^{-1}$of potatoes due to erosion, with 1,300 Mg yr^{-1} being lost due to erosion on Mollisols.

D. Soybeans

Soybeans are the only leguminous crop included on our calculations. The effect of erosion on soybean yield and production varies across continents; annual loss of soybean yield ranges from -1.08% yr^{-1} in Asia to 0.33% yr^{-1} in Central and South America. The small number of studies on soybeans in Asia (4) reviewed in Part I (den Biggelaar *et al*., this volume) showed no effect of erosion on soybean yield on Inceptisols, small losses of 0.04% Mg^{-1} of soil loss on Oxisols, but an increase in yield of 0.22% Mg^{-1} on Vertisols (Table X). Annual yield losses of 0.57% yr^{-1} are estimated for soybeans grown on Oxisols, with no losses recorded for soybeans on Inceptisols. All other soils show an increase in yield with progressive erosion, ranging from 0.08% yr^{-1} on Entisols to 3.67% yr^{-1} on Vertisols. For most soil orders, the production increases ranged from 0.5 to 1.0% yr^{-1}. Overall, we therefore estimate that erosion has no deleterious effect on the yield of soybeans in Asia; on the contrary, our calculations show a general increase in total soybean production of about 254,000 Mg yr^{-1} (Table X). Most of the increase (53%) occurs on Ultisols, which are the primary soil type on which soybeans are produced in Asia (56% of soybean is grown on Ultisols).

In Europe, soybeans are a minor crop, produced on about 1.2 Mha, primarily on Alfisols (52% of soybean area) and Mollisols (37% of the area) (Table X). The production loss amounts to 5,200 Mg yr^{-1}, or 0.22% yr^{-1}. Relative annual yield losses range from 0.02% yr^{-1} on Entisols to 0.33% yr^{-1} on Ultisols and Vertisols (Table X). For the soil orders on which most soybeans are produced in Europe, the annual losses are 0.25 and 0.24% yr^{-1} for Alfisols and Mollisols,

Table X
Estimated Absolute and Relative Annual Losses in Soybean Production by Continent and Soil Order

		Erosion-induced yield loss (% Mg^{-1})	Crop-specific estimated erosion rate ($Mg\ ha^{-1}\ yr^{-1}$)	Relative annual yield loss (% yr^{-1})	Normalized yield ($Mg\ ha^{-}$)	Estimated production area (10^3 ha)	Total Production (10^3 Mg)	Production loss ($10^3\ Mg\ yr^{-}$)
Asia	Alfisols	−0.05%	12.17	−0.61%	0.59	4,251.3	2,526.3	−15.4
	Andisols	−0.05%	13.83	−0.69%	1.23	279.0	344.2	−2.4
	Aridisols	−0.05%	19.49	−0.97%	0.40	1.9	0.8	0.0
	Entisols	−0.05%	1.60	−0.08%	2.03	581.1	1,180.7	−0.9
	Histosols	−0.05%	10.62	−0.53%	0.74	1.6	1.2	0.0
	Inceptisols	0.00%	13.48	0.00%	1.12	132.0	147.2	0.0
	Mollisols	−0.05%	12.48	−0.62%	1.48	283.5	418.2	−2.6
	Oxisols	0.04%	14.33	0.57%	0.30	0.7	0.2	0.0
	Ultisols	−0.05%	16.77	−0.84%	1.71	9,429.1	16,153.8	−135.4
	Vertisols	−0.22%	16.69	−3.67%	1.50	1,768.3	2,658.2	−97.6
	Total					16,728.5	23,430.7	−254.3
Europe	Alfisols	0.02%	12.26	0.25%	2.22	631.1	1,398.4	3.4
	Andisols	0.02%	14.29	0.29%	1.47	3.0	4.3	0.0
	Entisols	0.02%	0.79	0.02%	2.32	84.7	196.6	0.0
	Histosols	0.02%	5.64	0.11%	2.45	0.6	1.4	0.0
	Inceptisols	0.02%	10.56	0.21%	2.29	9.5	21.7	0.0
	Mollisols	0.02%	11.99	0.24%	1.41	457.3	643.6	1.5
	Oxisols	0.02%	13.29	0.27%	0.63	0.5	0.3	0.0
	Spodosols	0.02%	7.64	0.15%	2.37	1.7	4.1	0.0
	Ultisols	0.02%	16.66	0.33%	1.78	7.2	12.8	0.0
	Vertisols	0.02%	16.75	0.33%	1.14	26.8	30.7	0.1
	Total					1,222.4	2,313.9	5.2

North America	Alfisols	0.01%	10.66	0.11%	3.17	7,871.0	24,922.2	26.6
	Andisols	0.01%	14.06	0.14%	0.69	13.6	9.4	0.0
	Aridisols	0.01%	11.54	0.12%	1.32	6.2	8.2	0.0
	Entisols	0.03%	12.64	0.38%	2.04	28.8	58.6	0.2
	Histosols	0.01%	9.32	0.09%	2.90	0.2	0.7	0.0
	Inceptisols	0.02%	14.50	0.29%	2.62	80.9	211.9	0.6
	Mollisols	0.01%	14.53	0.15%	2.39	11,502.7	27,494.6	39.9
	Spodosols	0.01%	10.80	0.11%	3.48	6.9	24.2	0.0
	Ultisols	0.03%	16.80	0.50%	2.44	9,863.9	24,021.6	121.1
	Vertisols	0.01%	16.80	0.17%	1.56	836.8	1,307.3	2.2
	Total					30,211.1	78,058.8	190.7
Central +South America	Alfisols	0.03%	14.36	0.43%	1.25	10,923.2	13,676.5	58.9
	Andisols	0.03%	14.46	0.43%	3.24	551.9	1,785.6	7.7
	Aridisols	0.03%	23.35	0.70%	0.73	55.2	40.3	0.3
	Entisols	0.03%	2.09	0.06%	2.80	1,189.2	3,331.3	2.1
	Histosols	0.03%	11.82	0.35%	1.04	0.3	0.3	0.0
	Inceptisols	0.03%	14.09	0.42%	1.40	225.3	316.3	1.3
	Mollisols	0.02%	14.39	0.29%	3.74	7,735.4	28,908.5	83.2
	Oxisols	0.03%	11.96	0.36%	1.32	180.8	238.7	0.9
	Ultisols	0.03%	15.72	0.47%	1.83	547.7	1,000.9	4.7
	Vertisols	0.03%	15.25	0.46%	3.49	1,571.6	5,486.3	25.1
	Total					22,980.3	54,784.8	184.2

respectively (Table X). Almost all production losses in Europe occurred on Alfisols (65%) and Mollisols (29%).

Overall relative yield loss of soybeans in North America is 0.24% yr^{-1}, ranging from 0.09% yr^{-1} on Histosols to 0.50% yr^{-1} on Ultisols (Table X). High relative annual yield losses were also found for soybeans on Entisols (0.38% yr^{-1}) and Inceptisols (0.29% yr^{-1}). Relative yield losses were intermediate on the other soil orders, ranging from 0.11 − 0.17% yr^{-1}. In North America, soybeans are produced on about 30.2 Mha; primary soil orders on which soybeans are produced are Mollisols (11.5 Mha or 38% of the total area), Ultisols (9.9 Mha or 33%) and Alfisols (7.9 Mha or 26 %). Due to the high erosion rate of Ultisols and the high erosion-induced yield loss, most soybean production loss occurs on Ultisols (121,000 Mg yr^{-1} out of a total loss of 191,000 Mg yr^{-1}, or 63% of total losses). Production losses on Mollisols and Alfisols are much smaller, contributing about 21 and 14% of the total annual production losses, respectively.

Central and South America is the second soybean production region in the world, with a land area of about 23 Mha in soybeans. Nearly half of this area is estimated to be on Alfisols, and another one-third on Mollisols. The average relative annual yield loss in this continent was estimated at 0.33% yr^{-1}, with a range of 0.06–0.70% yr^{-1} (Table XII). The lowest relative losses are found on Entisols, while the highest relative loss occurs on Aridisols. However, few soybeans are produced on the latter (552,000 ha) (Table X). Relative yield losses on the major soybean producing soils were estimated at 0.43, 0.29, and 0.46% yr^{-1} on Alfisols, Mollisols and Vertisos, respectively (Table X). Total production losses in Central and South America were estimated at about 184,000 Mg yr^{-1}. Although Mollisols are not the major soils on which soybeans are grown in this continent, the amount of production loss is greatest on these soils with 83,000 Mg yr^{-1}, or 45% of the total loss in production. Losses on Alfisols constitute about 32% of the total loss of soybean production, with about 14% of the losses attributed to erosion on Vertisols (Table X).

E. WHEAT

Estimates on the erosion-induced losses in the production of wheat were made for five continents. Average relative wheat yield losses across soil orders range from 0.04% yr^{-1} in Europe to 0.67% yr^{-1} in Australia. Relative annual yield losses in Asia and Central and South America are similar at 0.29 and 0.27% $yr^{-1,}$ respectively, with average relative losses in North America estimated at less than half those rates at 0.11% yr^{-1}.

Relative yield losses across soil orders in Asia ranged from 003% yr^{-1} on Entisols to 0.42% yr^{-1} on Oxisols (Table XI). For the soil orders on which most of the wheat is grown in Asia (i.e. Alfisols, Inceptisols, and Mollisols), relative yield losses were estimated at 0.22, 0.37, and 0.27% yr^{-1}, respectively. The total

Table XI
Estimated Absolute and Relative Annual Losses in Wheat Production by Continent and Soil Order

		Erosion-induced yield loss (% Mg^{-1})	Crop-specific estimated erosion rate ($Mg\ ha^{-1}\ yr^{-1}$)	Relative annual yield loss (% yr^{-1})	Normalized yield ($Mg\ ha^{-1}$)	Estimated production area (ha)	Total production (10^3 Mg)	Production loss ($10^3\ Mg\ yr^{-1}$)
Asia	Alfisols	0.02%	10.97	0.22%	1.81	21,304.9	38,583.8	84.7
	Andisols	0.02%	14.34	0.29%	0.94	2,236.0	2,101.2	6.0
	Aridisols	0.02%	9.75	0.20%	2.55	58.6	149.6	0.3
	Entisols	0.02%	1.52	0.03%	2.97	6,692.9	19,897.7	6.0
	Histosols	0.02%	13.71	0.27%	1.49	10.1	15.1	0.0
	Inceptisols	0.02%	18.38	0.37%	2.80	33,152.8	92,861.3	341.4
	Mollisols	0.02%	13.33	0.27%	3.16	19,757.6	62,504.3	166.6
	Oxisols	0.02%	20.92	0.42%	2.13	9.6	20.6	0.1
	Ultisols	0.02%	15.25	0.31%	2.06	6,076.3	12,489.9	38.1
	Vertisols	0.02%	18.26	0.37%	2.80	9,412.7	26,359.8	96.3
	Total					98,711.7	254,983.3	739.5
Australia	Alfisols	0.05%	12.34	0.62%	1.78	5,698.0	10,163.8	62.7
	Andisols	0.04%	14.25	0.57%	0.69	52.8	36.5	0.2
	Aridisols	0.02%	13.54	0.27%	2.15	141.8	305.3	0.8
	Entisols	0.04%	11.84	0.47%	1.89	81.8	154.6	0.7
	Inceptisols	0.04%	22.55	0.90%	2.21	889.8	1,962.3	17.7
	Mollisols	0.04%	15.71	0.63%	2.30	597.5	1,374.3	8.6
	Oxisols	0.04%	12.99	0.52%	1.29	17.4	22.5	0.1
	Spodosols	0.04%	14.48	0.58%	2.09	13.4	28.0	0.2

(*continued*)

Table XI (*continued*)

		Erosion-induced yield loss (% Mg^{-1})	Crop-specific estimated erosion rate ($Mg\ ha^{-1}\ yr^{-1}$)	Relative annual yield loss (% yr^{-1})	Normalized yield ($Mg\ ha^{-1}$)	Estimated production area (ha)	Total production (10^3 Mg)	Production loss ($10^3\ Mg\ yr^{-1}$)
	Ultisols	0.04%	14.01	0.56%	1.61	253.9	409.9	2.3
	Vertisols	0.04%	17.75	0.71%	2.21	3,755.9	8,288.9	58.9
	Total					11,502.3	22,746.1	152.2
Europe	Alfisols	0.00%	5.35	0.00%	2.36	27,229.8	64,317.5	0.0
	Andisols	0.00%	11.16	0.00%	2.52	800.6	2,015.3	0.0
	Aridisols	0.00%	12.07	0.00%	3.21	8.2	26.4	0.0
	Entisols	0.00%	0.91	0.00%	3.78	3,230.4	12,226.6	0.0
	Histosols	0.00%	3.72	0.00%	2.35	59.0	138.4	0.0
	Inceptisols	0.00%	19.22	0.00%	3.26	8,980.3	29,318.1	0.0
	Mollisols	0.01%	10.61	0.11%	4.23	16,536.9	69,897.1	74.2
	Spodosols	0.00%	8.88	0.00%	3.12	57.2	178.7	0.0
	Ultisols	0.00%	8.09	0.00%	2.48	1.1	2.8	0.0
	Vertisols	0.00%	21.30	0.00%	3.65	868.6	3,168.1	0.0
	Total					57,772.0	181,288.9	74.2
North America	Alfisols	0.01%	10.74	0.11%	1.92	13,223.0	25,356.4	27.2
	Andisols	0.01%	5.75	0.06%	2.02	1,313.3	2,652.4	1.5
	Aridisols	0.01%	11.65	0.12%	2.09	29.7	62.2	0.1
	Entisols	0.01%	2.28	0.02%	2.04	276.3	564.0	0.1
	Histosols	0.01%	8.15	0.08%	1.31	12.7	16.7	0.0
	Inceptisols	0.01%	14.30	0.14%	2.45	1,874.9	4,597.9	6.6

	Mollisols	0.01%	13.21	0.13%	2.98	13,804.8	41,184.7	54.4
	Spodosols	0.01%	10.81	0.11%	2.16	26.5	57.3	0.1
	Ultisols	0.01%	15.00	0.15%	1.65	1,818.2	3,008.6	4.5
	Vertisols	0.01%	17.26	0.17%	1.85	545.2	1,010.7	1.7
	Total					32,924.6	78,510.9	96.3
Central + South America	Alfisols	0.02%	10.95	0.22%	1.67	1,632.9	2,725.4	6.0
	Andisols	0.02%	11.36	0.23%	1.51	828.3	1,253.8	2.8
	Aridisols	0.02%	7.28	0.15%	2.71	14.4	39.0	0.1
	Entisols	0.02%	1.68	0.03%	2.96	718.3	2,127.9	0.7
	Histosols	0.02%	9.32	0.19%	0.84	0.1	0.1	0.0
	Inceptisols	0.02%	21.27	0.43%	2.66	903.6	2,407.2	10.2
	Mollisols	0.02%	14.27	0.29%	2.89	4,336.0	12,546.8	35.8
	Oxisols	0.02%	9.77	0.20%	0.98	31.5	30.8	0.1
	Spodosols	0.02%	17.42	0.35%	2.78	3.3	9.1	0.0
	Ultisols	0.02%	15.37	0.31%	1.81	52.4	94.9	0.3
	Vertisols	0.02%	17.23	0.34%	2.46	217.0	533.4	1.8
	Total					8,737.6	21,768.3	57.9

annual amount of production lost as a result of erosion in Asia was estimated at 740,000 Mg yr^{-1}, 46% from erosion on Inceptisols, and 23% on Mollisols. Erosion on Alfisols and Vertisols generated about 11 and 13% of total production losses of wheat in Asia (Table XI).

Average relative annual yield losses in wheat were highest in Australia at 0.67% yr^{-1}. Comparing relative losses across soil orders shows that the lowest losses occurred on Aridisols (0.27% yr^{-1}) and the highest losses on Inceptisols (0.90% yr^{-1}) (Table XI). The major wheat production zone of Australia is on Alfisols and Vertisols with 5.7 and 3.8 Mha, respectively; relative yield losses on these two soil orders were estimated at 0.62 and 0.71% yr^{-1}, respectively. Soil erosion on these two soil orders combined lead to 80% of the loss of wheat production of about 152,000 Mg yr^{-1} (Table XI).

Studies on the effect of erosion on wheat yields in Europe showed that it has little to no effect on this crop. The mean relative yield loss across soil orders was estimated at 0.04% yr^{-1}. Of the 10 soil orders with a potential for wheat production in Europe, no losses occurred on nine soils orders; only Mollisols experienced a relative loss of 0.11% yr^{-1} (about 74,000 Mg yr^{-1}) (Table XI). Relative yield losses were also low in North America, declining at an average rate of 0.11% yr^{-1} across soil orders. Yield losses were estimated at less than 0.1% yr^{-1} on Andisols, Entisols and Histosols; on other soil orders, production losses ranged between 0.11 (Alfisols and Spodosols) and 0.17% yr^{-1} (Vertisols) (Table XI). Most wheat in North America is produced on Alfisols and Mollisols with 40 and 42% of the total area of 32.9 Mha; Inceptisols and Ultisols each have about 5.5% of the total wheat area (Table XI). The total amount of production lost due to erosion was estimated at 96,000 Mg yr^{-1}, with 56% of that total due to wheat production losses on Mollisols and 28% on Alfisols.

Relative annual yield losses of wheat in Central and South America range from 0.03% yr^{-1} on Entisols to 0.43% yr^{-1} on Inceptisols (Table XI). Relative loss on Mollisols, which represent half of the wheat area in Latin America, was estimated at 0.29% yr^{-1}, while losses on Alfisols (having the second largest area in wheat) amount to 0.22 % yr^{-1}. The total loss of production was estimated to be 58,000 Mg yr^{-1}; of this total, 62% was due to erosion-induced yield declines on Mollisols, with 18% due to yield decreases on Inceptisols. Although Inceptisols represent only about 10% of the area in wheat in Central and South America, they have the highest estimated erosion rate under wheat on this content (21.27 Mg ha^{-1} yr^{-1}).

F. Value of Production Losses

To aggregate production losses due to induced soil productivity declines across crops and continents, we used the 2000/01 prices of the USDA baseline projections to 2010 (USDA, 2001). We used the same prices for crops across

Table XII
Value of Erosion-Induced Production Losses, by Continent and Crop

		Total production[a] (10^3 Mg yr^{-1})	Production loss (10^3 Mg yr^{-1})	Price[b] (US\$ Mg^{-1})	Value of total production (10^6 US\$)	Value of production loss (10^3 US\$)	Estimated mean production/value loss (% yr^{-1})
Africa	Maize	41,198.1	202.2	\$72.83	\$3,000	\$14,726	0.49%
	Subtotal				\$3,000	\$14,726	0.49%
Asia	Maize	162,288.9	961.2	\$72.83	\$11,820	\$70,004	0.59%
	Millet	12,692.7	64.2	\$72.75	\$923	\$4,671	0.51%
	Soybeans	23,492.6	−254.3	\$180.04	\$4,230	−\$45,784	−1.08%
	Wheat	254,338.3	739.5	\$93.96	\$23,898	\$69,483	0.29%
	Subtotal				\$40,870	\$98,374	0.24%
Australia	Potatoes	1,872.0	2.3	\$129.00	\$241	\$297	0.12%
	Wheat	22,739.0	152.2	\$93.96	\$2,137	\$14,301	0.67%
	Subtotal				\$2,378	\$14,597	0.61%
Europe	Millet	1,059.8	2.4	\$72.75	\$77	\$175	0.23%
	Potatoes	136,831.9	51.1	\$129.00	\$17,651	\$6,592	0.04%
	Soybeans	2,313.8	5.2	\$180.04	\$417	\$936	0.22%
	Wheat	181,517.3	74.2	\$93.96	\$17,055	\$6,972	0.04%
	Subtotal				\$35,200	\$14,675	0.04%

(*continued*)

Table XII (*continued*)

		Total production[a] (10^3 Mg yr^{-1})	Production loss (10^3 Mg yr^{-1})	Price[b] (US$ Mg^{-1})	Value of total production (10^6 US$)	Value of production loss (10^3 US$)	Estimated mean production/value loss (% yr^{-1})
North America	Maize	259,121.8	399.3	$72.83	$18,872	$29,081	0.15%
	Potatoes	25,903.0	1030.9	$129.00	$3,341	$132,986	3.98%
	Sorghum	13,810.9	8.2	$64.96	$897	$533	0.06%
	Soybeans	77,878.5	190.7	$180.04	$14,021	$34,334	0.24%
	Wheat	90,360.1	96.3	$93.96	$8,490	$9,048	0.11%
	Subtotal				$45,622	$205,982	0.45%
Central + South America	Maize	74,608.3	703.6	$72.83	$5,434	$51,243	0.94%
	Potatoes	16,281.4	2.1	$129.00	$2,100	$271	0.01%
	Soybeans	55,425.5	184.2	$180.04	$9,979	$33,163	0.33%
	Wheat	21,719.9	57.9	$93.96	$2,041	$5,440	0.27%
	Subtotal				$19,554	$90,118	0.46%
Global total	Maize	537,217.1	2,266.3	$72.83	$39,126	$165,055	0.42%
	Potatoes	180,887.9	1086.4	$129.00	$23,335	$140,146	0.60%
	Millet	13,752.0	66.6	$72.75	$1,000	$4,845	0.48%
	Sorghum	13,810.9	8.2	$64.96	$897	$533	0.06%
	Soybeans	159,110.4	125.8	$180.04	$28,646	$22,649	0.08%
	Wheat	570,674.6	1120.1	$93.96	$53,621	$105,245	0.20%
	Total				$146,624	$438,472	0.30%

[a]Production data from FAOStat (2000).

[b]Prices based on the projected 2000/01 crop prices from the USDA Agricultural Baseline Projections to 2010 (USDA, 2001).

continents, namely \$72.83 Mg^{-1} for maize, \$93.96 Mg^{-1} for wheat, \$180.04 Mg^{-1} for soybeans, \$72.75 Mg^{-1} for millet, \$64.96 Mg^{-1} sorghum, and \$129.00 Mg^{-1} for potatoes. The estimated value of the losses by crop and continent are shown in Table XII.

The value of annual production losses for the selected crops amounts to \$14.7 million in Africa, \$98.4 million in Asia, \$14.6 million in Australia, \$14.7 million in Europe, \$205.9 million in North America and \$90.1 million in Central and South America (Table XII). Globally, the losses are estimated at \$165.1 million for maize, \$4.9 million for millet, \$140.1 million for potatoes, \$533 thousand for sorghum (North America only), \$22.7 million for soybeans and \$105.2 million for wheat (Table XII). These losses represent an annual decline of 0.3% in the value of 0.3% of the value of the global production of the selected crops, ranging from 0.04% yr^{-1} in Europe to 0.61% yr^{-1} in Australia.

These figures represent a rough estimate of the potential annual value of crop production losses to soil erosion for the selected crops. The true value of production losses is indeterminate. We have not been able to estimate the losses for all crops and regions in the absence of any erosion–productivity studies on which to base the estimates. For example, sorghum in North America represents only 23% of the total global production of this crop. It is, however, a major staple crop in both Africa and Asia, but no erosion–productivity studies using this crop have been done on these continents; hence it is not possible to provide a true global estimate of sorghum production losses. The production loss estimates for millet, potatoes, maize, wheat and soybeans represent about 49, 60, 89, 97, and 100% of the total global production of these crops, respectively.

Our estimates do not include the additional production costs incurred by farmers to offset the loss of soil, and of societal costs to mitigate sedimentation, water pollution and other off-site damages caused by soil erosion. On the other hand, the estimated potential production losses reported here may overstate actual losses to the extent that farmers' actions reduce losses to soil erosion. The true economic costs resulting from soil erosion are, therefore, likely to be significantly different from our estimated global total value of \$438.5 million (Table XII).

V. DISCUSSION AND CONCLUSION

In the companion paper (den Biggelaar *et al*., this volume), we presented a review of studies in the soil science literature on the effects of erosion on soil productivity on a soil and crop specific basis. The aim of the present paper was to extrapolate from the yield losses per cm or Mg of soil erosion determined in the previous report to estimate the annual impact of soil erosion on crop yields and production at various scales. Our aim was not to determine definite, final answers as to the amount or the value of crop production lost as a result of erosion-induced soil productivity declines, but mainly to (1) identify priority areas where, based on importance to crop production, erosion rates and erosion-induced yield impacts, erosion most affects crop yields, production, and food security; and (2) help guide policy makers in developing appropriate response to erosion accordingly.

As we estimated production losses only for crops for which regional soil-specific studies were available, the global total production losses and their values are not inclusive totals. However, the estimates do suggest the relative differences in the magnitude of the problem by crop, soil order, and location at both continental and global scales, and provide an indication of the losses incurred by the farm sector as a result of erosion-induced production declines. It should be noted that the additional costs associated with erosion at the farm level (such as extra costs for fertilizers, irrigation, soil preparation, and pesticides to maintain yields or, at least, limit their decline), and at the level of societies (such as costs of water pollution and sedimentation), are not included in our estimate of the economic costs of soil erosion.

Extrapolations from yield decline data per cm or Mg soil erosion on a soil-specific basis requires the availability of soil-based erosion, crop yield and crop area data. International statistics (for example, those of FAO and the World Bank) do not provide this detail, and are limited to only providing aggregate statistical data on a national level. In absence of global soil-based databases on soil erosion and crop production, our analyses are necessarily empirical and dependent upon the assumptions made in the methods employed to arrive at our estimates of potential soil erosion and crop areas by soil order. A further weakness in our analysis stems from the paucity of erosion-productivity studies which we used as the basis for the assessment of production losses and their values. This study takes the conclusion of Reich *et al*. (2000) that soil erosion and the resulting degradation remain a threat to world food production one step further by estimating the actual effects of erosion on crop production at various scales.

The estimation of erosion rates by soil order and continent shows that there is a large variation in erosion rates among soil orders, and according to the crops being grown on them. For policy making to combat erosion, the use of a global or continental average erosion rate (e.g. Brown, 1984; Brown and Wolf, 1984; Pimental *et al*., 1995), an average erosion for a specific soil order across an entire continent or country for all crops, or an average erosion rate for a specific crop across soil orders is, therefore, neither justified nor recommended. For example, in Central and South America, erosion rates for land under maize on most orders are higher than erosion rates for land under wheat on those same soil orders. In Central and South America, maize land has erosion rates ranging from 1.74 Mg ha^{-1} in Entisols to 25.78 Mg ha^{-1} on Spododols, whereas for wheat they range from 1.68 Mg ha^{-1} on Entisols to 21.27 Mg ha^{-1} on Inceptisols (with the rate on Spodosols being 30% less than those under maize at 17.45 Mg ha^{-1}). In addition, high average erosion rates on a particular soil order do not necessarily indicate a serious problem, as the order may be only a marginal one for crop production in general, or for a specific crop in particular. Globally, very little land under Andisols, Aridisol, Histosols, and Spodosols is used for crop production, with the exception of Spodosols in Europe and North America where about one-quarter of the potatoes are grown on these soils. On most continents, our estimates indicate that less than 0.5% of cropland consists of Aridisols and Histosols. It may, therefore, be environmentally and economically better to limit use of certain soil orders for agricultural production, or to restrict the production of specific crops on these orders. For example, potential average erosion rates on Spodosols in Central and South America are 25.78, and 17.42 Mg ha^{-1} under maize and wheat, respectively, but only 0.62 Mg ha^{-1} under potatoes. As the estimated areas in these crops on Spodosols are small (in Central and South America, 200, 9000, and 3300 ha of maize, potatoes, and wheat are grown on these soils, respectively), discouraging their cultivation, especially for maize and wheat, and encouraging their cultivation on less erosion prone soils would not greatly affect overall production and food security.

On the other hand, soil conservation measures should in preference be concentrated and encouraged on soil orders that are important in terms of both extent and production of particular crops, but presently prone to high erosion-induced production losses (for example, soybeans on Ultisols in North America and on Alfisols and Mollisols in Central and South America). We therefore recommend that our assessments primarily be used to identify specific soil orders that, according to our estimations, are important for the production of some of the world's major staple crops in terms of both area and production, and identify specific soil–crop combinations in which erosion has particularly large impacts in terms of lost production and value. Policy measures and soil conservation interventions should therefore be aimed, in particular, at producers growing those crops on soils on which they are particularly vulnerable to erosion.

Partial global production loss estimates (partial because estimates are made only on continents on which erosion–productivity studies have been done for a specific crop) suggest that, each year, farmers lose about 2.2 million Mg maize, 0.07 million Mg millet, 1.1 million Mg potatoes, 0.1 million Mg soybeans and 1.1 million Mg wheat as a result of erosion. Losses of sorghum in just North America amount to 8,200 Mg yr^{-1}. These partial production losses are 33–55% of the estimated gap between production and the amount necessary to maintain per capita consumption at 1995–1997 levels in 66 low-income developing countries (11 million Mg), or to meet minimum nutritional requirements (17.6 million Mg) (USDA, 1998). Reducing production losses by limiting erosion would, therefore, go a long way to attain food security. The economic value of this production loss is estimated at $489.9 million.

Three main conclusions can be drawn from our analyses: First, estimated annual losses at a global scale for the crops and continents considered in our analyses are small relative to the total agricultural production and value of the selected crops. The losses are likely to be masked over the short term by market fluctuations, weather, and other environmental perturbations, diminishing incentives for farmers to adopt conservation practices. Moreover, erosion's impacts are cumulative and may cause more serious losses if it continues unabated over a long period of time. Second, our estimated global annual losses in crop yields and production are at the lower end of the range of previously published estimates of erosion-induced productivity losses (Lal and Stewart. 1990; Janargin and Smith, 1993; Crosson, 1997; Lal, 1998; Young, 1999). Of more interest, especially for soil conservation policy is the finding that losses vary widely between crops, soil orders and regions, and in selected situations can be quite substantial. In general, though, little is known about these losses for many important crops in many developing countries. Third, estimated losses in productivity are probably small in relation to offsite impacts (such as sedimentation). These findings underscore the importance of continued policy measures to encourage soil conservation. They also underscore the importance of improved understanding of erosion and its impacts for these crops, soils, and regions where its impacts are most severe or least understood. Finally, more precise estimation of actual losses due to erosion (as opposed to the potential losses estimated here) depends on improved understanding of farmers' optimal response in the face of changing physical, market, and policy environments.

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