Agriculture **2013**, *3*, 443-463; doi:10.3390/agriculture3030443

OPEN ACCESS

agriculture

ISSN 2077-0472

www.mdpi.com/journal/agriculture

Article

Soil Erosion Threatens Food Production

David Pimentel * and Michael Burgess

College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853, USA;
E-Mail: mnb2@cornell.edu

* Author to whom correspondence should be addressed; E-Mail: dp18@cornell.edu;
Tel.: +1-607-255-2212; Fax: +1-607-255-0939.

Received: 14 June 2013; in revised form: 20 July 2013 / Accepted: 23 July 2013 / Published: 8 August 2013

Abstract: Since humans worldwide obtain more than 99.7% of their food (calories) from the land and less than 0.3% from the oceans and aquatic ecosystems, preserving cropland and maintaining soil fertility should be of the highest importance to human welfare. Soil erosion is one of the most serious threats facing world food production. Each year about 10 million ha of cropland are lost due to soil erosion, thus reducing the cropland available for world food production. The loss of cropland is a serious problem because the World Health Organization and the Food and Agricultural Organization report that two-thirds of the world population is malnourished. Overall, soil is being lost from agricultural areas 10 to 40 times faster than the rate of soil formation imperiling humanity's food security.

Keywords: soil erosion; malnutrition; cropland; rangeland; pasture; soil organic matter; assessment

1. Introduction

The loss of soil from land surfaces by erosion is widespread and reduces the productivity of all natural ecosystems as well as agricultural, forest, and pasture ecosystems [1–3]. Concurrently with the growing human population, soil erosion, water availability, climate change due to fossil fuel consumption, eutrophication of inland and coastal marine bodies of water, and loss of biodiversity rank as the prime environmental problems throughout the world.

Currently nearly 66% of the world population is malnourished [4,5], the largest number of malnourished people ever (malnutrition: faulty nutrition due to inadequate or unbalanced intake of nutrients or their impaired assimilation or utilization) [6]. With the world population now over seven billion and expected to reach 9.3 billion by 2050, more food will be needed [7]. Consider at present that more than 99.7% of human food (calories) comes from the land [8], while less than 0.3% comes from the marine and aquatic ecosystems. Maintaining and augmenting the world food-supply basically depends on the productivity and quality of all agricultural soils.

Human induced soil erosion and associated damage to all agricultural land over many years have resulted in the loss of valuable agricultural land due to abandonment and reduced productivity of the remaining land which is partly made up for by the addition of nitrogen and phosphate fertilizers [2,9–11]. This loss of cropland to the effects of soil erosion often results in the creation of new cropland out of forestland and pastureland and the need to enrich these new croplands with inputs of nitrogen and phosphate fertilizers [12]. In addition, soil erosion reduces the valuable diversity of plants, animals, and soil microorganisms.

In this paper, the diverse factors that cause soil erosion are assessed. The extent of damage associated with soil erosion is analyzed, with emphasis on the impact these causative factors may have on future human food security as well as on the natural environment.

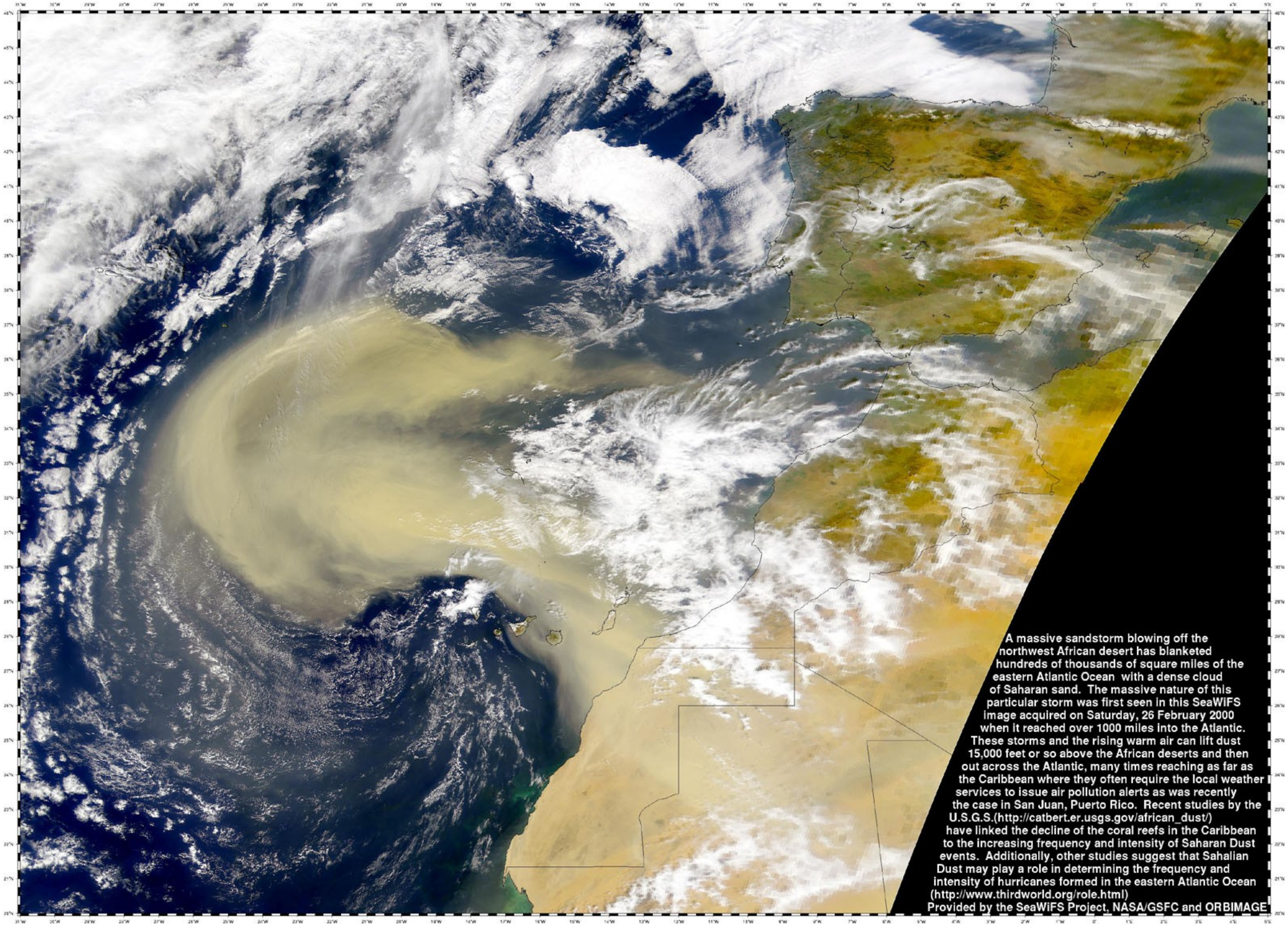
2. Causes of Erosion

Erosion occurs when soil is left exposed to rain drop or wind energy. The raindrops hitting a hectare of land in the New York State region of the United States provide the energy equivalent of 60,000 kcal (250×10^6 joules) per year with about 1000 mm of rainfall [13]. This 60,000 kcal roughly equals the energy in eight liters of gasoline. The raindrops hitting soil loosen the soil particles and with even a 2% slope start the movement of the soil downhill. Sheet erosion is the dominant type of erosion [3,14]. The impact of soil erosion is intensified on all sloping land, where with each degree of slope more of the surface soil is carried away as the water moves downhill into valleys and streams.

Wind energy also has great power to dislodge surface soil particles and transport them long distances. A dramatic example of this was the wind erosion in Kansas during the winter of 1995–1996 when it was relatively dry and windy. At this time approximately 65 t/ha of soil was eroded from this valuable cropland (Figure 1). Wind energy is sufficiently strong to propel soil particles thousands of kilometers. This is illustrated in the photograph by NASA (Figure 2) which shows a cloud of sand being blown from Africa to South and North America.

Figure 1. About 50 mm of soil blown from cropland in Kansas during the winter of 1995–1996 (E.L Skidmore, USDA, Manhattan, KS. photo spring of 1996).

Figure 2. Cloud of sand from Africa being blown across the Atlantic Ocean [15].



2.1. Soil Structure

Soil structure influences the ease with which soil can be eroded. Soils with a medium to fine texture, a low level of organic matter content, and weak structural development are most easily eroded [16]. Typically these soils have low water infiltration rates and therefore are subject to high rates of water erosion and are easily displaced by wind energy.

2.2. The Role of Vegetative Cover

Land areas covered by plant biomass, living or dead, are more resistant to wind and water soil erosion and experience relatively little erosion because rain drop and wind energy are dissipated by the biomass layer and the topsoil is held together by the biomass [17]. For example, in Utah and Montana, as the amount of ground cover decreased from 100% to less than 1%, erosion rates increased approximately 200-fold [18]. In forested areas, a minimum of 60% forest cover is necessary to prevent serious soil erosion and landslides [19–21]. The extensive removal of forests for cropland and pasture is followed by intensive soil erosion.

Loss of vegetative soil cover is especially widespread in developing countries where populations are large and growing, and agricultural practices are often inadequate to protect topsoils. In addition, cooking and heating in these countries frequently depend on the use of crop residues for fuel. For example, in the 1990s about 60% of crop residues in China and 90% in Bangladesh routinely were removed from the land and burned as fuel [22]. More recent estimates of the amount of crop residues in Bangladesh that could be harvested for biomass energy conversion without negatively impacting future crop yields amount to 50% of all rice crop residues and 80% of non-rice crop residues [23]. More recently crop residues in China are being used less as a domestic fuel source [24] due to the increased availability of fossil fuels. However China has plans to burn about half of the 600 billion tons of straw (from grains) crop residues produced annually to generate electricity [25]. In areas where fuelwood and other biomass are scarce, even the roots of grasses and shrubs are collected and burned [26,27]. All these practices leave the soil barren and fully exposed to rain and wind erosion forces.

2.3. Land Topography

The topography of a given landscape, its rainfall and/or wind exposure all combine to influence the land's susceptibility to soil erosion. In the Philippines, where more than 58% of the land has a slope greater than 11%, and in Jamaica where 52% of the land has a slope greater than 20%, soil erosion rates as high as 400 t/ha/year have been reported [1]. Erosion rates are high especially on marginal and steep lands which have been converted from forests to crops [1]. In addition under arid conditions with relatively strong winds soil erosion rates as high as 5600 t/ha/year have been reported in an arid region in India [28]. Even in a developed country with abundant farmland such as the United States where there is less need to exploit croplands with steeper slopes, erosion losses as of 2007 average 13 tons/ha/year [29]. In a developed region such as Europe, the measured rates of erosion range between 3 and 40 tons/ha/year with "losses due to individual storms of from 20–40 tons/ha, that may happen every two or three years, are measured regularly in Europe, with losses of more than 100 tons/ha in extreme events" [30,31].

2.4. Other Soil Disturbances

Although world agriculture accounts for about three-quarters of the soil erosion worldwide, erosion occurs whenever humans remove the vegetative cover [1,32]. The construction of roads, parking lots, and buildings are examples of this problem. Although the rate of soil erosion from construction sites may be exceedingly high, the erosion occurs for a relatively brief period. Once the land surface is seeded to grass or covered with other vegetation, the erosion declines [33–35].

Natural ecosystems also suffer erosion losses. This is especially evident along stream banks, where erosion occurs naturally due to the powerful action of the adjacent moving water. Increased soil losses occur on steep surfaces (30% or more) when a stream cuts through adjacent land. Even on relatively flat land with only a 2% slope, stream banks are eroded during heavy rains and flooding.

3. Assessing Soil Erosion

Although soil erosion has been taking place very slowly in natural ecosystems throughout geologic time, its cumulative impacts on soil quality over billions of years have been significant. Worldwide, erosion rates range from a low of 0.001 t/ha/year on relatively flat land with grass or forest cover, to rates ranging from 1 to 5 t/ha/year in mountainous regions with natural vegetation [36]. Yet even soil erosion with low rates sustained over billions of years can result in the displacement of enormous quantities of soil. In addition, eroded soil frequently accumulates in valleys forming alluvial plains. The large deltas of the world, such as those of the Nile, Ganges and Mississippi Rivers are the result of millennia of erosion [37].

Worldwide it is estimated that approximately 75 billion tons of fertile soil are lost from world agricultural systems each year [38,39]. An estimate of the total amount of soil eroded by water from the world's arable land per year for land quality classes I through VI is 67 billion tons [40]. In the 1990s, soil scientists Lal and Stewart [1] and Wen [41] report that 6.6 billion tons of soil per year are lost in India and 5.5 billion tons are lost annually in China. According to a study conducted by the Central Soil Water Conservation Research and Training Institute in Dehradun, India reported in 2010 that the average rate of soil loss due to erosion in India is 16.4 tons per hectare annually with an annual total loss of 5.334 billion tons [42]. A three-year study conducted by researchers associated with the Chinese Ministry of Water Resources, the Chinese Academy of Sciences and the Chinese Academy of Engineering reported in 2009 that all of China's 646 counties suffer from significant soil and water losses, equivalent to a combined area of 3.75 million km^2 [43]. A two-year study further reports that if the current rate of soil loss in China continues over the next 50 years, food production will decrease by 40% [44]. Considering these two countries together occupy only 13% of the world's total land area and have agricultural practices that have sustained agriculture for thousands of years, the estimated 75 billion tons of soil lost each year worldwide is conservative. The amount of soil lost from the United States cropland due to water and wind has decreased from 3.06 billion tons in 1982 to 1.725 billion tons in 2007 [29].

3.1. Loss of Productivity in Managed Ecosystems

Approximately 50% of the earth's land area is devoted to agriculture: About one-third is planted to crops and two-thirds is grazing land [45]. Forests occupy about 20% of the world's land area [46]. Of these three areas, cropland is most susceptible to erosion because of the frequent cultivation of soils and that vegetation is often removed before the crops are planted which exposes the soil to wind and rainfall energy. In addition, cropland is often left without vegetative cover between plantings which intensifies erosion on agricultural lands, erosion rates that are estimated to be 75 times greater than erosion in natural forest areas [38].

3.2. Worldwide Cropland

Currently, about 80% of the world's agricultural land suffers moderate to severe erosion, while 10% experiences slight erosion [47,48]. Worldwide, erosion on cropland averages about 30 t/ha/year and ranges from 0.5 to 400 t/ha/year [2]. As a result of soil erosion, during the last 40 years about 30% of the world's cropland has become unproductive and much of that has been abandoned for growing crops [49,50].

The nearly 1.5 billion ha of world cropland now under cultivation for crop production are almost equal in area to the amount of cropland (2 billion ha) that has been abandoned by humans since farming began [51,52] (D. Pimentel, Personal Communication, 19 July 2013). Such abandoned land, once biologically and economically productive, now only produces little biomass but also has lost considerable diversity of the plants, animals, and microbes it once supported [11,52]. Each year an estimated 10 million ha of cropland worldwide are abandoned due to lack of productivity caused by soil erosion [53]. Worldwide, soil erosion losses are highest in agro-ecosystems of Asia, Africa, and South America, averaging 30 to 40 tons/ha/year [11]. In developing countries, soil erosion is particularly severe on small farms that are often located on marginal lands where the soil quality is poor and the topography is frequently steep. In addition, poor farmers tend to raise row crops such as corn and beans; row crops are highly susceptible to erosion because the crop vegetation does not cover the entire tilled soil surface [54]. For example, in the Sierra Region of Ecuador, about 60% of the cropland was abandoned because erosion and inappropriate agricultural practices left the land devastated by water and wind erosion [55]. Similar problems are evident in the Amazonian region of South America, especially where vast forested areas have been cleared to provide land for sugarcane and other crops, plus livestock production. Past soil erosion for the African continent as a whole has caused an average annual crop yield decline of 8.2% and 6.2% for sub-Saharan Africa [56] and that if higher soil erosion rates continue unabated, average annual crop yield declines of 16.5% and 14.5% for sub-Saharan Africa may be possible.

3.3. U.S. Cropland

The lowest average erosion rates on cropland occur in the United States and Europe ranging from 10 to 15 t/ha/year [57]; erosion rates in the United States have dropped from an average 16.4 t/ha/year in 1982 to 10.8 t/ha/year in 2007 [29]. However, even these relatively low rates of erosion greatly exceed the average rate of natural soil formation from the parent soil material; under agricultural conditions the soil formation rate ranges from 0.5 to 1 t/ha/year [2,3,9,58]. This means that most U.S. cropland is losing soil faster than soil formation can replace it. Soil erosion is severe in some of the most productive agricultural ecosystems in the United States. For example, one-half the fertile topsoil of Iowa has been lost by erosion during the last 150 years of farming because of erosion [59]. These high rates of erosion in 1982, about 16.6 t/ha/year, have been reduced but remain high at 11.5 t/ha/year as of 2007 in Iowa and surrounding areas because of the rolling topography and the mostly corn and soybean production, row crops where the soil surface between rows is left exposed to wind and rain [29,60,61]. Similarly, 40% of the rich soil of the Palouse region in the northwestern U.S. has been lost during more than 100 years of cultivation [62]. In both of these regions, intensive agriculture is employed and mono-cultural plantings are common. In addition, most of the fields are left without a cover crop in the late fall and winter leaving the soil exposed to further erosion. Yearly many valuable hectares of cropland are abandoned after they have become unproductive due to wind and water erosion [63].

3.4. Pasture and Rangeland

In contrast to the average soil loss of 10.8 t/ha/year from U.S. cropland, pastures lose soil at about 6 t/ha/year [29,64]. However, erosion rates on pastures intensify whenever overgrazing occurs. Even in the United States, about 75% of non-Federal lands require conservation treatments to reduce grazing pressure [65]. More than half of the rangelands, including those on non-Federal and Federal lands, are now overgrazed and have become subject to high erosion rates [66,67].

Although erosion rates on U.S. cropland have decreased during the past three decades, erosion rates on rangelands and pastures remain high (6 t/ha/year) [64]. High erosion rates are typical on most of the world's pastures and rangelands [50]. In many developing countries, heavy grazing by cattle, sheep, and goats has removed most of the vegetative cover, exposing the soil to severe erosion. In Africa, about 80% of the pasture and rangeland is seriously eroded and degraded [68]. The prime causes for exposed soil are overgrazing and the removal of crop residues for cooking fuel but even by the 1990s researchers realized that these causes are so intertwined with the effects of rainfall variability and the occurrence of drought on the vegetation that it can be difficult to determine how much erosion is due to human activity [69]. Rangeland degradation and resultant soil erosion often occurs in sub-Saharan Africa but according to some researchers only under special circumstances such as when animals are concentrated, due to a restriction of the animals' movements, will a specific area of rangeland be overgrazed rather than the overall rangeland [70].

3.5. Forest Land

In stable forest ecosystems, where soil is protected by vegetation, erosion rates are very low, ranging from only 0.004 to 0.05 t/ha/year [47,71]. Tree leaves and branches not only intercept and diminish raindrop and wind energy, but leaves and branches also cover the soil under the trees to further protect the soil. However, the situation changes dramatically when forests are cleared for cropland or pastures are developed for livestock production and the soil is exposed to rain and wind energy [55,72].

4. Effects of Soil Erosion on Terrestrial Ecosystems

Soil erosion reduces the general productivity of terrestrial ecosystems [73,74]. In the order of importance, soil erosion increases water runoff thereby decreasing water infiltration and the water-storage capacity of the soil [3]. In addition, during the erosion process organic matter and essential plant nutrients are removed from the soil and soil depth is reduced. These changes not only inhibit vegetative growth but reduce the presence of valuable biota and the overall biodiversity of the soil [3,74]. These factors interact, making it almost impossible to separate the specific impacts of one factor from another. For example, the loss of soil organic matter increases water runoff which reduces the soil's water-storage capacity, which diminishes nutrient levels in the soil and also reduces the natural biota biomass and the biodiversity of soil ecosystems [73–75].

4.1. Water Availability

Water is a prime limiting factor for productivity in all terrestrial ecosystems because all vegetation requires enormous quantities of water for growth and for the production of fruit [76]. For example, 1 ha of corn will transpire about seven million liters of water during the growing season of about three months [77] and lose an additional two million liters of water by evaporation from the soil [76]. During soil erosion by rainfall, water runoff significantly increases with less water entering the soil and less water available to support the growing vegetation.

4.2. Nutrient Losses

Eroded soil carries away vital plant nutrients such as nitrogen, phosphorus, potassium, and calcium. Typically, the eroded soil contains about three times more nutrients per unit weight than are left in the remaining soil [78]. A ton of fertile topsoil averages 1 to 6 kg of nitrogen, 1 to 3 kg of phosphorus, and 2 to 30 kg of potassium, whereas the topsoil on the eroded land has an average nitrogen content of only 0.1 to 0.5 kg per ton [79,80]. To offset the nutrient losses inflicted by crop production, large quantities of fertilizers are often applied. Troeh *et al.* [3] estimate that lost soil nutrients cost U.S. agriculture several billion dollars annually. If the soil base is relatively deep, about 300 mm, and if only from 10 to 20 tons of soil is lost per hectare per year, the lost nutrients can be replaced with the application of commercial fertilizers and/or livestock manure. However, the replacement strategy is expensive for the farmer and nation and usually poor farmers cannot afford fertilizer. Not only are the fertilizer inputs fossil-energy dependent, these chemicals can harm human health and pollute the soil, water and air [64,81].

4.3. Soil Organic Matter

Fertile soils typically contain 100 tons of organic matter per hectare (4% to 5% of total topsoil weight) [17,58]. About 95% of the soil nitrogen and 25 to 50% of the phosphorus is contained in the soil organic matter [82]. Because most soil organic matter is found close to the soil surface as decaying leaves and stems, erosion significantly reduces the soil organic matter. Both wind and water erosion selectively remove the fine organic particles in the soil leaving behind larger soil particles and stones. Several studies have demonstrated that the soil removed by either water or wind erosion is 1.3 to 5 times richer in organic matter than the soil left behind [1]. For example, the reduction of soil organic matter from 0.9% to 1.4% (assuming a soil organic content of 4 to 5%) lowered the crop yield potential for grain by 50% [58,83].

Soil organic matter is a valuable resource because it facilitates the formation of soil aggregates and thereby increases soil porosity. The improved soil structure in turn facilitates water infiltration and ultimately the overall productivity of the soil [80]. In addition, organic matter aids cation exchange, enhances plant root growth, and stimulates the increase of important soil microbes [75,82,84].

Once the organic matter layer is depleted, the productivity of the ecosystem, as measured by plant biomass, declines both because of the degraded soil structure and the depletion of nutrients that were contained in the organic matter. In addition to low yields, the total biomass of the biota and overall biodiversity of these ecosystems is substantially reduced [85,86].

4.4. Soil Depth

Growing plants require soils of adequate depth in which to extend their roots. Various soil biota, like earthworms, also require a suitable soil depth [2,84]. Thus, when erosion substantially reduces soil depth of from 30 cm for deep soils to even less than 1 cm for thin soils, plant root space can be minimized, and the plants could be stunted.

5. Biomass, Soil Biota and Biodiversity

The biological diversity existing in any ecosystem is directly related to the amount of living and non-living organic matter present [52,84–87]. As mentioned, erosion, by diminishing soil organic matter, reduces the overall soil biomass and biological activity. Ultimately, this has a profound effect on the diversity of plants, animals, and microbes present in the soil ecosystem. Numerous positive associations have been established between biomass abundance and species diversity [88–91]. Vegetation is the main component of ecosystem biomass and provides the vital resources required both by animals and microbes for their survival. This is illustrated in Table 1 [92]. Along with plants and animals, microbes are a vital component of the soil and constitute a large percentage of the soil biomass. One cubic meter of soil may support up to 200,000 arthropods, 10,000 earthworms, plus billions of microbes [74,93,94]. A hectare of productive soil may have a biomass of invertebrates and microbes weighing up to 10,000 kg/ha (Table 1). In addition, soil bacteria and fungi add 4000 to 6000 species and in this way contribute significantly to biodiversity especially in moist, organic soils [52,74].

Erosion rates that are 10 to 20 times above the sustainability rate or soil formation rates of 0.5–1 t/ha/year reduce the diversity and abundance of soil organisms [74,95]. In contrast, agricultural practices that control erosion and maintain adequate soil organic matter favor the proliferation of soil biota [74,96,97]. The application of organic matter or manure also enhances the biodiversity in the soil [74,98]. Species diversity of macrofauna (mostly arthropods) increased 16% when organic matter or manure was added to experimental wheat plots in Russia [99]. Similarly, species diversity of macrofauna (mostly arthropods) more than doubled when organic manure was added to grassland plots in Japan [100], and increased 10-fold in Hungarian farm land [101].

Table 1. Biomass of various organisms per hectare in a temperate region pasture [92].

Organism	Biomass (kg fresh weight)
Plants	20,000
Fungi	4,000
Bacteria	3,000
Arthropods	1,000
Annelids	1,320
Protozoa	380
Algae	200
Nematodes	120
Mammals	1.2
Birds	0.3

Field experiments using collards confirm the relationship between biomass and biodiversity in which arthropods species diversity rose 4-fold in experimental plots with the highest collard biomass compared with that found in control collard plots [102]. Depending on the soil type, ecological characteristics of the area, and land use practices, one hectare of productive soil can contain as many as 21,000 species [74]. In a study of bird populations, a strong correlation between plant biomass productivity and bird species diversity was reported when a 100-fold increase in plant biomass yielded a 10-fold increase in bird species diversity [87].

Soil erosion has indirect effects on ecosystems that may be nearly as damaging as the direct effects in reducing plant biomass productivity. Tilman and Downing [103] found that the stability and biodiversity of grasslands were significantly reduced when the number of plant species decreased; as plant species richness decreased from 25 species to five or less, the grassland became less resistant to drought. The overall result was that the grassland was more susceptible to drought conditions and required more time to recover its productivity than when a greater abundance of plant species was present.

Sometimes soil erosion causes the loss of a keystone species, and that keystone species' absence may have a cascading effect on the survival of a wide array of other species within the ecosystem. Species that act as keystone species include the dominant plant type, like oaks, that maintain the biomass productivity and integrity of the ecosystem; predators and parasites that control the feeding pressure of some organisms on major plants; pollinators of various plants in the ecosystem; seed dispersers; as well as the plants and animals that provide habitats required by other essential species like biological nitrogen fixers [72,74]. Thus, in diverse ways, the normal activities within an ecosystem may be interrupted when the populations of keystone species are significantly altered. The damages inflicted can be severe in agro-ecosystems when, for instance, the numbers of pollinators are drastically reduced or even eliminated and there is little or no reproduction in the plants affected [2,74].

Soil biota perform many beneficial activities that improve soil quality and ultimately its productivity [74,96,104,105]. For example, soil biota recycle basic nutrients required by plants for their growth [74]. In addition, the tunneling and burrowing activities of earthworms and other soil biota enhance soil productivity by increasing water infiltration [104]. Earthworms, for instance, may construct up to 220 tunnel channels per square meter in old bush fallow areas in Nigeria while cultivated areas had only 34 channels per square meter and the channel diameters in the cultivated areas were narrower [106]. These channel openings enable the water to infiltrate rapidly into the soil. Other soil biota contribute to soil formation and productivity by mixing the soil components, enhancing aggregate stability, and preventing soil crusting. This churning and mixing of the upper soil redistributes nutrients, aerates the soil, exposes soil to the weather for soil formation, and increases water infiltration rates, thus making soil conditions favorable for increased soil formation and plant productivity. Earthworms bring from 10 to 500 t/ha/year of soil from underground to the soil surface [107,108], while some insects, like ants, may bring 34 t/ha/year of soil to the surface [109,110]. Snails are reported to help the formation of 1000 kg/ha of soil per year [111].

6. Sediments and Wind Blown Soil Particles

Beyond the damage to rain fed agricultural and forestry ecosystems, the effects of erosion reach far into surrounding environments [112]. For instance, large amounts of eroded soil are deposited into streams, rivers, lakes, and other ecosystems. The USDA [60] reports that 60% of water-eroded soil ends up in streams. In China, approximately 1–2 billion tons/year of soil was transported down the Yellow River into the Yellow Sea from 1950–1970 but since the late 1980s the sediment load has decreased due to better soil conservation practices on the Loess Plateau, and the greater use of Yellow River water for irrigation, human consumption and industrial uses [113–115]. The most costly off-site damages occur when soil particles enter lake or river systems [116,117]. Of the 75 billion tons of soil lost worldwide, approximately two-thirds become deposited in lakes and rivers [60,118]. In some areas, heavy sedimentation leads to river and lake flooding [38,39]. Some of the flooding that occurred in the midwestern United States during the summer of 1993 was caused by increased sediment deposition in the Mississippi and Missouri Rivers. These deposits raised the level of the waterways, making them more prone to overflowing and flooding [119]. Sediments disrupt and harm aquatic life by contaminating the water with soil particles, fertilizers, and pesticides [120]. Siltation of reservoirs and dams reduces water storage, increases the maintenance cost of the dams, and shortens the life of the reservoirs [2].

Wind-eroded soil also causes off-site damage because soil particles propelled by strong winds act as abrasives and air pollutants [121,122]. Soil particles sand-blast U.S. automobiles and buildings and caused an estimated $8 billion in damage each year during the 1980s [2,123]. A prime example of the environmental impact of wind erosion occurs in the U.S., where wind erosion rates average 13 t/ha/year on cropland and sometimes reach 65 t/ha/year [124]. Yearly off-site erosion costs in New Mexico in 1984, including health and property damage, are estimated to be nearly $500 million [123]. The estimated total damage from wind erosion in the U.S. was estimated to cost nearly $10 billion each year in the 1990s [2].

The long range transport of dust by wind has implications for health worldwide. Griffin *et al*. [125] report that about 20 human infectious disease organisms, like anthrax and tuberculosis, are easily carried in the soil particles transported by the wind. Inhaled dust can also cause problems such as irritation of the respiratory passages and diseases such as lung cancer and dust can carry harmful materials such as organic chemicals, heavy metals, and radioactive materials into the lungs [81].

Soil erosion contributes to global warming because CO_2 is added to the atmosphere when enormous amounts of biomass in the soil are exposed to the air and oxidized [86,126–129]. One hectare of soil may contain about 100 tons of organic matter or biomass; if eroded and oxidized, this erosion would contribute about 45 tons of carbon to the atmosphere. A feedback mechanism exists wherein increased global warming intensifies rainfall which, in turn, increases erosion and continues the cycle [128].

7. Conservation Technologies and Research

Estimates are that agricultural land degradation alone can be expected to depress world food production as much as 30% during the next 50 years [49]. This forecast emphasizes the need to implement known soil conservation techniques. These soil conservation techniques include biomass mulches, crop rotations, no-till, ridge-till, added grass strips, shelterbelts, contour row-crop planting, and various combinations of these. Basically all of these techniques require keeping the land protected from wind and rainfall energy by using some form of biomass cover on the land which means either leaving most of the crop residues on the cropland or planting cover vegetation on a harvested cropland [2,3,11].

In the U.S. during the past decade, soil erosion rates on croplands have been reduced over 25% using various soil conservation technologies [57,130]. Yet, even with the decline in erosion, soil is still being lost at a rate 10 to 15 times above sustainability [64]. However, soil erosion rates on pasture and rangelands have not declined during the past 20 to 30 years and still remain six times above sustainability [64].

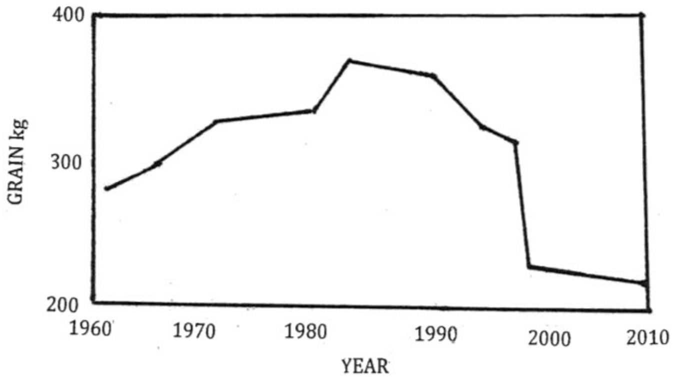
8. Conclusion: Productive Soils and Food Security

Soil erosion is a disastrous environmental problem throughout the world. Erosion is a slow insidious problem that is continuous. Indeed, 1 mm of soil, easily lost in one rain or wind storm, is so minute that its loss goes unnoticed by the farmer and others. Yet this loss of soil over a hectare of cropland amounts to about 15 t/ha. Replenishing this amount of soil under agricultural conditions requires approximately 20 years, meanwhile the lost soil is not available to support crops. Along with the loss of soil is the loss of water, nutrients, soil organic matter, and soil biota. The soil system is severely harmed when soil erosion is allowed to occur.

Future food security is threatened where cropland degradation is allowed to occur because of significantly reduced crop productivity. Shortages of cropland are already having negative impacts on world food production [131,132]. For example, the Food and Agricultural Organization (FAO) of the United Nations reports that the per capita grain production has been declining for more than two decades, based on the availability of grains (Figure 3). Note, cereal grains make up more than 80% of the world's food. Although grain yields per hectare in both developed and developing nations are still increasing, these increases are slowing.

Worldwide, soil erosion continues unabated while the human population continues to increase rapidly and 66% of the world population is now malnourished [4]. If soil conservation is ignored and population control is ignored, more malnourished people and more deaths will occur.

Figure 3. Cereal Grain Production per capita in the world from 1961 to 2010 [58,133].



Acknowledgments

We wish to express our sincere gratitude to the Cornell Association of Professors Emeriti for the partial support of our research through the Albert Podell Grant Program.

References

1. Lal, R.; Stewart, B.A. *Soil Degradation*; Springer-Verlag: New York, NY, USA, 1990.
2. Pimentel, D.; Harvey, C.; Resosudarmo, P.; Sinclair, K.; Kurz, D.; McNair, M.; Crist, S.; Sphpritz, L.; Fitton, L.; Saffouri, R.; *et al*. Environmental and economic costs of soil erosion and conservation benefits. *Science* **1995**, *267*, 1117–1123.
3. Troeh, F.R.; Hobbs, A.H.; Donahue, R.L. *Soil and Water Conservation: For Productivity and Environmental Protection*; Prentice Hall: Upper Saddle River, NJ, USA, 2004.
4. WHO. *Nutrition for Health and Development: A Global Agenda for Combating Malnutrition*; Progress Report; World Health Organization, Nutrition for Health and Development (NHD), Sustainable Development and Healthy Environments (SDE): Rome, Italy, 2000. Available online: http://whqlibdoc.who.int/hq/2000/WHO_NHD_00.6.pdf (accessed on 1 August 2013).
5. Pimentel, D.; Satkiewicz, P. Malnutrition. In *Encyclopedia of Sustainability, Volume Natural Resources and Sustainability*; Berkshire Publishing Group: Great Barrington, MA, USA, 2013, in press.
6. *Webster's Third New International Dictionary of the English Language Unabridged*; Gove, P.B., Ed.; G. & C. Merriam Co.: Springfield, MA, USA, 1971.
7. UN. World Population Prospects: The 2010 Revision. Volume I: Comprehensive Tables. ST/ESA/SER.A/313. United Nations, New York, USA, 2011. Available online: http://esa.un.org/unpd/wpp/Documentation/pdf/WPP2010_Volume-I_Comprehensive-Tables.pdf (accessed on 1 August 2013).
8. FAO. FAO Food Balance Sheets. FAOSTAT, Food and Agriculture Organization of the United Nations, 2004. Available online: http://faostat.fao.org/site/368/default.aspx#ancor (accessed on 1 August 2013).
9. Young, A. *Land Resources: Now and for the Future*; Cambridge University Press: Cambridge, UK, 1998.
10. Lal, R. Enhancing crop yield in the developing countries through restoration of soil organic carbon pool in agricultural lands. *Land Degrad. Dev.* **2006**, *17*, 197–209.

11. Pimentel, D. Soil erosion: A food and environmental threat. *Environ. Dev. Sustain.* **2006**, *8*, 119–137.
12. Pimentel, D. Cornell University, Ithaca, NY, USA. Personal Communication, 18 July 2013.
13. Troeh, F.R.; Hobbs, J.A.; Donahue, R.L. *Soil and Water Conservation*, 3rd ed.; Prentice Hall: Upper Saddle River, NJ, USA, 1999.
14. Oldeman, L.R. Soil degradation: A threat to food security? Report 98/01; International Soil Reference and Information Centre, Wageningen, The Netherlands, 1998. Available online: http://www.isric.org/isric/webdocs/Docs/ISRIC_Report_1998_01.pdf (accessed on 1 August 2013).
15. SeaWIFS Project, NASA/Goddard Space Flight Center and ORBIMAGE, 2000. Available online: http://visibleearth.nasa.gov/view.php?id=53872 (accessed on 1 August 2013).
16. Bajracharya, R.M.; Lal, R. Seasonal soil loss and erodibility variation on a Miamian silt loam soil. *Soil Sci. Soc. Am. J.* **1992**, *56*, 1560–1565.
17. Pimentel, D.; Hepperly, P.; Hanson, J.; Douds, D.; Seidel, R. Environmental, energetic and economic comparisons of organic and conventional farming systems. *BioScience* **2005**, *55*, 573–582.
18. Trimble, S.W.; Mendel, A.C. The cow as a geomorphic agent—A critical review. *Geomorphology* **1995**, *13*, 233–253.
19. Singh, T.V.; Kaur, J. *Studies in Himalayan Ecology and Development Strategies*, revised ed.; Himalayan Books: New Delhi, India, 1989.
20. Haigh, M.J.; Rawat, J.S.; Rawatc, M.S.; Bartarya, S.K.; Rai, S.P. Interactions between forest and landslide activity along new highways in the Kumaun Himalaya. *For. Ecol. Manag.* **1995**, *78*, 173–189.
21. Wye Research and Education Center. Riparian Forest Buffer Panel (Bay Area Regulatory Programs), 2002. Available online: http://www.riparianbuffers.umd.edu/manuals/regulatory.html (accessed on 1 August 2013).
22. Wen, D. Soil Erosion and Conservation in China. In *Soil Erosion and Conservation*; Pimentel, D., Ed.; Cambridge University Press: New York, NY, USA, 1993; pp. 63–86.
23. Hassan, M.K.; Pelkonen, P.; Pappinen, A. Assessment of bioenergy potential from major crop residues and wood fuels in Bangladesh. *J. Basic Appl. Sci. Res.* **2011**, *1*, 1039–1051.
24. Li, L.; Ishikawa, Y.; Mihara, M. Effects of burning crop residues on soil quality in Wenshui, Shanxi of China. IJERD 3-1, 2012. Available online: http://iserd.net/ijerd31/31030.pdf (accessed on 1 August 2013).
25. Lal, R. There is No Such Thing as a Free Biofuel From Crop Residues. Soil Science Society of America, Past President's Message Archive, 2007. Available online: https://www.soils.org/about-society/presidents-message/archive/2 (accessed on 1 August 2013).
26. McLaughlin, L. Soil Conservation Planning in the People's Republic of China: An Alternative Approach. Ph.D. Thesis, Cornell University, Ithaca, NY, USA, 1991.
27. Juo, A.S.R.; Thurow, T.L. Sustainable Technologies for Use and Conservation of Steeplands. Food & Fertilizer Technology Center for the Asian and Pacific Region Bulletin 448, 1997. Available online: http://www.agnet.org/library.php?func=view&id=20110804181442&type_id=4 (accessed on 1 August 2013).

28. Gupta, J.P.; Raina, P. Wind Erosion and Its Control on Hot Arid Areas of Rajasthan. In *Wind Erosion in West Africa: The Problem and Its Control*; Buerkert, B., Allison, B.E., von Oppen, M., Eds.; Margraf Verlag: Berlin, Germany, 1996; pp. 209–218.
29. USDA/NRCS. 2007 National Resources Inventory: Soil Erosion on Cropland. U.S. Department of Agriculture/National Resources Conservation Service, 2010. Available online: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_012269.pdf (accessed on 1 August 2013).
30. Grimm, M.; Jones, R.; Montanarella, L. Soil Erosion Risk in Europe (Revised). European Soil Bureau, Institute for Environment & Sustainability, Joint Research Centre, 2002 (revised). Available online: http://www.env-edu.gr/Documents/Soil%20Erosion%20Risk%20in%20Europe.pdf (accessed on 1 August 2013).
31. Verheijen, F.G.A.; Jones, R.J.A.; Rickson, R.J.; Smith, C.J. Tolerable versus actual erosion rates in Europe. *Earth Sci. Rev.* **2009**, *94*, 23–38.
32. FAO. Restoring the Land. Food and Agriculture Organization of the United Nations, Rome, Italy. Available online: http://www.fao.org/docrep/u8480e/u8480e0d.htm (accessed on 1 August 2013).
33. IECA. Erosion Control—A Global Perspective. In Proceedings of Conference XXII, International Erosion Control Association, Orlando, FL, USA, 20–22 February 1991.
34. Morrow, S.; Smolen, M.; Stiegler, J.; Cole, J. Using Vegetation for Erosion Control on Construction Sites. Oklahoma Cooperative Extension Service BAE-1514. Available online: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-2264/BAE-1514web.pdf (accessed on 1 August 2013).
35. SWCC. Alabama Handbook for Erosion Control, Sediment Control and Stormwater Management on Construction Sites and Urban Areas. Soil and Water Conservation Committee, State of Alabama, 2009. Available online: http://www.swcc.alabama.gov/pages/erosion_handbook.aspx (accessed on 1 August 2013).
36. Patric, J.H. Soil erosion in the eastern forest. *J. For.* **1976**, *74*, 671–677.
37. DeVere Burton, L. *Agricscience: Fundamentals and Applications*; Delmar Cengage Learning: Clifton Park, NY, USA, 2010.
38. Myers, N. *Gaia: An Atlas of Planet Management*; Anchor/DoubleDay: Garden City, NY, USA, 1993.
39. Eswaran, H.; Lal, R.; Reich, P.F. Land Degradation: An overview. In *Response to Land Degradation*, Proceedings of the 2nd International Conference on Land Degradation and Desertification, Khon Kaen, Thailand, 25–29 January 1999; Bridges, E.M., Hannam, I.D., Oldeman, L.R., Pening de Vries, F.W.T., Scherr, S.J., Sompatpanit, S., Eds.; Oxford University Press: New Delhi, India, 2002. Available online: http://soils.usda.gov/use/worldsoils/papers/land-degradation-overview.html (accessed on 1 August 2013).

40. Reich, P.; Eswaran, H.; Beinroth, F. Global Dimensions of Vulnerability to Wind and Rain Erosion. In *Sustaining the Global Farm*, Proceedings of the 10th International Soil Conservation Organization Meeting, 24–29 May 1999; Stott, D.E., Mohtar, R.H., Steinhardt, G.C., Eds.; pp. 838–846. Available online: http://topsoil.nserl.purdue.edu/nserlweb-old/isco99/pdf/ISCOdisc/tableofcontents.htm (accessed on 1 August 2013).
41. Wen, D. Agriculture in China: Water and Energy Resources. In *Agriculture in China: 1949–2030*; Tso, T., Tuan, F., Faust, M., Eds.; IDEALS: Beltsville, MD, USA, 1998; pp. 479–497. Available online: http://conservancy.umn.edu/handle/58873 (accessed on 1 August 2013).
42. The Hindu. India losing 5,334 million tonnes of soil annually due to erosion: Govt. The Hindu, 26 November 2010. Available online: http://www.thehindu.com/sci-tech/agriculture/india-losing-5334-million-tonnes-of-soil-annually-due-to-erosion-govt/article915245.ece (accessed on 1 August 2013).
43. Stedman, L. China: Study Finds Entire Country Suffering Significant Soil and Water Losses. IWA Publishing, 27 January 2009. Available online: http://www.iwapublishing.com/template.cfm?name=news245 (accessed on 1 August 2013).
44. Jie, D. Chinese Soil Experts Warn Of Massive Threat to Food Security. SciDevNet, 5 August 2010. Available online: http://www.scidev.net/global/earth-science/news/chinese-soil-experts-warn-of-massive-threat-to-food-security.html (accessed on 11 July 2013).
45. Pimentel, D.; Pimentel, M. *Food, Energy, and Society*; CRC Press: Boca Raton, FL, USA, 2008.
46. *World Resources 1996–1997: The Urban Environment*; World Resources Institute: Oxford University Press: New York, NY, USA, 1997. Available online: http://www.wri.org/publication/world-resources-1996-97-urban-environment (accessed on 1 August 2013).
47. Lal, R. Water management in various crop production systems related to soil tillage. *Soil Tillage Res.* **1994**, *30*, 169–185.
48. Speth, J.G. *Towards an Effective and Operational International Convention on Desertification*; International Convention on Desertification, Int. Negotiating Comm, United Nations: New York, NY, USA, 1994.
49. Kendall, H.W.; Pimentel, D. Constraints on the expansion of the global food supply. *Ambio* **1994**, *23*, 198–205.
50. *World Resources 1994–1995: People and the Environment*; World Resources Institute: Oxford University Press: New York, NY, USA, 1994. Available online: http://www.wri.org/publication/world-resources-1994-95-people-and-environment (accessed on 1 August 2013).
51. Lal, R. Soil Erosion and Land Degradation: The Global Risks. In *Soil degradation*; Lal, R., Stewart, B.A., Eds.; Springer-Verlag: New York, NY, USA, 1990; pp. 129–172.
52. Heywood, V.H. *Global Biodiversity Assessment*; Cambridge University Press: Cambridge, UK, 1995.
53. Faeth, P.; Crosson, P. Building the case for sustainable agriculture. *Environment* **1994**, *36*, 16–20.
54. Stone, R.P.; Moore, N. Control of Soil Erosion. Ontario Ministry of Agriculture Factsheet, 1997. Available online: http://www.omafra.gov.on.ca/english/engineer/facts/95-089.htm (accessed on 1 August 2013).
55. Southgate, D.; Whitaker, M. Promoting resource degradation in Latin America: Tropical deforestation, soil erosion, and coastal ecosystem disturbance in Ecuador. *Econ. Dev. Cult. Change* **1992**, *40*, 787–807.

56. Lal, R. Erosion-crop productivity relationships for soils of Africa. *Soil Sci. Soc. Am. J.* **1995**, *59*, 661–667.
57. USDA. *Changes in Average Annual Soil Erosion by Water on Cropland and CRP Land, 1992–1997*; Revised December 2000; USDA, Natural Resources Conservation Service: Washington, DC, USA, 2000. Available online: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/?cid=nrcs143_013789 (accessed 1 August 2013).
58. Sundquist, B. Chapter 9—Food Supply from Soil. In Topsoil Loss and Degradation—Causes, Effects and Implications, 2010. Available online: http://home.windstream.net/bsundquist1/se9.html (accessed on 1 August 2013).
59. Klee, G.A. *Conservation of Natural Resources*; Prentice Hall: Englewood Cliffs, NJ, USA, 1991.
60. USDA. *The Second RCA Appraisal. Soil, Water, and Related Resources on Nonfederal Land in the United States, Analysis of Conditions and Trends*; U.S. Department of Agriculture, U.S. Government Print Office: Washington, DC, USA, 1989.
61. Duffy, M. Value of Soil Erosion to the Land Owner. Agr Decision Maker, File A1-75 (August 2012). Iowa State University, Extension and Outreach, 2012. Available online: http://www.extension.iastate.edu/agdm/crops/html/a1-75.html (accessed on 1 August 2013).
62. Ebbert, J.C.; Roe, R.D. *Soil Erosion in the Palouse River Basin: Indications of Improvement*; Science for a changing world, USGS Fact Sheet FS-069-98; US Geological Survey: Reston, VA, USA, 1998.
63. World Problems. In *Encyclopedia of World Problems and Human Potential*, 4th ed.; Saur, K.D., Ed.; Union of International Associations: München, Germany, 1995; Volume 1.
64. NAS. *Frontiers in Agricultural Research: Food, Health, Environment and Communities*; National Academy of Sciences, National Research Council, National Academies Press: Washington, DC, USA, 2003.
65. Johnson, P.W. *Agriculture. Food and Drug Administration, Rural Development*; U.S. Government Printing Office: Washington, DC, USA, 1995.
66. Bailey, A.W. Managing Canadian Rangelands as a Sustainable Resource: Policy Issues. In *Rangelands in a Sustainable Biosphere*, Proceedings of the Fifth International Rangeland Congress, Salt Lake City, UT, USA, 23–28 July 1995; Society for Range Management: Denver, CO, USA, 1996; Volume 2, pp. 5–7.
67. Campbell, L.C. Managing soil fertility decline. *J. Crop Prod.* **1998**, *1*, 29–52.
68. UN-NADAF. UN-NADAF mid-term review: Focus on key sectors: Environment. *Afr. Recovery* **1996**, *10*, 23.
69. Behnke, R.H., Jr.; Scoones, I. Rethinking Range Ecology: Implications for Rangeland Management in Africa. In *Range Ecology at Disequilibrium: New Models of Natural Variability and Pastoral Adaptation in African Savannas*; Behnke, R.H., Jr., Scoones, I., Kerven, C., Eds.; Overseas Development Institute, International Institute for Environment and Development Commonwealth Secretariat: London, UK, 1993; pp. 1–30.

70. Bartels, G.B.; Norton, B.E.; Perrier, G.K. An Examination of the Carrying CapaCity Concept. In *Range Ecology at Disequilibrium: New Models of Natural Variability and Pastoral Adaptation in African Savannas*; Behnke, R.H., Jr., Scoones, I., Kerven, C., Eds.; Overseas Development Institute, International Institute for Environment and Development Commonwealth Secretariat: London, UK, 1993; pp. 89–103.
71. Roose, E. Soil and Water Conservation Lessons from Steep-Slope Farming in French Speaking Countries of Africa. In *Conservation Farming on Steep Lands*; Moldenhauer, W.C., Hudson, N., Eds.; Soil and Water Conservation Society, World Association of Soil and Water Conservation: Ankeny, IA, USA, 1988; pp. 130–131.
72. Daily, G. *Nature's Services: Societal Dependence on Natural Ecosystems*; Island Press: Washington, DC, USA, 1996.
73. Jones, A.J.; Lal, R.; Huggins, D.R. Soil erosion and productivity research: A regional approach. *Am. J. Altern. Agric.* **1997**, *12*, 183–192.
74. Pimentel, D.; Petrova, T.; Riley, M.; Jacquet, J.; Ng, V.; Honigman, J.; Valero, E. Conservation of Biological Diversity in Agricultural, Forestry, and Marine Systems. In *Focus on Ecology Research*; Burk, A.R., Ed.; Nova Science Publishers: New York, NY, USA, 2006; pp. 151–173.
75. Brevik, E.C. Soil Health and Productivity. In *Soils, Plant Growth and Crop Production*; Verheye, W., Ed.; Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, EOLSS Publishers: Oxford, UK, 2009. Available online: http://www.eolss.net (accessed on 1 August 2013).
76. Pimentel, D.; Houser, J.; Preiss, E.; White, O.; Fang, H.; Mesnick, L.; Barksy, T.; Tariche, S.; Schreck, J.; Alpert, S. Water resources: Agriculture, the environment, and society. *BioScience* **1997**, *47*, 97–106.
77. Pimentel, D.; Berger, B.; Filiberto, D.; Newton, M.; Wolfe, B.; Karabinakis, B.; Clark, S.; Poon, E.; Abbett, E.; Nandagopal, S. Water resources: Agricultural and environmental issues. *BioScience* **2004**, *54*, 909–918.
78. Young, A. *Agroforestry for Soil Conservation*; CAB: Wallingford, UK, 1989.
79. Schertz, D.L.; Moldenhauer, W.C.; Livingston, S.J.; Weesies, G.A.; Hintz, E.A. Effect of past soil erosion on crop productivity in Indiana. *J. Soil Water Conserv.* **1989**, *44*, 604–608.
80. Langdale, G.W.; West, L.T.; Bruce, R.R.; Miller, W.P.; Thomas, A.W. Restoration of eroded soil with conservation tillage. *Soil Technol.* **1992**, *5*, 81–90.
81. Brevik, E.C. Soils and Human Health—An Overview. In *Soils and Human Health*; Brevik, E.C., Burgess, L.C., Eds.; CRC Press: Boca Raton, FL, USA, 2012; pp. 29–56.
82. Allison, F.E. *Soil Organic Matter and Its Role in Crop Production*; Elsevier: New York, NY, USA, 1973.
83. Libert, B. *The Environmental Heritage of Soviet Agriculture*; CAB International: Wallingford, UK, 1995.
84. Wardle, D.A.; Bardgett, R.D.; Klironomos, J.N.; Setala, H.; van der Putten, W.H.; Wall, D.H. Ecological Linkages between aboveground and belowground biota. *Science* **2004**, *304*, 1629–1633.

85. Lazaroff, C. Biodiversity Gives Carbon Sinks a Boost. Environment News Service, 13 April 2001. Available online: http://www.ens-newswire.com/ens/apr2001/2001-04-13-06.asp (accessed on 1 August 2013).
86. Walsh, K.N.; Rowe, M.S. Biodiversity Increases Ecosystems' Ability to Absorb CO_2 and Nitrogen. Brookhaven National Laboratory, 2001. Available online: http://www.bnl.gov/bnlweb/pubaf/pr/2001/bnlpr041101.htm (accessed on 1 August 2013).
87. Wright, D.H. Human impacts on energy flow through natural ecosystems, and replications for species endangerment. *Ambio* **1990**, *19*, 189–194.
88. Elton, C.S. *Animal Ecology*; Sidgwick and Jackson: London, UK, 1927.
89. Odum, E.P. *Fundamentals of Ecology*; Saunders: New York, NY, USA, 1978.
90. Sugden, A.M.; Rands, G.F. The ecology of temperate and cereal fields. *Trends Ecol. Evol.* **1990**, *5*, 205–206.
91. Giampietro, M. Socioeconomic constraints to farming with biodiversity. *Agric. Ecosyst. Environ.* **1997**, *62*, 145–167.
92. Pimentel, D.; Stachow, U.; Takacs, D.A.; Brubaker, H.W.; Dumas, A.R.; Meaney, J.J.; O'Neil, J.; Onsi, D.E.; Corzilius, D.B. Conserving biological diversity in agricultural/forestry systems. *BioScience* **1992**, *42*, 354–362.
93. Wood, M. *Soil Biology*; Blackie, Chapman and Hall: New York, NY, USA, 1989.
94. Lee, E.; Foster, R.C. Soil fauna and soil structure. *Aust. J. Soil Res.* **1991**, *29*, 745–776.
95. Atlavinyte, O. The effect of erosion on the population of earthworms (Lumbricidae) in soils under different crops. *Pedobiologia* **1965**, *5*, 178–188.
96. FAO. Soils. In *Land Resources*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2001. Available online: http://www.fao.org/nr/land/soils/en/ (accessed on 1 August 2013).
97. Reid, W.S. Regional Effects of Soil Erosion on Crop Productivity-Northeast. In *Soil Erosion and Crop Productivity*; Follett, R.F., Stewart, B.A., Eds.; American Society of Agronomy: Madison, WI, USA, 1985; pp. 235–250.
98. Hepperly, P.; Seidel, R.; Pimentel, D.; Hanson, J.; Douds, D. Organic Farming Enhances Soil Carbon and Its Benefits. In *Soil Carbon Management: Economic, Environmental and Social Benefits*; Kimble, J.M., Rice, C.W., Eds.; CRC Press: Boca Raton, FL, USA, 2007; pp. 129–153.
99. Bohac, J.; Pokarzhevsky, A. Effect of Manure and NPK on Soil Macrofauna in Chernozem Soil. In Proceedings of the 9th International Symposium on Soil Biology and Conservation of Biosphere, Budapest, Hungary, 27–30 September 1985; Szegi, J., Ed.; Akademiai Kiado: Budapest, Hungary, 1987; pp. 15–19.
100. Kitazawa, Y.; Kitazawa, T. Influence of Application of a Fungicide, an Insecticide, and Compost upon Soil Biotic Community. In *Soil Biology as Related to Land Use Practices*; Sindal, D.L., Ed.; Environmental Protection Agency, Office of Pesticide and Toxic Substances: Washington, DC, USA, 1980; pp. 94–99.
101. Olah-Zsupos, A.; Helmeczi, B. The Effect of Soil Conditioners on Soil Microorganisms. In Proceedings of the 9th International Symposium on Soil Biology and Conservation of Biosphere, Budapest, Hungary, 27–30 September 1985; Szegi, J., Ed.; Akademiai Kiado: Budapest, Hungary, 1987; pp. 829–837.

102. Pimentel, D.; Warneke, A. Ecological effects of manure, sewage sludge, and other organic wastes on arthropod populations. *Agric. Zool. Rev.* **1989**, *3*, 1–30.
103. Tilman, D.; Downing, J.A. Biodiversity and stability in grasslands. *Nature* **1994**, *367*, 363–365.
104. Witt, B. Using Soil Fauna to Improve Soil Health. University of Minnesota Digital Conservancy, 1997. Available online: http://conservancy.umn.edu/bitstream/58873/1/2.8.Witt.pdf (accessed on 1 August 2013).
105. Sugden, A.M.; Stone, R.; Ash, C. Ecology in the underworld. *Science* **2004**, *304*, 1613.
106. Aina, P.O. Contribution of earthworms to porosity and water infiltration in the tropical soil under forest and long-term cultivation. *Pedobiologia* **1984**, *26*, 131–136.
107. Lavelle, P. The soil fauna of tropical savannas II. The earthworms. *Ecosyst. World* **1983**, *13*, 485–504.
108. Lee, K.E. *Earthworms: Their Ecology and Relationships with Soils and Land Use*; Academic Press: Orlando, FL, USA, 1985.
109. Lockaby, B.G.; Adams, J.C. Pedoturbation of a forest soil by fire ants. *Soil Sci. Soc. Am. J.* **1985**, *49*, 220–223.
110. Van Vliet, P.C.J.; Hendrix, P.F. Role of Fauna in Soil Physical Processes. In *Soil Biological Fertility: A Key to Sustainable Land Use in Agriculture*; Abbott, L.K., Murphy, D.V., Eds.; Springer: Dordrecht, The Netherlands, 2007; pp. 61–80.
111. Shachak, M.; Jones, C.G.; Brand, S. The Role of Animals in an Arid Ecosystem: Snails and Isopods as Controllers of Soil Formation, Erosion and Desalinization. In *Arid Ecosystems*; Blume, H.-P., Berkowicz, S.M., Eds.; Catena: Cremlingen-Destedt, Germany, 1995; pp. 37–50.
112. Ziemer, R.R. Flooding and stormflows. In *Proceedings of the Conference on Coastal Watersheds: The Caspar Creek story, Ukia, CA*; Technical Report PSW-GTR-168; Pacific Southwest Research Station, USDA Forest Service: Albany, CA, USA, 1998; pp. 15–24.
113. McLaughlin, L. A Case Study in Dingxi County, Gansu Province, China. In *World Soil Erosion and Conservation*; Pimentel, D., Ed.; Cambridge University Press: Cambridge, UK, 1993; pp. 87–107.
114. Zhang, X.; Walling, D.E.; Quine, T.A.; Wen, A. Use of reservoir deposits and caesium-137 measurements to investigate the erosional response of a small drainage basin in the rolling loess plateau region of China. *Land Degrad. Dev.* **1997**, *8*, 1–16.
115. Yang, Z.S.; Milliman, J.D.; Galler, J.; Liu, J.P. Yellow River's Water and Sediment Discharge Decreasing Steadily. *Eos. Trans. Am. Geophys. Union* **1998**, *79*, 589–592.
116. Watershed. Cumulative Watershed Effects. Klamath Resource Information System (KRIS), 2002. Available online: http://www.krisweb.com/watershd/impacts.htm (accessed on 1 August 2013).
117. Ontario Envirothon. [Chapter 7] Soil Erosion. Ontario Envirothon, A Program of Ontario Forestry Association, 2007. Available online: http://www.ontarioenvirothon.on.ca/files/soil/soil_Chapter7.pdf (accessed on 1 August 2013).
118. Pimentel, D. Soil erosion. *Environment* **1997**, *39*, 4–5.
119. Britt, R.R. History Repeats: The Great Flood of 1993. LiveScience, 2008. Available online: http://www.livescience.com/7508-history-repeats-great-flood-1993.html (accessed on 1 August 2013).
120. Clark, E.H. Soil Erosion: Offsite Environmental Effects. In *Soil Loss: Processes, Policies, and Prospects*; Harlin, J.M., Bernardi, G.M., Eds.; Westview: New York, NY, USA, 1987; pp. 59–89.

121. WSU Extension. *Controlling Cropland Wind Erosion and Off-Site Impacts in the PNW*; MISC0177; Washington State University Extension Publishing and Printing: Pullman, WA, USA, 1994.
122. USGS. Human Health: Potential Contaminants and Pathogens in Air, Dusts and Soils. U.S, Geological Survey, U.S. Department of the Interior, 2007. Available online: http://health.usgs.gov/inhalation/ (accessed on 1 August 2013).
123. Huszar, P.C.; Piper, S.L. Off-Site Costs of Wind Erosion in New Mexico. In *Off-Site Costs of Soil Erosion: The Proceedings of a Symposium*; Waddell, T.E., Ed.; The Conservation Foundation: Washington, DC, USA, 1985; pp. 143–166.
124. Pimentel, D.; Kounang, N. Ecology of soil erosion in ecosystems. *Ecosystems* **1998**, *1*, 416–426.
125. Griffin, D.W.; Kellogg, C.A.; Shinn, E.A. Dust in the wind: Long range transport of dust in the atmosphere and its implications for global public and ecosystem health. *Glob. Change Hum. Health* **2001**, *2*, 20–33.
126. Phillips, D.L.; White, D.; Johnson, B. Implications of climate change scenarios for soil erosion potential in the USA. *Land Degrad. Dev.* **1993**, *4*, 61–72.
127. Lal, R.; Follett, R.F.; Kimble, J.; Cole, C.V. Managing U.S. cropland to sequester carbon in soil. *J. Soil Water Conserv.* **1999**, *54*, 374–381.
128. Lal, R. One Answer for Cleaner Air, Water: Better Agricultural Practices. Ohio State Research News, 2002. Available online: http://researchnews.osu.edu/archive/sequest.htm (accessed on 12 May 2011).
129. Lal, R. Soil carbon sequestration impacts on global climate change and food security. *Science* **2004**, *304*, 1623–1627.
130. USDA. *Summary Report 1992 National Resources Inventory*; Soil Conservation Service, USDA: Washington, DC, USA, 1994.
131. Pimentel, D.; Bailey, O.; Kim, P.; Mullaney, E.; Calabrese, J.; Walman, L.; Nelson, F.; Yao, X. Will limits of the Earth's resources control human numbers? *Environ. Dev. Sustain.* **1999**, *1*, 19–39.
132. Pimentel, D.; Marklein, A.; Toth, M.A.; Karpoff, M.; Paul, G.S.; McCormack, R.; Kyriazis, J.; Krueger, T. Food versus biofuels: Environmental and economic costs. *Hum. Ecol.* **2009**, *37*, 1–12.
133. FAO. *FAO Quarterly Bulletin of Statistics*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1988–1999; Volume 1–12.