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Review

The Potential Impact of Climate Change on Soil Properties and Processes and Corresponding Influence on Food Security

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Abstract: According to the IPCC, global temperatures are expected to increase between 1.1 and 6.4 °C during the 21st century and precipitation patterns will be altered. Soils are intricately linked to the atmospheric/climate system through the carbon, nitrogen, and hydrologic cycles. Because of this, altered climate will have an effect on soil processes and properties. Recent studies indicate at least some soils may become net sources of atmospheric C, lowering soil organic matter levels. Soil erosion by wind and water is also likely to increase. However, there are many things we need to know more about. How climate change will affect the N cycle and, in turn, how that will affect C storage in soils is a major research need, as is a better understanding of how erosion processes will be influenced by changes in climate. The response of plants to elevated atmospheric CO_2 given limitations in nutrients like N and P, and how that will influence soil organic matter levels, is another critical research need. How soil organic matter levels react to changes in the C and N cycles will influence the ability of soils to support crop growth, which has significant ramifications for food security. Therefore, further study of soil-climate interactions in a changing world is critical to addressing future food security concerns.

Keywords: climate change; food security; soil properties; soil processes; soil health/quality

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1. Introduction

The most recent report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the average global temperature will probably rise between 1.1 and 6.4 °C by 2090–2099 as compared to 1980–1999 temperatures, with the most likely rise being between 1.8 and 4.0 °C (Figure 1) [1]. Climate change will also influence global precipitation patterns, altering both the amount of precipitation received and the distribution of precipitation over the course of an average year in many locations (Figure 2) [1]. With this change in climate there will be effects on the environment, including the soil [2]. Soils are also important to food security [3–6], and climate change has the potential to threaten food security through its effects on soil properties and processes [7]. Understanding these effects, and what we may do to adapt to them, requires an understanding of how climate and soils interact and how changes in climate will lead to corresponding changes in soil. Therefore, this paper will focus on what we know about soil-climate interactions with a particular focus on the C and N cycles, how climate change may alter soil properties and processes, and what that might mean for soil erosion and food security in the future.

Figure 1. Solid lines are global averages of surface warming (relative to 1980–1999) for four climate change models, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for an experiment where concentrations were held constant at year 2000 values, the other lines show increases in greenhouse gas concentrations relative to 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for six modeled scenarios. Figure from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [1].

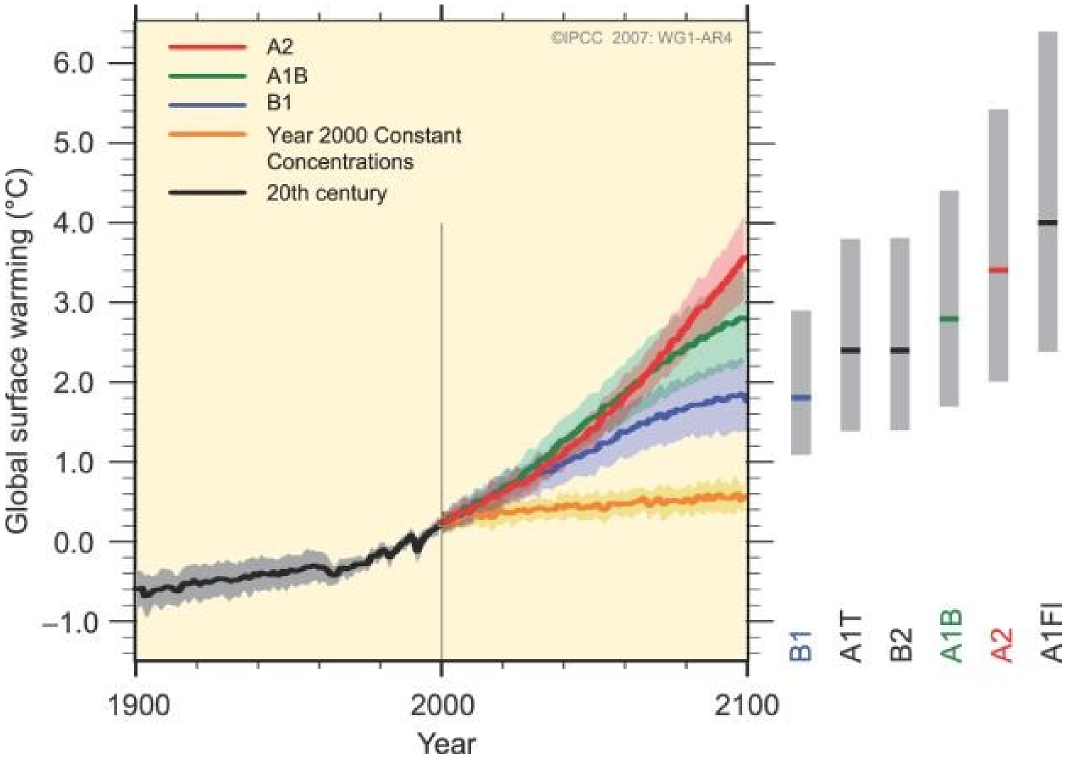
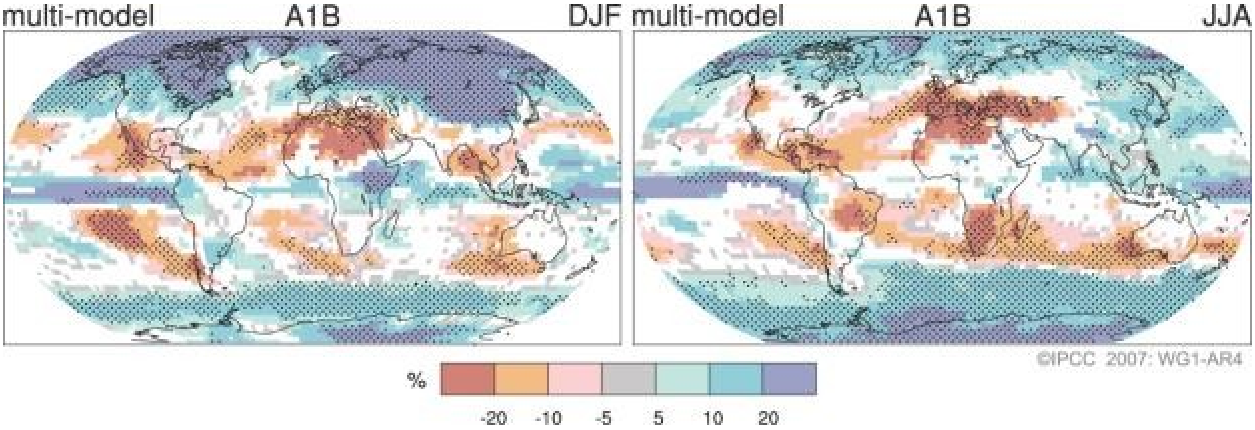


Figure 2. Projected relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages for December to February (**left**) and June to August (**right**). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. Figure from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [1].



2. Soils as a Part of the Global C and N Cycles

Soils are integral parts of several global nutrient cycles. The two that are the most important from the perspective of soils and climate change interactions are the carbon and nitrogen cycles because C and N are important components of soil organic matter [8] and because carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the most important of the long-lived greenhouse gases [9]. The global C and N cycles were in balance with inputs approximately equaling outputs prior to the industrial revolution when low populations and levels of technology minimized the anthropogenic generation of greenhouse gases, but the burning of fossil fuels, tilling of soil, and other human activities have altered the natural balance such that we are now releasing more C and N into the atmosphere each year than is taken up by global sinks [10]. Human management of soils can have a profound impact on the balance of C and N gas emissions from those soils, and therefore influences global climate change [2].

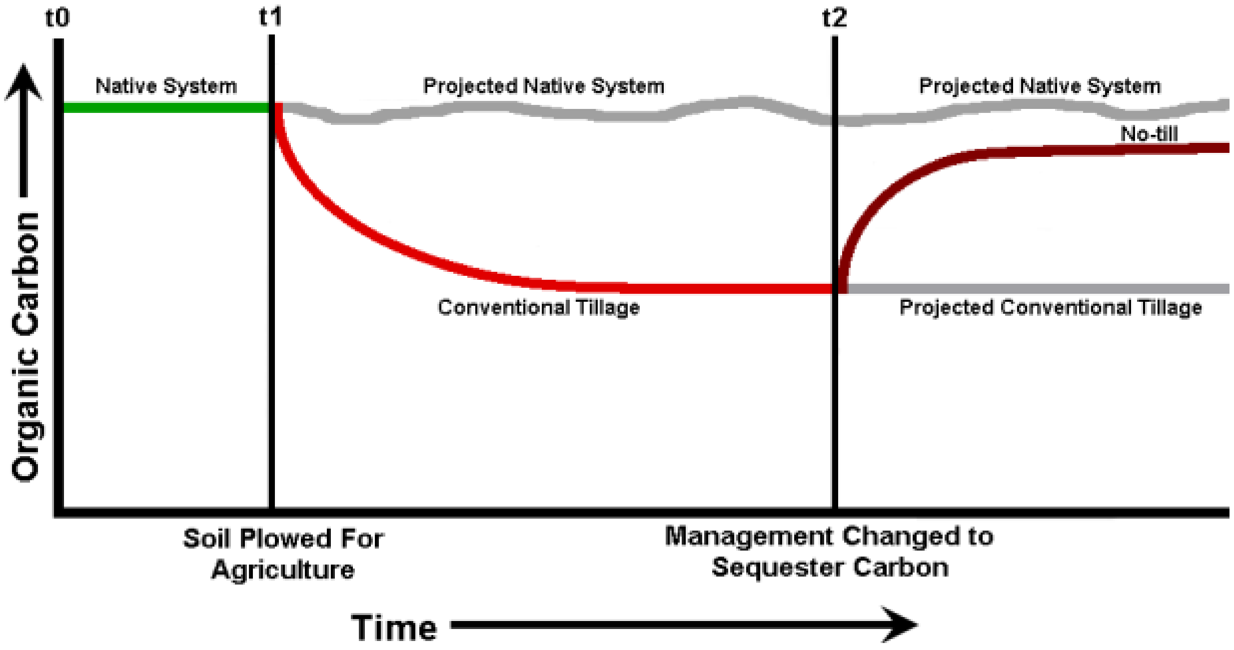
The largest active terrestrial C pool is in soil, which contains an estimated 2,500 Pg of C compared to 620 Pg of C in terrestrial biota and detritus and 780 Pg of C in the atmosphere [4]. Carbon is readily exchanged between these pools; therefore, they are called active pools. In addition to the active pools, there are approximately 90,000,000 Pg of C in the geological formations of Earth's crust, 38,000 Pg of C in the ocean as dissolved carbonates, 10,000 Pg of C sequestered as gas hydrates, and 4,000 Pg of C in fossil fuels [11]. However, most of the C in these pools is locked up over long periods of geologic time and not readily exchanged, leading to these pools being referred to as inactive pools. When discussing agriculturally related aspects of climate change the active pools receive more attention due to the ability of C to move rapidly between them, but the release of C from the inactive pools, particularly though the combustion of fossil fuels, is also an important anthropogenic source of greenhouse gases.

Soils naturally sequester C through the soil-plant system as plants photosynthesize and then add dead tissues to the soil [12–14]. Carbon is also naturally emitted from soils as CO_2 and CH_4 gases due to microbial respiration, with the form of the C gas depending on the oxygen status of the soil system.

Well-aerated soils are dominated by CO_2 emissions, while anaerobic conditions are associated with CH_4 generation. The balance between C added to the soil and C emitted from the soil determines whether the overall C levels in a given soil increase or decrease [13,15]. When C levels in a soil increase that C is taken from the atmosphere, decreasing atmospheric levels, and when C levels in a soil decrease that C is added to the atmosphere, increasing atmospheric levels.

Human actions strongly influence the C balance in managed soils. Soil management techniques such as no-till systems may result in lower CO_2 emissions from and greater C sequestration in the soil as compared to management systems based on intensive tillage (Figure 3) [16–20], although some recent studies have indicated that no-till systems may simply result in higher C accumulations in the upper 15–20 cm of the soil with no increase in C when the entire soil profile is considered [21–23]. Other management changes such as using cover crops, crop rotations instead of monocropping, and reducing or eliminating fallow periods can lead to C sequestration in soil [16,24] as can returning land from agricultural use to native forest or grassland [25,26]. Sequestration of C tends to be rapid initially with declining rates over time (Figure 3) [26–28]. Most agricultural soils will only sequester C for about 50–150 years following management changes before they reach C saturation [4,13].

Figure 3. Tilling a native soil leads to reduced soil organic C levels, while management changes such as a conversion to no-till techniques may lead to increased soil organic C as compared to conventional tillage techniques [2].



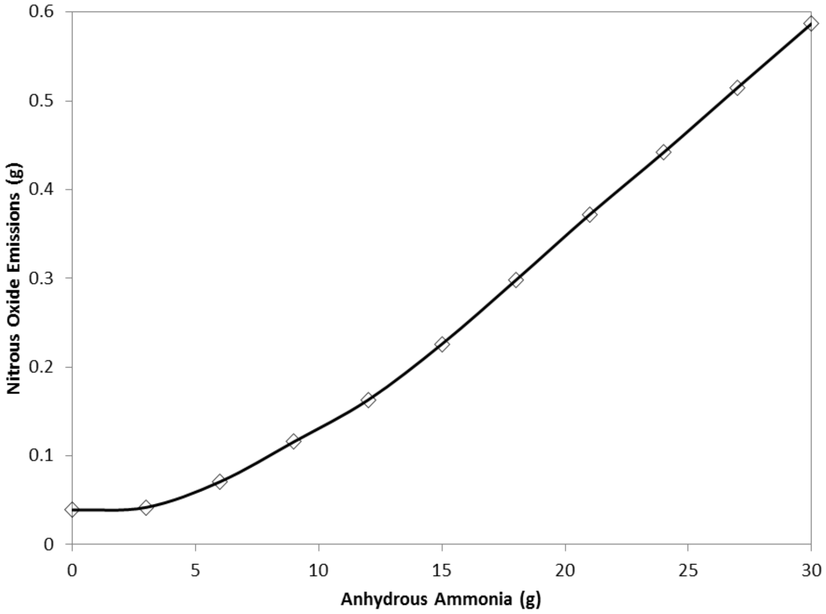
Management decisions can restrict the ability of a soil to sequester C as well. For example, the extensive use of heavy equipment in modern production agriculture has made soil compaction a major problem that has been shown to limit C sequestration [28–30]. Organic soils can be a particular C management challenge as they typically form in wet conditions and have to be drained for agricultural uses. This drainage changes the soil environment from anaerobic to aerobic, which speeds decomposition of the organic matter in the soil and releases greenhouse gases into the atmosphere. A study in Finland that looked at the effect of crops on greenhouse gas fluxes from soils showed that the organic soils in their study were a net source of CO_2 for all cropping systems studied, with average annual emissions ranging from 1500 to 7500 kg CO_2 ha^{-1} [31]. Plowing native soils for agricultural production (Figure 3), introducing more aggressive forms of tillage to an agricultural management system, and draining wetlands are examples of management changes that increase CO_2 emissions from soils [8,25]. It is also true that C that has been sequestered can be returned to the atmosphere at a future time if the management changes that led to its sequestration are altered. In short, managed soils can be either net sinks or net sources of CO_2 depending on their management [13,15].

Methane is another part of the C cycle associated with soils. Agriculture accounts for about 47% of annual global anthropogenic emissions of CH_4 [32]; the main anthropogenic source of soil-derived methane is rice (*Oryza sativa*) production [33,34]. Different vegetation growing on the same soil will cause differences in CH_4 emission or consumption. In a study by Hu *et al.* [35], a soil under forest vegetation acted as a net sink of CH_4 while the same soil in a nearby field planted with maize (*Zea mays*) was essentially CH_4 neutral and a third field of the same soil planted with grass (Poaceane family) cover was a net source of CH_4 to the atmosphere. Hu *et al.* [35] concluded this was due to different physical properties in the soils, controlled by the dominant vegetation, which led to differences in methanotroph survival and gas exchange rates. As with CO_2, management makes a difference in CH_4 fluxes in soil. Dryland tillage and dry seeding or other means of reducing the period of soil saturation during rice production leads to less CH_4 production [34,36]. Wassmann *et al.* [37] found no effect on CH_4 generation in rice paddy soils when adding mineral-based K fertilizers, but Lu *et al.* [38] found that P fertilizers decreased CH_4 emissions. Lu *et al.* [38] attributed the increase in CH_4 emissions in P-deficient soils to increased root exudates as the plant tried to manipulate the soil environment to increase P uptake. Stepniewski *et al.* [34] noted that adding oxidizing mineral fertilizers can reduce CH_4 emissions by 20%–70%. Zhang *et al.* [39] also noted that a mixed management system that incorporated ducks (Anatidae family) into the rice system decreased CH_4 emissions due to mixing of oxygen into paddy waters by the swimming motion of the ducks, increasing oxidation of the CH_4.

Nitrous oxide (N_2O) is created when soil water contents approach field capacity and biological reactions in the soil convert NO_3^- to NO, N_2O, or N_2 [40]. Enhanced microbial production in expanding agricultural lands that are amended with fertilizers and manure is believed to be the primary driver behind increased atmospheric N_2O levels [17,41]. As N fertilizer applications increase, denitrification and the generation of N_2O in the soil also increases (Figure 4) [34,40,42]. Emissions of N_2O are usually lower in organic farming systems than in conventional systems [34]. Some studies have found higher N_2O emissions from tilled soils than from no-till soils [18,34,43], but this is not true in all cases [44]. The conversion of tropical forest to pasture led to an initial increase in N_2O emissions followed by a decline in emissions relative to the original forest in a Brazilian study [45]; however, conversion of tropical forest to fertilized crop production on Borneo led to an order of magnitude increase in N_2O emissions from the agricultural soils as compared to the forest soils [46].

The C and N cycles are key parts of the global climate system, and soils are an integral part of these cycles. Agriculture contributes a particularly large percentage of annual anthropogenic CH_4 emissions to the atmosphere. Agricultural management decisions have a profound influence on whether soils are net sources or sinks of the greenhouse gasses CO_2, CH_4, and N_2O, meaning management systems have the potential to influence climate change. Climate change, in turn, is expected to influence soil erosion and food security, as will be discussed in the next sections. Therefore, the interactions between soils and the atmosphere in a changing climate are important variables as we seek to understand climate change and its potential influence on food security through the erosion cycle. At present, our understanding of how changes in climate will influence the C and N cycles is incomplete, meaning additional research into these questions is needed.

Figure 4. Modeled nitrous oxide emissions per m^2 at various application rates of anhydrous ammonia fertilizer (Data from [42]).



3. Influence of Climate Change on Soil Properties and Processes

Carbon and nitrogen are major components of soil organic matter [8]. Organic matter is important for many soil properties, including structure formation and maintenance, water holding capacity, cation exchange capacity, and for the supply of nutrients to the soil ecosystem [47,48]. Soils with an adequate amount of organic matter tend to be more productive than soils that are depleted in organic matter [47], therefore, one of the biggest questions concerning climate change and its effects on soil processes and properties involve how potential changes in the C and N cycles will influence soils.

Early expectations were that increased atmospheric CO_2 would lead to increased plant productivity coupled with increased C sequestration by soil, meaning increased plant growth and the soil-plant system would help offset increasing atmospheric CO_2 levels [49,50]. This increase in plant growth is known as the CO_2 fertilization effect. However, recent studies indicate the CO_2 fertilization effect may not be as large as originally thought [51–56]. Increasing levels of ozone as the climate changes may actually counteract the CO_2 fertilization effect leading to reduced plant growth under elevated CO_2 [53] and the negative effects of increased temperatures on plant growth may also cancel out any CO_2−fertilization effect that does take place [55]. Nitrogen limitations may negatively affect plant growth [57], and modeling of C dynamics as influenced by N indicates less C sequestration by soil than originally expected given CO_2 fertilization [56]. A long-term elevated CO_2 experiment in a grasslands ecosystem indicated that N and P became limiting within two years, again limiting plant biomass response to elevated CO_2 [58]. Niklaus and Körner [58] concluded that the increases in plant productivity they did see were due primarily to soil moisture status as opposed to a CO_2 fertilization effect. Experiments looking at the decomposition of plant tissues grown under elevated atmospheric CO_2 also indicate that increased levels of CO_2 are emitted during that decomposition [59], and research by Carney *et al.* [60] observed soil organic C levels declining under increased atmospheric CO_2 levels due to increased microbial activity. Therefore, elevated CO_2 levels will not necessarily lead to increased soil C sequestration, but may instead result in more C turnover [61].

Increased temperature is likely to have a negative effect on C allocation to the soil, leading to reductions in soil organic C and creating a positive-feedback in the global C cycle (increased temperatures lead to increased CO_2 release from soils to the atmosphere, which leads to more increases in temperature) as global temperatures rise [62,63]. In a study of soils in a semi-arid steppe, Link *et al.* [64] observed that soil warming and drying led to a 32% reduction in soil C over a five year time period, a much more rapid reduction in soil C than reductions that have been observed due to increased tillage. Modeling of C responses to climate change in Canada predicted small increases in aboveground biomass in forest and tundra ecosystems but larger decreases in soil and litter pools, for an overall increase in atmospheric C [65]. Another modeling study predicted decreases in soil organic C of 2.0%–11.5% in the North Central United States by 2100 as compared to 1990 C values [66]. Niklińska *et al.* [67] measured humus respiration rates under increased temperatures in samples from European Scots pine stands and concluded that the ecosystems studied would switch from net sinks to net sources of atmospheric C with global warming. It is important to keep in mind that in all these cases, the soil would only be a net source of C to the atmosphere until a new equilibrium was reached.

When CO_2 enrichment increases the soil C:N ratio, decomposing organisms in the soil need more N, which can reduce N mineralization [57,68,69]. Mineralization is an essential step in supplying N to plants [10,40]. Therefore, if N mineralization is reduced, it would be expected that plant-available N levels in the soil would also be reduced and plant productivity would be negatively affected. Holland [70] reports that N limitation of CO_2 fertilized plants in their study is consistent with the results reported by Hungate *et al.* [57], but that increased temperatures stimulate N availability in the soil leading to more terrestrial C uptake than would be expected based on the results of Hungate *et al.* [57]. However, the stimulated C uptake is not enough to offset the N limitation and the net result is still an increase in atmospheric CO_2 and an overall reduction in soil C levels [70]. Some researchers have reported that increasing temperatures increase N mineralization [71–73], which could have a positive effect on plant growth. However, a warming study by An *et al.* [74] showed that N mineralization was stimulated in the first year but depressed afterward.

Through climate change and anthropogenic activities, many of our world's soils have become or are expected to become more susceptible to erosion by wind and/or water [75–77]. Simulations ran for Australia showed that increased rainfall due to climate change could lead to significant increases in runoff, with amplification greater in arid areas (up to five times more runoff than the percentage increase in rainfall) than in wet and temperate areas (twice as much runoff as the percentage change in rainfall) [78]. Greater runoff would be expected to cause increased erosion. Water erosion models in the United Kingdom predicted that a 10% increase in winter rainfall could increase annual soil erosion by as much as 150% during wet years, but that long-term averages of soil erosion would show a modest increase over current conditions [79]. Li *et al.* [80] predicted changes in water erosion of −5% to 195% for conventional tillage and 26%–77% for conservation tillage in China's Loess Plateau region, while Zhang *et al.* [75]

predicted increased erosion in Oklahoma, USA of 19% and 40% under conservation and conventional tillage, respectively by 2056–2085 as compared to average annual erosion in the period from 1950 to 1999.

4. Food Security in a Changing Climate

"Food security (is) a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [81]. Over 97.5% of human food needs, as measured by calories consumed, come from the land while less than 2.5% comes from aquatic systems (Table 1) [82]. Furthermore, aquatic systems do not represent a potential source of significantly increased food supply in the future as overfishing is already a major problem in many of the world's prime fishing grounds, including both marine and freshwater fisheries [83,84]. This means our food supply will need to come almost exclusively from the terrestrial environment, making soils critical to food security. Climate change has already caused and will continue to cause changes in global temperature and precipitation patterns [85,86] as well as changes in soil processes and properties as previously discussed. This has led to considerable concern that climate change could compromise food security [4,53,87–96], which would lead to an overall decline in human health.

Table 1. Daily per capita food intake as a worldwide average, 2001–2003 (from [82]).

Food Source	Calories [a]	Percent of Calories
Rice	557	25.5
Wheat	521	23.9
Maize	147	6.7
Sorgum	33	1.5
Potatoes	60	2.7
Cassava	42	1.9
Sugar	202	9.3
Soybean Oil	87	4.0
Palm Oil	50	2.3
Milk	122	5.6
Animal Fats (raw and butter)	62	2.8
Eggs	33	1.5
Meat (pig)	117	5.4
Meat (poultry)	46	2.1
Meat (bovine)	40	1.8
Meat (sheep and goats)	11	0.5
Fish and other aquatic products [b]	52	2.4
TOTAL	2182	

[a] Aquatic products data from 2003. All other data from 2001–2003; [b] Includes both marine and freshwater products.

As previously established, climate change is expected to increase soil erosion. The negative effects of soil erosion on crop yields and food production are well established (Figure 5) [3,21,97,98]. During their study of a semi-arid Mediterranean ecosystem in Spain, García-Fayos and Bochet [99] found strong correlations between climate change and soil erosion and negative impacts on aggregate stability, bulk density, water holding capacity, pH, organic matter content, total N, and soluble P in the soil, all properties important for good crop growth [47]. Therefore, it can be stated that if climate change increases soil erosion, it will also damage soil properties that are important in the production of food and fiber resources needed by humans.

Figure 5. Erosion along this hilltop has reduced the ability of the soil to support crop growth, as evidenced by the nearly complete lack of plant cover. If this process repeats itself over large enough land areas food security will be compromised (Photo by Gene Alexander, USDA NRCS).

There were at least 1 billion people living in a state of food insecurity in 2010; eliminating this insecurity and feeding the additional 2.3 billion people expected by 2050 will require global cereal production, for example, to be increased by 70% [100,101]. Instead, world cereal grain production per capita decreased steadily from the early 1980s through 2000 [3]. The IPCC expects that climate change will impact all four dimensions of food security, (1) food availability, (2) stability of food supplies, (3) access to food, and (4) food utilization [102]. Global food production is projected to increase if the rise in local average temperatures averages 1 to 3 °C, but to decrease if average temperature increases surge beyond 3 °C [102]. However, the distributions of the projected changes in food production are not uniform. As a general trend, food production is expected to increase at mid- to high latitudes and to decrease near the equator if the average rise in temperature stays in the lower range (1–3 °C) and to decrease less at mid- to high latitudes than near the equator if the average rise in temperature moves into the upper range (>3 °C) (Figures 6 and 7) [95,103,104].

Figure 6. Expected sensitivity of cereal yields to climate change. The upper (green) trend lines are for yields with adaptations to address climate change; the lower (orange) trend lines are for yields without adaptations to address climate change. The boxes are individual data points for yields with adaptations, the diamonds for yields without adaptations. Figure 5.2 from [102].

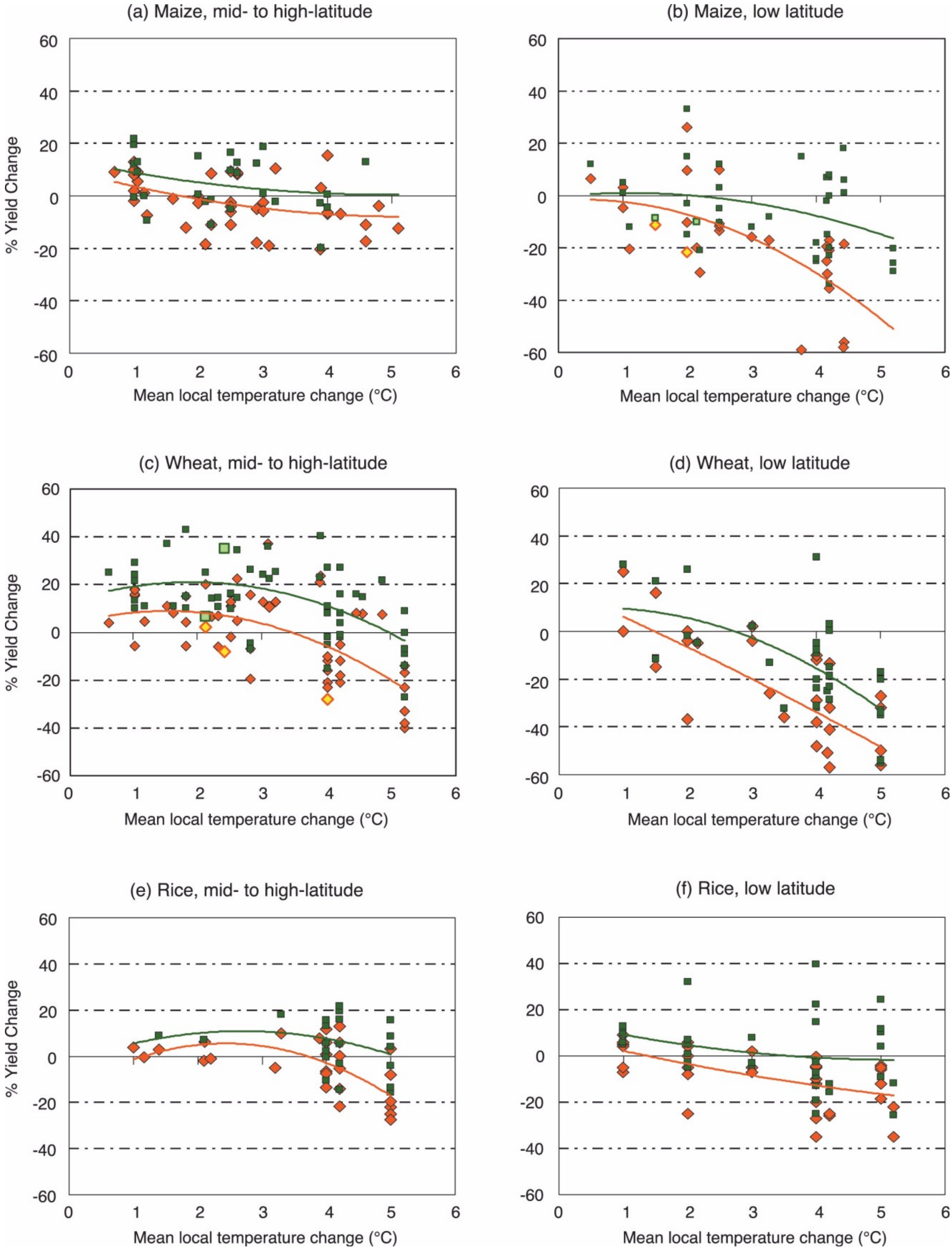
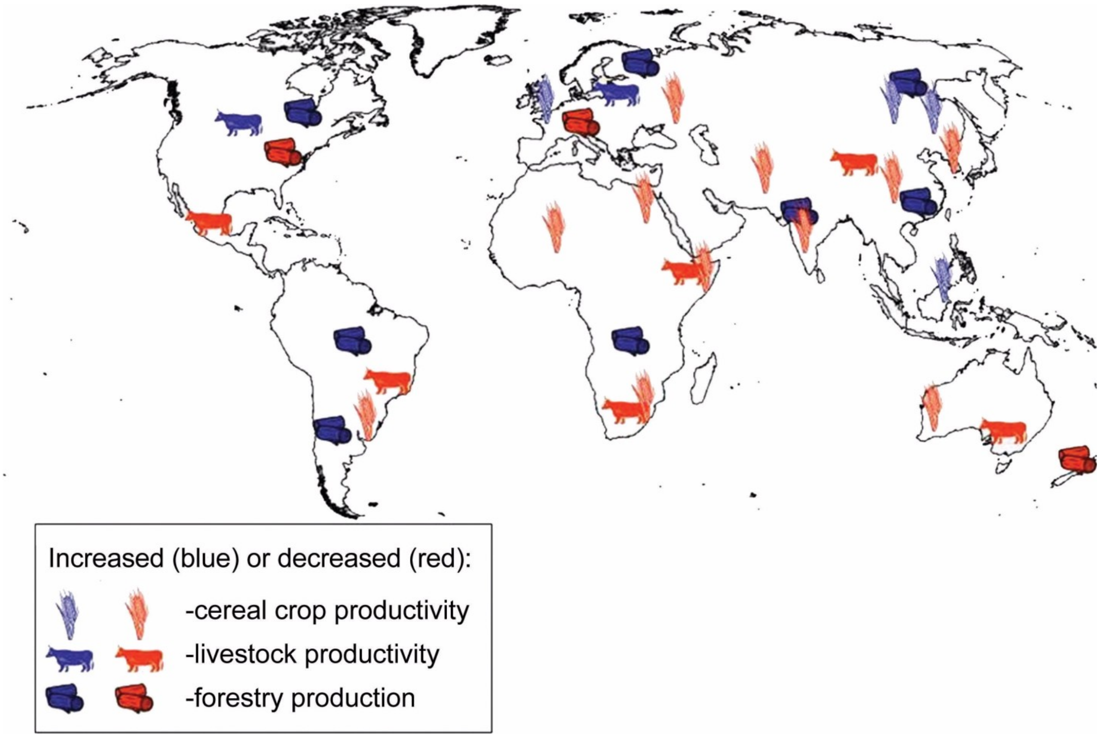


Figure 7. Expected major impacts of climate change on crop and livestock yields and forestry production by 2050, shown by region. Figure 5.4 from [102].



Low soil fertility is currently a food security problem in many developing countries, particularly in Africa and South Asia [101,105,106]. Africa and South Asia are also among the regions most at risk of food insecurity [100,105,107] and to deteriorating soil health due to climate change [108]. Proper soil management has the potential to drastically reduce food security issues in these regions. For example, an increase of one ton of soil organic matter per ha has increased grain yield by 40 kg ha^{-1} in Argentina, maize yields by 17 kg ha^{-1} in Thailand and 10 kg ha^{-1} in Nigeria, and cowpea yield by 1 kg ha^{-1} in Nigeria [106]. Tan *et al.* [108] concluded that soil organic C losses in West Africa could be stopped with the addition of 30–60 kg of N fertilizer per hectare by increasing biomass production, thus adding more residues to the soil. Increasing soil organic C in degraded soils would be a major step forward in enhancing food security in developing countries [4,101]. However, if C sequestration practices are started in these countries, accelerated decomposition of soil organic matter due to global warming could potentially thwart these efforts and have a negative impact on food security. If C sequestration practices are not started, these already degraded soils are even more vulnerable to the effects of climate change than relatively healthier soils in developed countries [108]. Therefore, climate change has the potential to exacerbate food security issues through its potential effects on soil health.

Healthy soils are important because they supply nutrients to the crops grown in those soils. However, if the nutrient is not present in the soil, or if it is not plant available due to being tied up in the soil or through antagonistic affects from other ions, plants cannot access the nutrient and pass it up the food chain [82]. Unhealthy soils tend to have a lower overall nutrient status. Low nutrient status in agricultural soils not only reduces the amount of food available for human consumption, it also makes the resulting crops less nutrient-rich which makes those who rely on the low nutrient soils for crop production more susceptible to disease [105]. If problems from vector-borne diseases, for example, become more pronounced with changes in climate [7], low-nutrient status soils will simply make those who rely on them even more prone to experience disease problems [109]. In this case, soils could have both direct (e.g., production of lower nutrient content foods) and indirect (e.g., making the population more susceptible to vector-borne disease) effects on human health due to climate change.

Toxicity issues can also be passed on from soil to humans through the food we consume [6]. Li *et al*. [110] found that elevated atmospheric CO_2 concentrations may lead to increased uptake of Cd in rice. Other studies have indicated that elevated CO_2 may increase uptake of Cu and Cs by some crops [111,112]. In contrast, several researchers have reported reductions in Cu uptake under elevated atmospheric CO_2, and other research has indicated no significant variation in the uptake of various metals under elevated CO_2 [110]. Whether or not elevated CO_2 causes increased heavy metal uptake, which metals are or are not problems, and which crop varieties have or do not have such metal uptake problems are key questions that need to be addressed in regards to climate change and food security.

5. Conclusions

The Earth's climate system is changing due to changing levels of greenhouse gases in the atmosphere; the most important of these gases are C and N based. Because soils are part of the C and N cycles and C and N are both important components of soil organic matter, the organic matter content of soils will be influenced by climate change. Changes in average temperatures and in precipitation patterns will also influence soil organic matter. This in turn will affect important soil properties such as aggregate formation and stability, water holding capacity, cation exchange capacity, and soil nutrient content. Exactly how soil organic matter will be influenced by climate change involves highly complex and interconnected systems that make it difficult to isolate a single variable, such as temperature or precipitation patterns, and reach meaningful conclusions about how a change in that single variable affects the system being studied. However, we do know that there is the possibility that soils could contribute increasing amounts of greenhouse gases to the atmosphere and lose their ability to act as a sink for C as global temperatures increase. There is the chance we will see negative impacts on physical and chemical properties of our soils that are essential for the production of food and fiber products. However, the research done on soils and climate change to date has generated many questions with few firm answers. It is critical that we better understand how C sequestration in soil is influenced by limitations in nutrients like N and P. We also need to know more about the effects of climate change on the N cycle, an area of research that has received far less attention than the C cycle. At present, little is known about how climate change will impact soil organisms [2], and those organisms are very important in driving the portions of the C and N cycles that take place in the soil. Changes in atmospheric CO_2 levels might alter metal uptake by plants, which could lead to food products with unsafe levels of those metals in their tissues, but research in this area has not provided consistent results. A better understanding of these areas is crucial to provide us with insight on how changes in soil processes and properties might influence soil erosion and food security. Therefore, it is critical that we support continued research into these areas, with the particular goal of understanding the complex interactions that take place in the natural environment. This type of research is beyond the scope of a single discipline to address, interdisciplinary teams capable of addressing complex issues will be essential [113]. It is also important to note that there is an imbalance in terms of who will suffer most from climate change. It is the inhabitants of developing countries who are least prepared to cope with a changing climate and with potential soil degradation due to climate change; developed countries are better equipped to mitigate those changes and cope than developing countries are.

Conflict of Interest

The authors declare no conflict of interest.

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