Soils and Climate Change: Gas Fluxes and Soil Processes

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According to the Intergovernmental Panel on Climate Change, global temperatures are expected to increase 1.1 to 6.4°C during the 21st century, and precipitation patterns will be altered by climate change. Soils are intricately linked to the atmospheric–climate system through the carbon, nitrogen, and hydrologic cycles. Altered climate will, therefore, have an effect on soil processes and properties, and at the same time, the soils themselves will have an effect on climate. Study of the effects of climate change on soil processes and properties is still nascent, but has revealed that climate change will impact soil organic matter dynamics, including soil organisms and the multiple soil properties that are tied to organic matter, soil water, and soil erosion. The exact direction and magnitude of those impacts will be dependent on the amount of change in atmospheric gases, temperature, and precipitation amounts and patterns. Recent studies give reason to believe at least some soils may become net sources of atmospheric carbon as temperatures rise and that this is particularly true of high latitude regions with currently permanently frozen soils. Soil erosion by both wind and water is also likely to increase. However, there are still many things we need to know more about. How climate change will affect the nitrogen cycle and, in turn, how the nitrogen cycle will affect carbon sequestration in soils is a major research need, as is a better understanding of soil water–CO₂ level–temperature relationships. Knowledge of the response of plants to elevated atmospheric CO₂ given limitations in nutrients like nitrogen and phosphorus and associated effects on soil organic matter dynamics is a critical need. There is also a great need for a better understanding of how soil organisms will respond to climate change because those organisms are incredibly important in a number of soil processes, including the carbon and nitrogen cycles.

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 (IPCC, 2007a). The idea that the Earth’s climate is changing is now almost universally accepted in the scientific community (Cooney, 2010; Corfee-Morlot et al., 2007), and even many scientists who dispute that climate change is anthropogenic are in agreement that it is happening (i.e., Kutílek, 2011; Carter, 2007; Bluemle et al., 1999). Therefore, even if we can’t agree on why climate change is happening, it should be possible to agree that it is happening, and with climate change happening, there will be effects on the environment, including the soil.

Studies into the effects climate change will have on soils are in their early stages; therefore, there is still much more to be learned in this area. However, through the results of the studies that have been done and our understanding of soil processes and properties it is possible to provide some insight into the expected effects of climate change. For example, we know that changing climates will influence the carbon and nitrogen cycles, which will in turn affect soil processes and fertility (Hungate et al., 2003; Gorissen et al., 2004; Davidson and Janssens, 2006; Wan et al., 2006; Wan et al., 2011). Climate change will also influence soil moisture levels (Chiew et al., 1995; Backlund et al., 2008; Kirkham, 2011). Soil erosion by water is expected to increase as climate changes (Favis-Mortlock and Boardman, 1995; Ravi et al., 2010), and aeolian erosion of soils is expected to increase in dryland regions (Ravi et al., 2010). This brief discussion serves as an opening into the study of the effects of climate change on soils. Moreover, this paper will assess what we currently know about gas fluxes in soil related to climate change, as well as some of the potential effects of climate change on soil processes and properties.

Gas Fluxes and Soils

In 2004 carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) made up most of the anthropogenic greenhouse gas emissions (IPCC, 2007b). These three gases are also the most important of the long-lived greenhouse gases (Hansen et al.,...

Abbreviations: IPCC, Intergovernmental Panel on Climate Change.
Soil Horizons

These gases are a part of the global carbon and nitrogen cycles (Fig. 1 and 2). Before the Industrial Revolution, the global carbon and nitrogen cycles were in balance, with inputs approximately equaling outputs. Burning of fossil fuels, tilling of soil, and other human activities have altered the natural balance such that we are now releasing more carbon and nitrogen into the atmosphere each year than is taken up by global sinks (Pierzynski et al., 2009).

Because soils are part of the carbon and nitrogen cycles, it is possible to influence atmospheric levels of carbon- and nitrogen-based gases through soil management (Lal, 2007; Hobbs and Govaerts, 2010; Wagner-Riddle and Weersink, 2011). A fourth group of greenhouse gases, the halocarbons, will not be discussed here. However, halocarbons can be created naturally, and halocarbon formation has been documented in the soil (Hoekstra et al., 1999; Keene et al., 1999; Gribble, 2003). It should also be noted that the discussions of CO₂, CH₄, and N₂O presented here are brief and are only meant to demonstrate that ties exist between these gases, the soil system, and the atmosphere and to provide some examples of how human management can influence those relationships. Readers are referred to the references cited for more complete discussion of the topics covered.

**Soils and Carbon Dioxide**

The largest active terrestrial carbon pool is in soil, which contains an estimated 2500 Pg of carbon, compared to 620 Pg of carbon in terrestrial biota and detritus and 780 Pg of carbon in the atmosphere (Fig. 3) (Lal, 2010). In addition to these pools, there are approximately 90,000,000 Pg of carbon in the geological formations of Earth’s crust, 38,000 Pg of carbon in the ocean as dissolved carbonates, 10,000 Pg of carbon sequestered as gas hydrates, and 4000 Pg of carbon in fossil fuels (Rustad et al., 2000). While the Earth’s crust, the ocean, and the gas hydrates are much larger carbon pools than the soil, humans are not able to easily manipulate conditions that influence carbon exchange in these pools. We could reduce carbon emissions sharply by ceasing the use of fossil fuels, but this would require the development of alternative fuel sources. Therefore, we are left looking for other ways to manage ever-growing levels of CO₂ in our atmosphere. One of the potential ways that is readily available to mitigate CO₂ additions to the atmosphere is carbon sequestration by soils using the soil–plant system. Plants remove CO₂ from the atmosphere during photosynthesis and create carbohydrates, some of which are incorporated into plant tissues. As plants or plant parts die, some of the plant tissues are incorporated into the soil as soil organic matter (Lal et al., 1998). Given the

Fig. 1. The main components of the global carbon cycle. Carbon is able to move between different pools within the cycle. For example, burning of fossil fuels or decomposition of soil organic matter sends carbon gases into the atmosphere, while photosynthesis locks atmospheric carbon up in plant tissues and deposition of organic-rich sediments on the ocean floor locks carbon up in geologic rocks and sediments. (Courtesy of NASA.)

Fig. 2. The main components of the global nitrogen cycle. As with the carbon cycle, nitrogen is able to move between pools in its cycle, including the soil pool. Some processes put gases such as N₂O into the atmosphere, while other processes remove those gases from the atmosphere and transfer them into other pools. (Courtesy of NASA.)

Fig. 3. Relative size of the active terrestrial carbon pools. The size of the soil carbon pool relative to the biological and atmospheric pools demonstrates the importance of soils in the carbon cycle. Data from Lal (2010).
proper conditions, some soils can become net carbon sinks, effectively removing CO₂ from the atmosphere (Fig. 4) (Mosier, 1998). Because of this capability of the soil–plant system, carbon sequestration by soils as a potential means of mitigating climate change has received a considerable amount of research interest.

Carbon can potentially be sequestered in any soil, but humanity has the greatest potential control over sequestration in intensively managed systems such as agricultural and agroforestry soils. Soil management techniques such as no-till systems often result in lower CO₂ emissions from the soil and greater carbon sequestration in the soil as compared to management systems based on intensive tillage (Fig. 5) (Post et al., 2004; Lokupitiya and Paustian, 2006; Steinback and Alvarez, 2006; Hobbs and Govaerts, 2010), as do changes such as using cover crops, crop rotations instead of monocropping, and reducing or eliminating fallow periods (Post et al., 2004; Álvaro-Fuentes and Paustian, 2011). The use of reduced or no-till systems has the added benefit of using less fuel for working the soil, which reduces CO₂ emissions by agricultural machinery (Schneider and Smith, 2009; Hobbs and Govaerts, 2010; Wagner-Riddle and Weersink, 2011); fuel savings of around 32.7 L ha⁻¹ (3.5 gallons per acre) have been estimated for no-till versus conventional tillage systems in cotton (Gossypium hirsutum L.) farming (Wolf and Snyder, 2003). Returning land from agricultural use to native forest or grassland can also lead to significant carbon sequestration in soils (Post and Kwon, 2000; Silver et al., 2000). Sequestration of carbon tends to be rapid initially, with declining rates over time (Fig. 5) (Neill et al., 1998; Silver et al., 2000; Dixon-Coppage et al., 2005). Maximizing carbon sequestration in soils requires adequate nitrogen to allow carbon accumulation. Hungate et al. (2003) questioned whether or not there will be enough nitrogen available to maximize carbon sequestration as climate change occurs.

Management decisions can restrict the ability of a soil to sequester carbon 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 carbon sequestration (Brevik, 2000; Brevik et al., 2002; Dixon-Coppage et al., 2005). Organic soils can be a particular carbon 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 on the effect of crops on greenhouse gas fluxes from soils showed that the organic soils were a net source of CO₂ for all cropping systems studied (Martikainen et al., 2002).

Most agricultural soils only sequester carbon for about 50 to 150 yr following management changes before they reach carbon saturation (Mosier, 1998; Lal, 2010), putting a limit on the ultimate effectiveness of soils in mitigating CO₂ additions to the atmosphere. The IPCC estimates that 0.4 to 0.8 Pg C yr⁻¹ (the equivalent of 1.4–2.9 Pg of CO₂ yr⁻¹) could be sequestered globally in agricultural soils, with soil carbon saturation occurring after 50 to 100 yr (Smith et al., 2007). Estimated anthropogenic CO₂ emissions to the atmosphere in 2004 totaled about 38 Pg C yr⁻¹ (IPCC, 2007b), and natural carbon sinks have taken about 45% of anthropogenic CO₂ emissions out of the atmosphere since 1959 (Denman et al., 2007), meaning about 21 Pg C yr⁻¹ of anthropogenic C remained in the atmosphere for the long term in 2004. Using the numbers above, carbon sequestration by agricultural soils would be able to remove about 2 to 4% of the annual anthropogenic additions of carbon to the atmosphere for the next 50 to
Arctic soils are of particular concern in terms of the release of carbon to the atmosphere. Due to the cold conditions under which they form, microbial activity and decomposition rates tend to be low in Arctic soils; thus, soil organic carbon reaches high levels (Barber et al., 2008). However, warming these soils can switch them from a carbon sink to a carbon source (Oechel and Vourlitis, 1995; Welker et al., 1999; Bliss and Maursetter, 2010), with well-drained soils releasing CO₂ to the atmosphere (Sjögersten et al., 2006; Barber et al., 2008). This is of particular concern because Arctic soils contain about 30% of the world's soil carbon (Oechel and Vourlitis, 1995; Chapin et al., 2004) and thus have the potential to release large quantities of greenhouse gases into the atmosphere as they thaw (Chapin et al., 2004).

**Soils and Methane**

Methane concentrations in the atmosphere did not increase between 1998 and 2005, but were more than 2.5 times higher than in 1800 (Forster et al., 2007). Agriculture accounts for about 47% of annual global anthropogenic emissions of CH₄ (Smith et al., 2007). Production of CH₄ in the soil is associated with the anaerobic decomposition of organic matter. Because of this, the main anthropogenic source of soil-derived methane is rice (*Oryza sativa* L.) production, while natural soil-derived methane comes primarily from wetlands (Fig. 6) (Heilig, 1994; Stepniewski et al., 2011). Termites (**Termitidae**) are also a major natural source of methane (Heilig, 1994). A significant portion of the CH₄ produced in soil is oxidized by soil microorganisms aerobiocally (Schütz et al., 1990; Mosier, 1998; Stepniewski et al., 2011) into products including CO₂ (Fig. 6) (Heilig, 1994). Increasing soil temperatures lead to increased CH₄ production in rice paddy soils and wetlands, which is a concern with rising global temperatures (Schütz et al., 1990; Stepniewski et al., 2011). The melting of soils that have been permanently frozen (permafrost) (Fig. 7) is also becoming a major source of atmospheric CH₄ (Barber et al., 2008).

Management makes a difference in CH₄ fluxes in soil. The presence of ammonium ions in the soil from nitrogen fertilization has been shown to inhibit the ability of agricultural soils to

![Fig. 6. Generation and emission of methane from wet soils. (Courtesy of Josef Zeyer, ETH Zurich, Switzerland.)](image-url)
serve as a CH₄ sink (Stępniewski et al., 2011). Different vegetation growing on the same soil will also cause differences in CH₄ emission or consumption. In a study by Hu et al. (2001), a soil under forest vegetation acted as a net sink of CH₄, while the same soil in a nearby field planted with maize (Zea mays L.) was essentially CH₄ neutral, and a third field of the same soil planted with grass (Poaceae family) cover was a net source of CH₄ to the atmosphere.

Rice production management has the greatest potential to reduce anthropogenic additions of soil-derived CH₄ (Neue, 1992). Dryland tillage and dry seeding or other means of reducing the period of soil saturation leads to less CH₄ production (Neue, 1992; Stępniewski et al., 2011). However, the production of CH₄ and N₂O are inversely related in rice soils; managing soil moisture levels to prevent the generation of one tends to encourage generation of the other (Neue, 1992). Since both are greenhouse gases, the balance between them must be carefully assessed. Adding organic amendments such as manure to flooded soils as a nutrient source increases CH₄ emissions (Wassmann et al., 1993; Stępniewski et al., 2011; Zhang et al., 2011). Fertilizer experiments have produced some mixed results (Neue, 1992). Wassmann et al. (1993) found no mineral fertilizer effect on methane generation in rice paddy soils when adding potassium fertilizers, but Lu et al. (1999) found that phosphorus fertilizers decreased CH₄ emissions. Lu et al. (1999) attributed this to increased root exudates in phosphorus-deficient soils as the plant tried to manipulate the soil environment to increase phosphorus uptake. Stępniewski et al. (2011) noted that adding oxidizing mineral fertilizers can reduce CH₄ emissions by 20 to 70%. Zhang et al. (2011) also noted that a mixed management system that incorporated ducks (Anatidae family) into the rice system decreased methane emissions.

**Soils and Nitrous Oxide**

Agriculture accounts for about 58% of anthropogenic N₂O emissions (Smith et al., 2007). From a soil perspective, N₂O is created when soil water contents approach field capacity and biological reactions in the soil convert NO₃⁻ to NO, N₂O, or N₂ (Mullen, 2011). Enhanced microbial production in expanding agricultural lands that are amended with fertilizers and manure is believed to be the primary driver behind increased atmospheric N₂O levels (Lokupitiya and Paustian, 2006; Forster et al., 2007). Well over one-half of the global emissions of N₂O appear to come from the equator to 30° N and S (Forster et al., 2007), with 13 to 37% of global N₂O emissions coming from tropical forest soils (Melillo et al., 2001). Nitrous oxide emissions typically increase with increasing soil clay content when other factors are held constant (Chatskikh et al., 2005). There are also some indications that warming of cold-region soils could lead to increased N₂O emissions from those soils (Brooks et al., 1997; Williams et al., 1998).

Agricultural management is a major factor in N₂O emissions. As nitrogen fertilizer applications increase, denitrification and the generation of N₂O in the soil also increases (Fig. 8) (Grant et al., 2006; Mullen, 2011; Stępniewski et al., 2011). Emissions of N₂O are usually lower in organic farming systems than in conventional systems (Stępniewski et al., 2011). Some studies have found higher N₂O emissions from tilled soils than from no-till soils (Steinbach and Alvarez, 2006; Stępniewski et al., 2011; Wagner-Riddle and Weersink, 2011), but this is not true in all cases (Grandy et al., 2006). The conversion of tropical forest to pasture led to an initial increase in N₂O emissions followed by a decline in emissions relative to the original forest in a Brazilian study (Melillo et al., 2001); however, conversion of tropical forest to fertilized crop production in Borneo led to an order of magnitude increase in N₂O emissions from the agricultural soils as compared to the forest soils (Hall et al., 2004).

**Gas Fluxes and Soils Summary**

In summary, human management can have a profound impact on processes that emit or consume CO₂, CH₄, and N₂O in the soil. Current soil carbon estimates for soils of the world are given in...
Table 1. Any land management changes that lead to reduced production (i.e., the use of oxidizing mineral fertilizers or decreased flood times to reduce CH₄ emissions from rice fields) or increased sequestration (i.e., converting to a no-till system with cover crops to sequester carbon) of greenhouse gases in the soil system have the overall effect of reducing atmospheric greenhouse gases. However, soils can also serve as a source of greenhouse gases. In fact, soils are a major source of anthropogenic non-CO₂ emissions from agriculture. Nitrous oxide emissions from soils constituted 38% and CH₄ emissions from rice production 11% of the total non-CO₂ greenhouse gas emissions from agriculture in 2005 (Smith et al., 2007). Additionally, increasing soil temperatures have been shown to lead to increased CH₄ production in rice paddies and wetlands (Schütz et al., 1990; Stepniewski et al., 2011). However, soils are not currently considered to be a major net source of CO₂. While agricultural soils produce large quantities of CO₂ each year, they also take up large quantities, such that agricultural soils are estimated to contribute less than 1% of net global anthropogenic CO₂ emissions (Smith et al., 2007).

**Climate Change and Soil Processes**

Climate change is expected to have several effects on the soil system. Changes in atmospheric concentrations of CO₂ temperature, and precipitation amounts and patterns will modify the soil–plant system and influence decomposition rates, which will have impacts on soil organic carbon levels. Organic carbon in turn has a significant influence on soil structure, soil fertility, microbial processes and populations in the soil, and other important soil properties. The challenge in figuring out how climate change will influence soil properties and processes is in working out the complex interactions that take place as conditions change.

**Soil Organic Carbon**

Early expectations were that increased atmospheric CO₂ would lead to increased plant productivity coupled with increased carbon sequestration by soil, with the implication that increased plant growth and the soil–plant system would help offset increasing atmospheric CO₂ levels (Coughenour and Chen, 1997; Hättenschwiler et al., 2002). This increase in plant growth is known as the CO₂ fertilization effect. However, recent studies indicate the CO₂ fertilization effect may not be as large as originally thought (Poorter and Navas, 2003; Zavaleta et al., 2003; Long et al., 2005; Körner, 2006; Jarvis et al., 2010; Zaehle et al., 2010). Increasing levels of ozone may actually counteract the CO₂ fertilization effect, leading to reduced plant growth under elevated CO₂ (Long et al., 2005), and the negative effects of increased temperatures on plant growth may also cancel out any CO₂ fertilization effect that does take place (Jarvis et al., 2010).

Nitrogen limitations may negatively affect plant growth (Hungate et al., 2003), and modeling of carbon dynamics as influenced by nitrogen indicates less carbon sequestration by soil than originally expected given CO₂ fertilization (Zaehle et al., 2010). A long-term elevated CO₂ experiment in a grasslands ecosystem indicated that nitrogen and phosphorus became limiting after a time, again limiting plant biomass response to elevated CO₂ (Niklaus and Körner, 2004). Niklaus and Körner (2004) concluded that the increases in plant productivity they did see were primarily due to soil moisture status as opposed to a CO₂ fertilization effect. Experiments looking at the decomposition of plant

Table 1. Soil organic and total carbon for soils of the world and carbon per square meter to a depth of 1 m. Organic and total carbon data for each order are from Eswaran et al. (1995), and total area of ice-free land is from Blum and Eswaran (2004). The average organic and total carbon per square meter for each order is calculated using the data from Eswaran et al. (1995) and Blum and Eswaran (2004).

<table>
<thead>
<tr>
<th>Order†</th>
<th>Organic C</th>
<th>Total C</th>
<th>Ice-free land surface</th>
<th>Organic C</th>
<th>Total C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pg</td>
<td>km²</td>
<td>kg m⁻²</td>
<td></td>
<td></td>
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<tr>
<td>Alfisols</td>
<td>136</td>
<td>236</td>
<td>12,620,000</td>
<td>10.8</td>
<td>18.7</td>
</tr>
<tr>
<td>Andisols</td>
<td>69</td>
<td>70</td>
<td>912,000</td>
<td>75.7</td>
<td>76.8</td>
</tr>
<tr>
<td>Aridisols</td>
<td>110</td>
<td>1154</td>
<td>15,700,000</td>
<td>7.0</td>
<td>73.5</td>
</tr>
<tr>
<td>Entisols</td>
<td>106</td>
<td>223</td>
<td>23,390,000</td>
<td>4.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Histosols</td>
<td>390</td>
<td>390</td>
<td>3780,000</td>
<td>103.2</td>
<td>103.2</td>
</tr>
<tr>
<td>Inceptisols</td>
<td>267</td>
<td>552</td>
<td>15,110,000</td>
<td>17.7</td>
<td>36.5</td>
</tr>
<tr>
<td>Mollisols</td>
<td>72</td>
<td>211</td>
<td>11,260,000</td>
<td>6.4</td>
<td>18.7</td>
</tr>
<tr>
<td>Oxisols</td>
<td>150</td>
<td>150</td>
<td>9810,000</td>
<td>15.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Spodosols</td>
<td>98</td>
<td>98</td>
<td>5600,000</td>
<td>17.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Ultisols</td>
<td>101</td>
<td>101</td>
<td>11,050,000</td>
<td>9.1</td>
<td>9.1</td>
</tr>
<tr>
<td>Vertisols</td>
<td>38</td>
<td>63</td>
<td>3160,000</td>
<td>12.0</td>
<td>19.9</td>
</tr>
<tr>
<td>Misc. land‡</td>
<td>18</td>
<td>18</td>
<td>18,400,000</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

† Eswaran et al. (1995) was published before the Gelisols order was established in 1998. Before 1998, most of the soils currently classified as Gelisols were classified in the Entisols, Inceptisols, Histisols, Mollisols, and Spodosols orders (Buol et al., 2003). For the purposes of this table, the Gelisols area has been split equally among these soil orders.
‡ Ice-free land without soil cover.
tissues grown under elevated atmospheric CO₂ also indicate that increased levels of CO₂ are emitted during that decomposition (Kirkham, 2011), and Carney et al. (2007) observed soil organic carbon levels declining under increased atmospheric CO₂ levels due to increased microbial activity. Therefore, elevated CO₂ levels will not necessarily lead to increased soil carbon sequestration, but may instead result in more carbon turnover (Eglin et al., 2011).

Increased temperature is likely to have a negative effect on carbon allocation to the soil, leading to reductions in soil organic carbon and creating a positive-feedback in the global carbon cycle as global temperature rise (Gorissen et al., 2004; Wan et al., 2011). Link et al. (2003) observed that soil warming and drying led to a 32% reduction in soil carbon during a 5-yr time period. Modeling of carbon 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 carbon (Price et al., 1999). Another modeling study predicted decreases in soil organic carbon of 2.0 to 11.5% in the north-central United States (Grace et al., 2006). Niklinska et al. (1999) 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 carbon with global warming.

What this all means from a soils perspective is that soils cannot necessarily be expected to become massive carbon sinks as atmospheric CO₂ levels rise. The actual impact of elevated atmospheric CO₂ on carbon storage in soils is very difficult to predict. However, if the results of the studies above are representative of what does occur, soils may actually lose organic matter as atmospheric CO₂ levels and global temperatures increase, creating a positive feedback system that could push temperatures even higher. If too much organic matter is lost that will also have negative impacts on soil physical, chemical, and biological properties (Wolf and Snyder, 2003; Brevik, 2009).

Soil Nitrogen

When CO₂ enrichment increases the soil C/N ratio, decomposing organisms in the soil need more nitrogen, which can reduce nitrogen mineralization (Gill et al., 2002; Hungate et al., 2003; Reich et al., 2006a). Mineralization is an essential step in supplying nitrogen to plants (Pierzynski et al., 2009; Mullen, 2011). Therefore, if nitrogen mineralization is reduced, it would be expected that plant-available nitrogen levels in the soil would also be reduced, and plant productivity would be negatively affected. Holland (2011) reported that nitrogen limitation of CO₂ fertilized plants is consistent with the results reported by Hungate et al. (2003), but that increased temperatures stimulate nitrogen availability in the soil, enhancing terrestrial carbon uptake relative to the results of Hungate et al. (2003). However, the stimulated carbon uptake is not enough to offset the nitrogen limitation, and the net result is still an increase in atmospheric CO₂ and an overall reduction in soil carbon levels (Holland, 2011).

It should be noted that nitrogen supplements (i.e., fertilizer) can alter these results (Reich et al., 2006a). Fertilization occurs much more often on agricultural soils than on forest or grassland soils. However, Mulvaney et al. (2009) reported that adding synthetic nitrogen fertilizers in excess of crop needs has the long-term effect of decreasing both soil organic carbon and total soil nitrogen, negatively impacting soil productivity and agronomic efficiency. Therefore, nitrogen fertilization needs to be used carefully.

Some researchers have reported that increasing temperatures increase nitrogen mineralization (Norby and Luo, 2004; Joshi et al., 2006; Reich et al., 2006b), which could have a positive effect on plant growth. However, a warming study by An et al. (2005) showed that nitrogen mineralization was stimulated in the first year but depressed afterward. Szukics et al. (2010) studied the effects of increasing temperature (5–25°C) and soil water (30, 55, and 70% water-filled pore space) on the activity of microorganisms responsible for nitrification and denitrification. They found that increasing soil temperature from 5 to 25°C induced a rapid stimulation of nitrogen cycling rates. The nitrification rate and NO₃⁻ concentration increased most rapidly at the 55% water content. In the 70% water content soils, the NO₃⁻ pool was increasingly depleted as soil temperature increased, and was almost completely depleted at 25°C. The depletion in hot, wet soils was attributed to complete denitrification and the release of nitrogen gases into the atmosphere. Nitric oxide was the primary nitrogen gas released from the 30% water content soils, and N₂O emissions were highest from the 55% water content soils. This research demonstrates that increased emissions of N gases into the atmosphere from soils are possible as global temperatures warm.

Symbiotic biological N₂ fixation often increases with elevated CO₂ levels, but usually only in experiments where phosphorus, potassium, and/or other non-nitrogen nutrients were added (Reich et al., 2006b). In experiments where increases in N₂ fixation were observed without the addition of non-nitrogen nutrients they tended to be short-term responses to elevated CO₂ levels that declined with time (Reich et al., 2006b). Free-living and associate N₂-fixing organisms appear to be unresponsive to elevated CO₂ levels in the limited long-term field experiments that have been conducted (Reich et al., 2006b). Therefore, it is unlikely that increased rates of atmospheric nitrogen fixation can be relied on to ensure that nitrogen does not become a limiting factor to carbon sequestration by soils in a warmer world.

The relationships between climate change and soil nitrogen and how that relationship will affect carbon sequestration by soils are among the more controversial issues being addressed right now in the study of soil science and climate change, and more
study is needed to resolve it (Holland, 2011; Reich et al., 2006b). Understanding these carbon–nitrogen interactions is critical to determine whether soil organic matter levels will increase or decline under elevated CO₂ levels.

**Soil Water**

Water content in soils of semiarid grassland systems is expected to be higher under elevated atmospheric CO₂, a condition attributed to reduced transpiration due to increased stomatal resistance (Kirkham, 2011). An experiment in a desert scrub ecosystem did not find increased soil water content under elevated CO₂ levels (Nowak et al., 2004), presumably because the stomata of desert plants already act to reduce transpiration. However, another study in an irrigated desert agroecosystem showed a trend toward higher soil water contents under elevated CO₂ as compared to ambient CO₂ (Kirkham, 2011). In short, different parts of the world will be impacted differently in terms of soil water (Kang et al., 2009).

Doubling atmospheric CO₂ has been shown to reduce seasonal evapotranspiration by 8% in wheat (Triticum aestivum L.) and cotton and by 9% in soybean [Glycine max (L.) Merr.] grown under day/night temperatures of 28/18°C (Hatfield, 2011). However, the reduction in transpiration by soybeans was eliminated if the plants were grown under temperatures of 40/30°C (Hatfield, 2011). In a study on rice doubling CO₂ decreased evapotranspiration by 15% at 26°C but increased evapotranspiration at 29.5°C (Hatfield, 2011). Elevated CO₂ levels increase the water use efficiency and decrease evapotranspiration rates of many plants. However, evapotranspiration rates appear to be temperature dependent, meaning the water benefits of increased atmospheric CO₂ could be reduced or lost in areas where temperatures rise too high.

**Erosion**

Through climate change and anthropogenic activities, many of our world’s soils have or are expected to become more susceptible to erosion by wind and/or water (Zhang et al., 2004; Ravi et al., 2010; Sivakumar, 2011). 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) (Chiew et al., 1995). 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 (Favis-Mortlock and Boardman, 1995). Li et al. (2011) predicted changes in water erosion of −5 to 195% for conventional tillage and 26 to 77% for conservation tillage in China’s Loess Plateau region, while Zhang et al. (2004) predicted increased erosion in Oklahoma, USA of 19 and 40% under conservation and conventional tillage, respectively.

The negative effects of soil erosion on crop yields and food production are well established (Fig. 9) (Poudel et al., 1999; Sparovek and Schnug, 2001; Pimentel, 2006; Bakker et al., 2007). During their study of a semiarid Mediterranean ecosystem in Spain, García-Fayos and Bochet (2009) 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 nitrogen, and soluble phosphorus in the soil. 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.

**Soil Organisms**

Soil organisms are essential to create a well-functioning soil (Wolf and Snyder, 2003; Brevik, 2009). Some soil organisms break down fresh organic matter added to the soil, releasing nutrients that can be used by plants and cycling nutrients through the soil system. Other soil organisms fix atmospheric nitrogen, making it available to plants. During organic matter decomposition soil organisms create organic “glues” that help arrange individual sand, silt, and clay particles in the soil into peds. Pores between the peds serve as pathways for the movement of water, air, and roots through the soil, and pores within the peds act to store water between rain events. The role of soil organisms in decomposing organic matter means they are an integral part of the global carbon and nitrogen cycles, which influence the concentrations of greenhouse gases in the atmosphere.

The effect of climate change on soil organisms is not easy to determine. Soil organisms respond to a wide array of soil conditions, including temperature, water content, pH, nutrient

Fig. 9. Erosion of topsoil from this hilltop has led to reduced crop production in the eroded areas. (Photo by Gene Alexander, USDA-NRCS.)
levels, oxygen status, and the presence or absence of other soil organisms (Brady and Weil, 2008). It is very difficult if not impossible to predict how all these variables will change at any single location given changes in global climate. Therefore, studies in this area tend to look at how changes in one or two variables, temperature and/or rainfall, for example, would influence soil organisms at a given location. The results of some of those studies are summarized here.

Briones et al. (1997) conducted an experiment with intact soil cores, raising the average annual temperature of those cores by 2.5°C. They tracked Enchytraeidae, Tardigrada, and Diptera responses to changes in temperature and determined that some species were tolerant to the new, higher temperatures and would increase their numbers, some species would migrate to deeper layers of the soil, and some would go dormant or extinct. Briones et al. (1997) concluded that predicted global temperature changes would have significant effects on the soil ecosystem that would have important implications for organic matter decomposition and nutrient cycling.

Kardol et al. (2011) looked at the influence of CO₂ level, temperature, and precipitation on microarthropods. They found that the community composition shifted in response to the treatments, with most of the composition shift attributed to the effects of precipitation and temperature and how those two variables affected soil water content. They concluded that climate change can affect the structure of soil microarthropod communities, which could in turn have an impact on ecosystem functions such as soil organic matter decomposition.

Drennan and Nobel (1996) performed a study to look at the effects of elevated CO₂ concentrations and temperature on the root systems of three desert plants, Encelia farinosa A. Gray ex Torr. (a C₃ plant), Pleuraphis rigida Thurb. (C₄), and Agave deserti Engelm. (CAM). They found that A. deserti increased its average daily root elongation under elevated CO₂ but there was no root elongation effect on the other two species. They also found that shading of the soil reduced daily variations in soil temperature and altered root distribution and elongation patterns.

While this brief discussion of climate change effects on soil organisms does not definitively answer how soil organisms will change in response to climate change, it does indicate that soil ecosystems will change as a result of climate change and that some very important processes involving soil organisms, like organic matter decomposition and nutrient cycling, will also likely change. This conclusion differs substantially from the assumption by some early in the study of soil organisms and climate change that predicted temperature changes would likely produce little response from the soil ecosystem except in response to shifts in vegetation (Whitford, 1992).

Conclusions

The Earth’s climate system is changing—of that we are certain. Beyond that, most of what is covered in this paper is less certain. There are still many things we need to know more about. How climate change will affect the nitrogen cycle and, in turn, how the nitrogen cycle will affect carbon sequestration in soils constitute a major research need, as is a better understanding of soil water–CO₂ level–temperature relationships. Knowledge of the response of plants to elevated atmospheric CO₂ given potential limitations in nutrients like nitrogen and phosphorus and how that affects soil organic matter dynamics is a critical need. There is also a great need for a better understanding of how soil organisms will respond to climate change because those organisms are incredibly important in a number of soil processes, including the carbon and nitrogen cycles.

All of these questions involve highly complex and interconnected systems that make it difficult to isolate a single variable, such as temperature or precipitation patterns, to reach meaningful conclusions about how a change in that single variable affects the system being studied. However, we do know that there is the potential for some undesirable things to occur as a result of climate change. There is the possibility that soils could contribute increasing amounts of greenhouse gases to the atmosphere, losing their ability to act as a sink for carbon as global temperatures increase, and there is the chance that we will see negative impacts on the physical and chemical properties of our soils that are essential for the production of food and fiber products. Therefore, it is critical that continued research into these areas be supported, with the particular goal of understanding the complex interactions that take place in the natural environment.

References


