soil and CARBON climate change

Carbon exchange in the terrestrial domain and the role of agriculture

by Daniel Hillel and Cynthia Rosenzweig

The earth's ecosystem constitutes a bio-thermodynamic machine that is driven by solar energy and the exchanges of water, oxygen, carbon dioxide, and other components in the pedosphere–hydrosphere–atmosphere continuum. Green plants in the terrestrial domain perform photosynthesis by absorbing atmospheric CO_2 and reducing it to forms of organic carbon in combination with soil-derived water, while utilizing the energy of sunlight. In the process, radiant energy is transformed into chemical energy that is stored in the molecular bonds of organic compounds produced by the plants. This in turn provides the basis for the food chain, which sustains all forms of animal life.

Roughly 50% of the carbon photosynthesized by plants is returned to the atmosphere as CO_2 in the process of plant respiration. The rest, being the carbon assimilated and incorporated in leaves, stems, and roots, is deposited on or within the soil. There, organic compounds are ingested by a diverse biotic community, including primary decomposers (bacteria and fungi) and an array of mesofauna and macrofauna (nematodes, insects, earthworms, rodents, etc.). The ultimate product of organic matter decay in the soil is a complex of relatively stable compounds known collectively as *humus*. It generally accounts for some 60 to 80% of the total organic matter present, the balance consisting of recent organic debris of partially decomposed litter, dead roots, and the waste products of soil fauna.

Since the beginning of the Industrial Revolution in the late 1800s, the expansion of agriculture, the clearing of forests, and especially the burning of fossil fuels have led to a dramatic increase in the atmospheric content of carbon dioxide, from about 270 ppm to more than 380 ppm. Concurrently, there has been an increase in the content of other radiatively active gases (the so-called greenhouse gases), such as methane and nitrous oxide. The effect, so far, appears to be a rise of more than 0.6°C in the global average temperature. This warming trend is expected to increase markedly in the coming decades, unless strong measures are taken to mitigate it.

Carbon Exchange in the Terrestrial Domain

The soils of the world, with the biota they support, are major absorbers, depositories, and releasers of organic carbon. Soils altogether contain an estimated 1,700 Gt (billion metric tons) to a depth of 1 m and as much as 2,400 Gt to a depth of 2 m (Fig. 1). An estimated additional 560 Gt is contained in terrestrial biota (plants and animals). In contrast, the carbon in the atmosphere is estimated to total 750 Gt. Thus, the amount of organic carbon in soils is more than four times the amount of

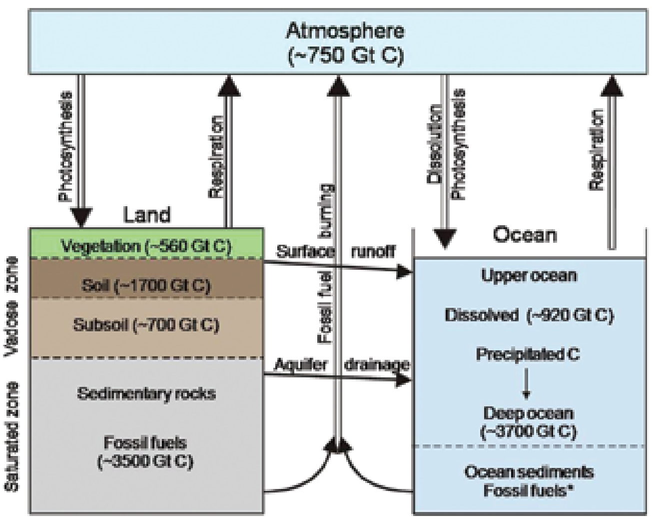

Fig. 1. Carbon reserves and exchange in the land–ocean–atmosphere continuum.
***Quantitative estimates regarding fossil fuels in ocean sediments vary widely.**

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carbon in terrestrial biota and three times that in the atmosphere.

The quantity of organic carbon in soils is spatially and temporally variable, depending on the balance of inputs versus outputs. The inputs are due to the absorption of carbon dioxide from the atmosphere in the process of photosynthesis and its incorporation into the soil by the residues of plants and animals. The outputs are due to the decomposition of soil organic matter, which releases carbon dioxide under aerobic conditions and methane under anaerobic conditions (both CO_2 and CH_4 being greenhouse gases). In certain conditions, decomposition of organic matter may also cause the release of nitrous oxide, which is another powerful greenhouse gas.

The content of organic carbon in soils in most cases constitutes less than 5% of the mass of soil material and is generally concentrated mainly in the upper 20 to 40 cm (the so-called topsoil). However, that content varies greatly, from less than 1% by mass in some arid-zone soils (Aridisols) to 50% or more in waterlogged organic soils such as Histosols (Table 1). In addition to their content of organic carbon, some soils (mainly those of arid and semiarid regions) also contain large reserves of inorganic carbon in the forms of calcium and magnesium carbonates. These carbon reserves are estimated to total some 695 to 748 Gt. Though not nearly so labile as organic carbon, soil inorganic carbon tends to be solubilized under acidic conditions and is subject to leaching.

Table 1. Estimated mass of carbon in the world's soils. *Source: USDA.*

Soil orders	Area	Organic C
	10^3 km^2	Gt
Alfisols	**13,159**	**90.8**
Andisols	**975**	**29.8**
Aridisols	**15,464**	**54.1**
Entisols	**23,432**	**232.0**
Gelisols	**11,869**	**237.5**
Histosols	**1,526**	**312.1**
Inceptisols	**19,854**	**323.6**
Mollisols	**9,161**	**120.0**
Oxisols	**9,811**	**99.1**
Spodosols	**4,596**	**67.1**
Ultisols	**10,550**	**98.1**
Vertisols	**3,160**	**18.3**
Other soils	**7,110**	**17.1**
TOTALS	**130,667**	**1,699.6**

Soils with a high content of carbonaceous matter, known as organic soils, typically form where prolonged saturation with water results in a deficiency of oxygen, which in turn inhibits decomposition and promotes the accumulation of incompletely decomposed organic matter, called peat. Such waterlogged areas are variously termed bogs, fens, swamps, marshes, or—more generally—wetlands. These soils tend to emit carbon in the form of CH_4 (marsh gas), but at a rate much lower than would be the emission rate of CO_2 if the soil were well aerated. When converted to agricultural use, such soils are generally drained, and the consequent aeration accelerates decomposition and spurs the emission of CO_2. Cultivated peat soils may lose as much as 20 Mg C ha^{-1} yr^{-1} in tropical and subtropical climates and roughly half that amount in temperate climates. They tend to shrink and subside unevenly and can even catch fire and burn uncontrollably.

Of special concern are the permafrost wetlands of cold regions (termed Gelisols), which are abundant in Siberia and parts of Canada and Alaska (Fig. 2). They contain huge stocks of undecomposed organic matter. As large areas of peat-rich permafrost are subjected to warming, they will tend to thaw out and, while still saturated, emit methane. Later, when drained of excess water and aerated, aerobic decomposition will take place, and the peat will release carbon dioxide. In a warming climate, the enhanced emission of greenhouse gases from thawing permafrost is an example of a positive feedback, by which the global warming due to anthropogenic greenhouse gas emissions may cause the secondary release of still more greenhouse gases from drained peatlands and thus further exacerbate global warming.

Apart from the peatlands of cold regions, about 10% of global peatlands occur in the tropical lowlands and contain an estimated 70 Pg of carbon in deposits

Fig. 2. Global distribution of principal soil orders. *Source: USDA.*

as deep as 20 m. Tropical peatlands are abundant in such regions as Southeast Asia (Indonesia, Malaysia, Brunei, and Thailand) as well as in parts of the Amazon Basin. Some of these deposits appear to have been destabilized by agricultural drainage as well as by the occurrence of more intense droughts that seem to be associated with El Niño periods. Such dry spells may result in the spontaneous burning of peat and vegetation that may cause the rapid emissions of great quantities of carbon dioxide. As more tropical swamp forests and peatlands are drained and converted to agriculture, they will likely contribute still greater emissions of CO_2 to the atmosphere, especially if El Niño events become more intense or frequent in a warming climate.

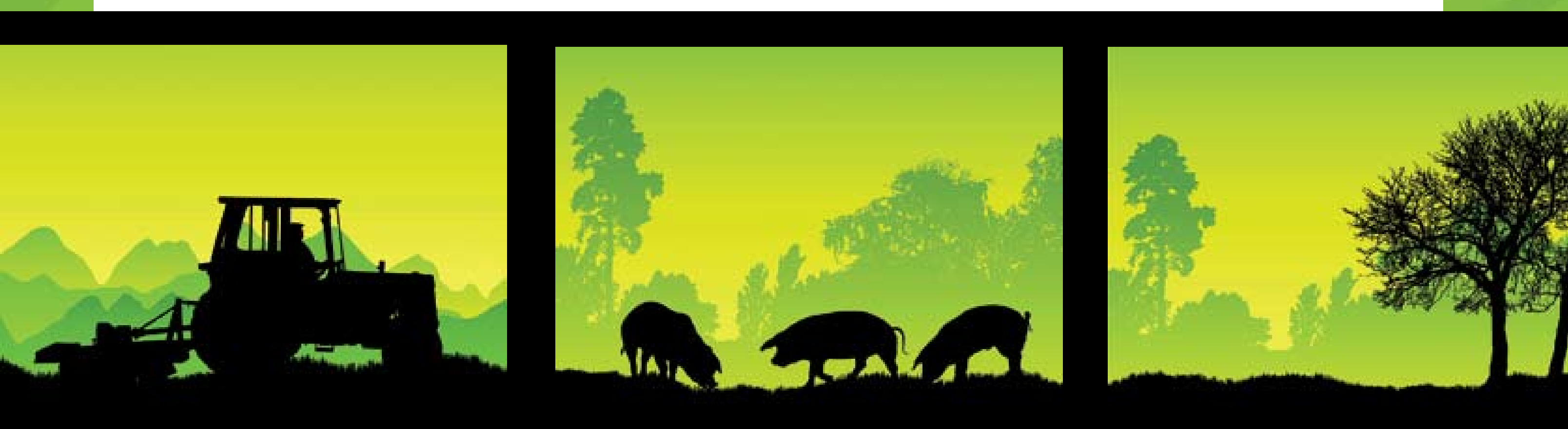
Histosols and Aridisols are two other groups of soils likely to be strongly affected by climate change. Histosols are organic soils containing large concentrations of peat. As they tend to dry out in a warmer and drier climate, enhanced oxidation could result in accelerated oxidation and the release of large quantities of carbon dioxide to the atmosphere. Aridisols cover about 12% of the land surface. They are particularly vulnerable to processes of soil erosion, salination, and desertification. Higher temperatures can be expected to increase the intensity of evaporation, and hence seasonal water shortages.

Climate change is likely to affect soil erosion through its impact on rainfall intensity and amount, vegetative cover, and patterns of land use. Whereas wetter conditions may exacerbate the hazard of water erosion, drier conditions may intensify wind erosion. *Desertification* can occur when the climate becomes drier and/or the vegetative cover of an area is so degraded that the denuded landscape comes to resemble a desert.

Human Management of Soils

The balance of soil carbon is greatly influenced by human management, including the clearing or restoration of natural vegetation and the patterns of land use in pastoral, agricultural, industrial, and urban areas (Fig. 3). Cultivation spurs the microbial decomposition of soil organic matter while depriving it of replenishment, especially if the cropping program involves removal of plant matter (leaving little organic residues in the field) and if the soil is fallowed (kept bare) during considerable periods. Organic carbon is lost from soils both by oxidation and by erosion of topsoil. Some cultivated soils may, over time, lose as much as one-third to two-thirds of their original organic matter content. Consequently, these soils degrade in quality, as their fertility diminishes and their structure is destabilized. Such soils are therefore important targets for mitigating the greenhouse effect by reducing and even reversing their tendency to emit greenhouse gases.

Though agricultural soils acted in the past as significant sources of atmospheric CO_2 enrichment, their present carbon deficits offer an opportunity to absorb substantial amounts of CO_2 from the atmosphere and store it as added organic matter in the coming decades. The historical loss of carbon in the world's agricultural soils has been estimated to total some 42 to 78 Gt. Ideally, we might hope for complete restoration of that loss, i.e.,



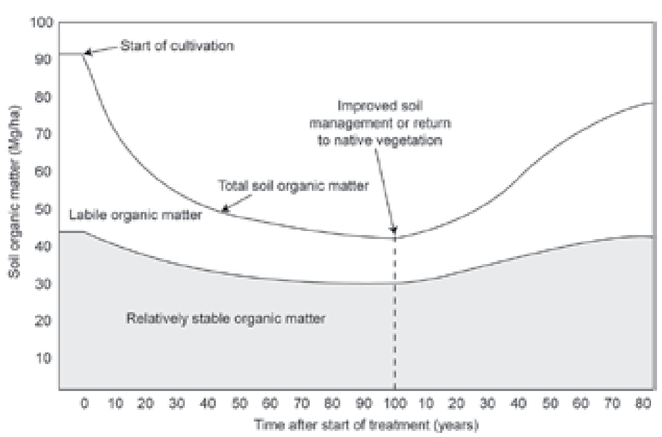


Fig. 3. Changes in soil carbon content after deforestation/ cultivation and reforestation.

a return of soils to a pre-agricultural state of "carbon saturation." The way to restore soil organic matter is by minimizing soil disturbance while optimizing nutrient and water supply to maximize plant production and residue retention.

In reality, soil degradation (resulting from burning of vegetative cover, tillage, erosion, leaching, pollution, compaction, salination, and/or other processes) diminishes the capacity of soils to fully recover their original state. Even where such restoration is possible, it may not be economically feasible. The actual carbon-sink capacity of many soils (i.e., the potential restoration of their carbon content in practice), assuming the adoption of recommended strategies of soil management, may be on the order of one-half to two-thirds of the historic C loss. Still, that amount can be very significant. Only in certain special circumstances (e.g., irrigating and intensively fertilizing high-residue vegetation or anaerobically charring organic matter so that it is highly resistant to decay and then applying it to the soil) might the organic carbon content of soils be raised above the original "virgin" levels.

The potential of soils to sequester carbon is intimately associated with the content and nature of their clay fraction. Sandy soils, which tend to be well aerated and have little adsorptive capacity, generally retain little organic matter. Clayey soils, on the other hand, form strong physicochemical bonds between the active surfaces of the clay particles and the organic macromolecules of humus, which thus become resistant to further decay. Moreover, clayey soils tend to form tight water-resistant aggregates, the interiors of which restrict aeration and further resist the decay of occluded organic matter. Whenever soil aggregates are disrupted by mechanical tillage, soil structure is prone to deteriorate and soil organic matter tends to decompose more rapidly.

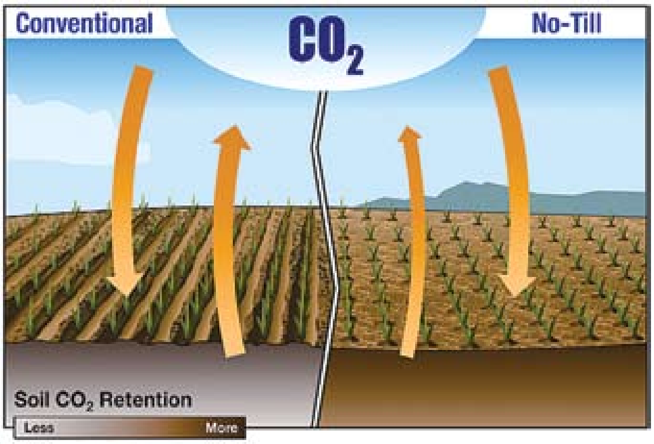


Fig. 4. No-till agriculture offers one way of slowing down increases in atmospheric carbon dioxide. The practice produces crop yields similar to those obtained with conventional tillage, protects soil against erosion, and results in increased storage of carbon in the soil. *Source: Pacific Northwest National Laboratory, Richland, WA.*

The combined losses from the earth's native biomass and soils due to deforestation and cultivation during the past three centuries have been estimated to total about 170 Gt of carbon, much of which has been absorbed in the ocean and some of which has accumulated in the atmosphere. Continuing land clearing for agriculture in the tropics apparently results in additional emissions on the order of some 1.6 Gt of carbon per year.

Taking a positive view, we may surmise that agricultural soils present a significant opportunity for greenhouse gas mitigation through reduction of emissions, as well as through enhancement of carbon sequestration. This can be done by improving the efficiency of agricultural operations (avoiding unnecessary fuel-burning operations) and by promoting increased absorption of CO_2 by green plants and its stable storage in the soil. The potential sequestration of carbon in global agricultural soils through changes in management practices has been variously estimated to total between 600 and 900 Mt per year over a period of several decades.

The recommended practices include reforestation, agroforestry, no-till farming (Fig. 4), planting of cover crops, augmentation of soil nutrients (by fertilizers, manures, composts, and sludge), application of soil amendments (e.g., lime to neutralize acidity), improved grazing, water conservation, and the production of energy crops to replace fossil fuels. If adopted and implemented efficiently and consistently on a large scale, such practices can help to mitigate the greenhouse effect, reduce soil erosion, improve soil structure and water quality, enhance biodiversity, boost crop yields, and promote food security.

A necessary caveat is that climate, soil, and economic conditions differ greatly from one location to another and from one period to another. Therefore, there can be no simple universal prescriptions regarding practices to manage soils so as to help mitigate the greenhouse effect. While the basic principles can be stated in universal terms, their application to different sites will require specific adjustments. Over time, practices designed to sequester carbon in soils are likely to diminish in efficacy, as the soil in each location approaches an equilibrium state or as its organic carbon content attains effective saturation. In fact, there is even danger that the gains of soil carbon achieved over years or decades of conservation practices may be reversed by reverting even temporarily to inappropriate tillage methods or by outbreaks of fire.

However, other advantages of carbon conservation management, such as reduced energy use and the production of renewable energy (e.g., biofuels) as substitutes for fossil fuels, can continue. The important principle is that improving the management of soil organic matter is a worthy task in itself, beyond its potential benefits in mitigating the atmospheric greenhouse effect. It can not only turn the soil from a net source to a net sink for greenhouse gases, but can also boost soil productivity and reduce environmental damage due to erosion.

Various feedback mechanisms are involved in the interactions between climate change and the carbon cycle. Increasing concentrations of CO_2 in the atmosphere can stimulate greater rates of photosynthesis, an effect called CO_2 fertilization. In principle, a portion of the extra products of photosynthesis (plant biomass) is transferred to the soil via surface litter and the root system, and a fraction of that is stabilized therein as soil humus. Moreover, rising temperatures tend to hasten plant growth and prolong the growing season in regions where growth is normally inhibited by cold weather. Such processes tend to moderate the greenhouse effect.

On the other hand, rising temperatures may exceed optimal levels for some plants in some regions, thus restricting carbon assimilation, and also hasten decomposition of organic matter and the emission of carbon dioxide (as well as, perhaps, methane and nitrous oxide), thus tending to exacerbate the greenhouse effect. Rising temperatures may also favor infestations of insect pests and fungal diseases of crops. Whether positive feedbacks are likely to outweigh the negative feedbacks or vice versa will depend on site-specific conditions as well as on human intervention and management of the ecosystem. In any case, the change in the soil temperature regime, which generally entails a change in the soil moisture regime, is certain to affect the content and turnover rate of soil organic matter.

Agricultural Practices Affecting Soil Organic Matter

Depletion of organic matter in soils initiates a vicious cycle of degradation, affecting food security and environmental quality, often on a regional scale. Reversing that depletion via carbon sequestration can induce a benign cycle of productivity gain. Enrichment of the topsoil with organic matter makes it less prone to compaction, crust formation, and erosion, which in turn affects the quality of the environment downstream. It also improves the quality of the soil with respect to infiltration, aeration, seed germination, and plant nutrition. The agricultural sector can thus contribute to the mitigation of global warming in three principal ways:

1. reducing its emissions by adopting such practices as no-till plantings;
2. absorbing CO_2 from the atmosphere by enhanced photosynthesis and storing a sizable fraction of the carbon in the soil; and
3. producing renewable sources of energy, known as biofuels, derived from agriculturally grown biomass that can be converted to ethanol and biodiesel.

Conventional tillage is defined as the mechanical manipulation (pulverization, mixing, and inversion) of the topsoil that leaves no more than 15% of the ground surface covered with crop residues. Such tillage tends to disrupt soil structure, accelerate the decomposition of soil organic matter, and render the bared topsoil vulnerable to erosion by rain and wind. In contrast, no-till management is defined as the avoidance of all unnecessary mechanical manipulation of the topsoil so as to leave it largely undisturbed and covered with surface residues throughout the sequence from harvesting of the prior crop to the planting and establishment of the new crop. Such vegetative residues constitute a protective mulch, which shields the soil against the direct impact of raindrops during the wet season as well as against extreme desiccation and deflation by wind during subsequent dry periods.

The best agricultural practices are those that result in augmentation of soil carbon and enhanced productivity due to better soil structure and soil moisture conservation. The relevant practices include precise and timely applications of fertilizers, use of slow-release fertilizers

Dr. Daniel Hillel (far left) and Dr. Cynthia Rosenzweig (third from left) of the Goddard Institute for Space Studies take soil samples with students.

(to minimize leaching or volatilization), prevention of erosion, shortening or elimination of fallow periods, use of high-residue cover crops, and minimization of mechanical disturbance of the soil. Such practices can help to protect and even restore the soil's organic carbon content. Conversion to no-till farming has been found to boost carbon storage in soils at rates varying from 0.1 to 0.7 Mg C ha^{-1} yr^{-1}. However, such positive increments cannot be expected to continue indefinitely as any historically depleted soil will tend to approach its prior equilibrium (or C saturation) state within a few decades.

Since one of the classical functions of tillage is the eradication of weeds, the contrary practice of no-till farming may result in greater infestation of weeds and hence require increased use of herbicides. The manufacturing, transport, and application of herbicides raise the consumption of fuel and thus cause additional emissions of greenhouse gases. Where the soils have been badly degraded in the past and their agricultural productivity severely impaired, they may be converted to perennial grassland or afforested so as to become substantial carbon sinks.

Needed altogether is a new paradigm of greenhouse gas–efficient farming and land management in general, based on lowered energy consumption, greater reliance on renewable energy (rather than fossil fuels), and increased storage of carbon in soils. Especially important is the adoption of conservation tillage and zero tillage, which not only conserve energy but also enhance soil productivity. That, in turn, can relieve pressure on marginal land, stop deforestation, and maintain ecosystem function and biodiversity.

There are, however, necessary caveats. Some of the practices aimed at intensifying agricultural production entail increased use of energy. Among those practices are irrigation, fertilization, pest and weed control, and transportation. Some benefits of conservation farming may diminish in time. The potential for sequestration of organic matter in soils is generally finite. Soil organic carbon saturation (where absorption and emission processes are in dynamic equilibrium) may be attained in several decades. Higher temperatures due to global warming may accelerate organic matter decomposition and hence inhibit C sequestration. The balance of carbon in the soil is in any case labile and vulnerable to turning negative (i.e., from net absorption to net emission of atmospheric CO_2) if the carbon-augmenting management is not maintained or if it is interrupted by the occurrence of some perturbation such as drought, flooding, or fire.

Some benefits of conservation management can persist indefinitely. Reduction of fuel use brought about by efficient operations, especially with the adoption of zero tillage, can continue as long as that form of conservation soil management is maintained. The same is true with the improvement of soil quality, including the enhancement of soil fertility and the control of soil erosion. The efficient and sustainable production of energy crops to replace fossil fuels can also be a continuing benefit although careful accounting is needed to ensure that the energy equation of such production is indeed positive (i.e., that the energy produced is greater than the energy invested in farming operations and transportation).

Policies are needed to promote and guide C-efficient practices. Schemes to reward carbon sequestration must, however, be based on an effective system of monitoring the results on a continuing basis since the gains painstakingly achieved by such practices as conservation tillage, cover crops, and residue retention can be lost very rapidly by reversion to traditional tillage, residue removal or burning, and fallowing. Research is necessary to develop appropriate methods of monitoring by sampling or, preferably, by remote sensing. Modern precision agriculture, recognizing the heterogeneity of soils in the field, applies fertilizers preferentially where they are most needed and at precisely calibrated rates so as to maximize nutrient use efficiency and minimize nutrient losses (which may cause environmental pollution such as eutrophication of freshwater bodies). Increased reliance on green manure plants (legumes and their associated nitrogen-fixing bacteria) can help. Finally, the mode of soil moisture management in irrigated as well as dryland farming can greatly influence greenhouse gas emissions or absorption.

Announcing a Forthcoming Symposium

To further clarify the fundamental and practical issues related to the role of agriculture in the context of global and regional climate change, the authors of this article have taken the initiative to convene a daylong symposium, to be held during this November's ASA–CSSA–SSSA International Annual Meetings in Pittsburgh, PA, under the auspices of Division A3. The title of the symposium is "Climate Change and Agro-ecosystems: Impacts, Adaptation, and Mitigation." The specific aims are to generate a vigorous and rigorous interdisciplinary examination of the key factors, processes, and challenges ahead; to stimulate cooperative research; and to formulate strategies to deal effectively with the potential consequences of climate change on the environment in general and on future food security in particular. More information on this session and on this year's meetings will be posted to www.acsmeetings.org in the coming months.

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