# *The Wicked Problem of Climate Change*

*with Karl E. Peters, "Living with the Wicked Problem of Climate Change"; Paul H. Carr, "What Is Climate Change Doing to Us and for Us?"; James Clement van Pelt, "Climate Change in Context: Stress, Shock, and the Crucible of Livingkind"; Robert S. Pickart, "Climate Change at High Latitudes: An Illuminating Example"; Emily E. Austin, "Soil Carbon Transformations"; David A. Larrabee, "Climate Change and Conflicting Future Visions"; Panu Pihkala, "Eco-Anxiety, Tragedy, and Hope: Psychological and Spiritual Dimensions of Climate Change"; Carol Wayne White, "Re-Envisioning Hope: Anthropogenic Climate Change, Learned Ignorance, and Religious Naturalism"; Matthew Fox, "Climate Change,* Laudato Si', *Creation Spirituality, and the Nobility of the Scientist's Vocation"; Christopher Volpe, "Art and Climate Change: Contemporary Artists Respond to Global Crisis"; Jim Rubens, "The Wicked Problem of Our Failing Social Compact"; and Peter L. Kelley, "Crossing the Divide: Lessons from Developing Wind Energy in Post-Fact America."*

## SOIL CARBON TRANSFORMATIONS

### *by Emily E. Austin*

*Abstract.* Climate change is a wicked problem with causes and consequences overlapping with other wicked problems and no single solution (Hulme 2015). For example, the frequent droughts associated with climate change exacerbate another major problem facing humanity as we enter the Anthropocene: how to produce adequate food to feed a growing population without increasing pollution or "more food with low pollution (MoFoLoPo)" (Davidson et al. 2015). Soils represent an intersection of these two wicked problems, because they are integral to food production through agriculture and also are an important component of global climate models. Recent focus in the field of soil carbon cycling has facilitated a transformation in our understanding of the processes that control this important resource. This understanding is critical to responding to both wicked problems.

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Soil organic matter (SOM) contains more carbon than the atmosphere and biosphere combined (Batjes 2014), and will release increasing quantities of greenhouse gases to the atmosphere as the climate warms, serving as a reinforcing feedback to anthropogenic climate change. SOM is also an

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indicator of fertile soils that retain water and nutrients making agricultural systems resilient to drought and reducing pollution from agricultural runoff or fertilizer volatilization. Conventional agricultural practices, however, have caused a decline in soil organic matter contributing to greenhouse gas emissions (Sanderman et al. 2017). In contrast, sustainable agricultural practices such as no-till, cover crops, and intensive grazing aim to build SOM, which represents a rare win-win for humans and the environment.

## SOIL AS A SOURCE: A REINFORCING FEEDBACK LOOP TO CLIMATE CHANGE

Respiration from plant roots and soil organisms, collectively termed soil respiration, increases exponentially with warming. Therefore, a small change in the average soil temperature may result in a massive release of the greenhouse gas carbon dioxide to the atmosphere, especially in high latitudes which are experiencing the most rapid warming and contain the largest soil carbon stocks. Increased soil respiration could accelerate warming in a reinforcing feedback loop to exacerbate anthropogenic climate change. The magnitude and duration of the response represents a critical uncertainty in our predictions of future climates. This uncertainty has led to a surge of research focused on soil carbon cycling.

Despite the importance of the response of soil respiration to warming, there are few long-term, large-scale experiments manipulating soil temperature. Field scale manipulations are indispensable to disentangle the mechanisms driving carbon cycling in the context of complex interactions between the myriad biotic and abiotic factors in soils. For example, the competitive, predatory, symbiotic, and parasitic relationships between soil organisms may interact or respond differently to abiotic drivers such as climate or nitrogen deposition (acid rain).

One soil warming experiment has been running for over twenty years at the Harvard Forest in Petersham, Massachusetts. Following the initiation of 5°C soil warming, a drastic increase in soil respiration was observed. However, after ten years of warming, respiration in the warmed plots declined to a level similar to respiration in control plots (Melillo et al. 2004). This phenomenon instigated a surge of research from numerous groups testing for mechanisms for the acclimation of soil respiration in response to warming. Had the decomposer community adapted to the warmer temperatures physiologically or via shifts in the relative abundance of different taxa? Had the easily decomposed, labile carbon substrates been depleted? Most of all, did this balancing response represent a negative feedback to the increased release of greenhouse gases predicted under climate change?

Last year, Melillo et al. published the results of twenty years of warming in the Harvard Forest soils in the journal *Science* (Melillo et al. 2017). The audience of ecologists gasped when the graph was presented by

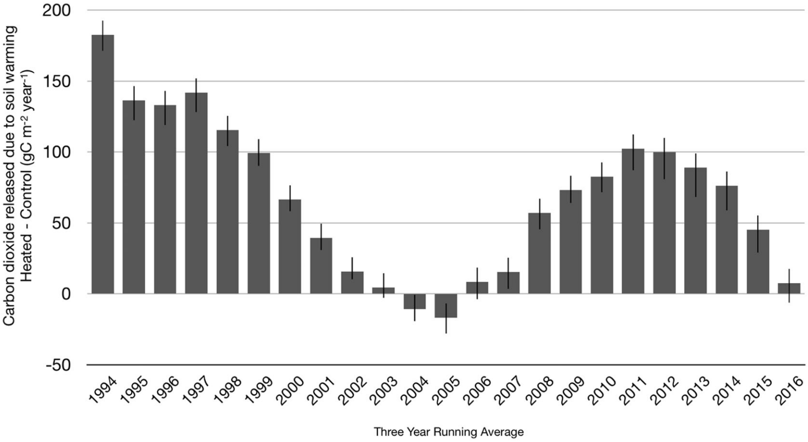

**Figure 1.** Increased carbon dioxide released from soil respiration due to warming. Data extracted from Melillo et al., 2017. In 2004, the conclusion from this experiment had been that the increased greenhouse gas emissions associated with warming soils would acclimate after about ten years of warming. Continued warming resulted in a cyclical pattern where carbon continues to be released from soils, highlighting the need for continued research.

co-author Serita Frey at the Ecological Society of America conference in Portland, Oregon (see Figure 1). The respiration response to temperature was apparently cyclical over a decadal timescale with periods of additional soil respiration punctuated by periods of reorganization of the microbial decomposer community (Fig 1). This surprising result highlights our lack of understanding of the underlying mechanisms that control soil carbon dynamics.

## SOIL AS A BLACK BOX: THE TWENTIETH-CENTURY PARADIGM

Carbon fluxes into and out of soil are well constrained and relatively easily quantified but carbon cycling within soil is impossible to observe or measure *in situ* without disturbance. Soil has been called a "black box" because we can measure what goes in and what comes out but not what happens within the soil. Carbon inputs from roots are difficult to measure due to their position inside the "black box"; root biomass inputs are often estimated, therefore, relative to leaf inputs.

The organisms responsible for the decomposition of these inputs are mostly soil bacteria and fungi. These are difficult to culture, and therefore microbial activity is often estimated as the whole soil respiration rate. Our long-time understanding of soil carbon storage is a net balance of inputs (leaf litter) and outputs (soil respiration). Based on this paradigm, increasing organic inputs or decreasing decomposition rates should increase soil carbon storage.

Inputs of leaf litter vary in their chemical composition. Tissues with higher concentrations of structural compounds or defensive chemicals that deter herbivores decompose more slowly than those with higher concentrations of nitrogen and phosphorus. Soil respiration comes from plant roots and from decomposers which are mainly microorganisms. Decomposition and soil respiration are both strongly correlated with temperature and moisture. Both processes can be inhibited by too dry or too wet conditions and both increase with increasing temperature. The size of the soil carbon pool varies with climate and vegetation, with the highest concentrations in cold regions and wetlands where microbial activity is limited by temperature and oxygen, respectively.

To summarize our twentieth-century understanding of soil carbon cycling: soil carbon stocks are a net balance of inputs and respiration. Inputs are mostly plant biomass from above-ground tissues, such as leaves. Below-ground inputs are considered biomass inputs reciprocal to leaf litter inputs. Respiration is a product of decomposition and it increases exponentially with warming. Soil carbon stocks can increase with greater biomass inputs or with reduced decomposition. For example, declines in SOM associated with agricultural production can be attributed, in part, to the act of plowing. Turning the soil gives microbial decomposers access to carbon by mixing the communities and the substrates together (West and Post 2002).

## SOIL CARBON TRANSFORMATION: A NEW TWENTY-FIRST CENTURY PARADIGM

The recent focus on soil carbon along with advances in methods to measure unseen components of the soil ecosystem have led to a revelation in our understanding of soil carbon cycling (Schmidt et al. 2011). The emerging paradigm recognizes the importance of below-ground inputs, and that decomposition of inputs will not necessarily deplete soil carbon stocks. Rather than undecomposed leaf litter, stable soil carbon pools are protected physically within aggregates or chemically on mineral surfaces. Biological, physical, and chemical factors contribute to whether soil will be a carbon sink (increasing storage) or source (increasing release).

The oldest soil carbon pools are composed of organic material that has been decomposed and processed by the microbial community at least once. Therefore, microbial decomposition of inputs could result in either carbon storage or carbon loss, and long-term carbon sequestration will be a result of the physiology of decomposer organisms (Allison et al. 2010; Sinsabaugh et al. 2013).

Most decomposition is done by bacteria and fungi in the soil, collectively termed soil micro-organisms. Bacterial activity has been difficult to quantify and attribute to different species or taxa because less than 1 percent of bacterial taxa are cultured in the lab. Most bacteria need to live in community with one another, as any given organism may not have the biochemical mechanism to break down a given substrate. Bacteria work in concert, each producing different enzymes to process and digest organic inputs. Advances in sequencing technology have revealed the development of bacterial networks in the area immediately surrounding the root (the *rhizosphere*), where many below-ground inputs enter the soil (Shi et al. 2016).

Soil fungi are categorized into two functional groups representing different life histories, decomposers and symbionts. Decomposer fungi are free living organisms that colonize all areas of soil with root-like filamentous *hyphae* and obtain all nutrients and carbon from decomposing organic materials. Mycorrhizal fungi are symbiotic with plant roots and acquire all their carbon directly from plants while providing nutrients to plants. Almost all plants are symbiotic with mycorrhizal fungi; the hyphae are much finer than plant roots and therefore are able to reach nutrients across a much greater area of soil. Some mycorrhizae have been shown to increase physical protection of soil carbon in aggregates (Jones et al. 2004) and deposit carbon obtained from plant roots onto mineral surfaces where it may be chemically protected (Kaiser et al. 2015). These contributions of mycorrhizal fungi to SOM pools are ignored when one considers below-ground inputs as symmetrical to above-ground leaf litter inputs.

## Root and Shoot Carbon Inputs

In the past, below-ground inputs (root biomass, exudates, and other root inputs) were generally assumed to be directly proportional to more easily measured above-ground inputs, and standard equations have been applied to estimate those below-ground inputs. Although ecologists have been advocating for a better understanding of below-ground inputs for decades, the inherent difficulties of sampling below-ground inputs limited research in this field. Below-ground inputs differ from above-ground inputs in their input frequency, chemical composition, proximity, and the physiological controls and environmental conditions which stimulate their production. Our emerging understanding of soil carbon cycling acknowledges that most soil organic matter is not undecomposed leaf litter. In fact, below-ground inputs such as roots and root deposits are retained in soil carbon pools longer than above-ground inputs.

To compare the relative importance of different inputs to SOM storage, we measured the relative contributions of below-ground and above-ground carbon inputs to SOM. We used carbon isotopes to label rye cover crop plants while they were growing, then cut the above-ground portion of the plant and transferred it to a new plot. This resulted in three plots, one with labeled decomposing shoots, one with labeled decomposing roots (including all the carbon inputs that transferred to the soil while the plant was growing), and one control plot. Using this design, we were able to measure that below-ground carbon was retained 2.6 times longer than above-ground carbon in SOM, and much of this was in the stable, mineral-associated, and aggregate SOM pools (Austin et al. 2017).

## SOIL AS A SINK

Agricultural soils are some of the most extensively managed ecosystem components on Earth and represent a potential for climate change mitigation. Current agricultural practices are associated with declines in SOM (Sanderman et al. 2017). Yet SOM can improve soil fertility by increasing nutrient and water retention. Shifting soil from a source, which releases carbon to the atmosphere, to a sink, which collects and sequesters carbon, could therefore benefit agricultural production and mitigate climate change. As climate change leads to more irregular precipitation patterns and frequent drought, the resilience of agricultural systems and water use efficiency are increasingly important. We will need to produce more food to avoid massive famines as the human population continues to grow. Fertilization can improve yield, but the runoff of excess fertilizer has destroyed ecosystems in streams, rivers, and along the coast. In contrast, SOM serves as a savings account, storing water and nutrients which can be later accessed by plants and reducing nutrient loss via runoff or groundwater. SOM offers a potential to improve agricultural yield, sequester atmospheric carbon dioxide, and reduce pollution from fertilizer runoff.

Declines in SOM associated with agricultural conversion have been attributed to reduced biomass inputs and increased disturbance via tillage. However, there are several other environmental changes associated with agriculture, such as fertilization increasing nutrient availability and decreasing plant diversity from natural communities to monoculture crops.

Nitrogen fertilization increases crop yield and therefore the biomass input from residues. However, increased biomass production and inputs are not always associated with gains in soil carbon stock. Furthermore, optimizing soil nitrogen amendments for maximum growth exceeds the quantity of nitrogen that can be retained by most agricultural soils.

Converting natural landscapes to agricultural production reduces plant community diversity, but the extent of diversity maintained varies. A monoculture crop with a fallow period represents the lowest level of diversity; however, a crop rotation where corn, soy, and wheat may be grown in successive years increases temporal diversity. Further, some sustainable agricultural practices include additional plants as cover crops. Cover crops are not intended for harvest and are grown during a time when soil would otherwise be left bare fallow. Legumes are often used for their unique microbial associations which fix atmospheric nitrogen and act as natural fertilizers. Recent research indicates that most soil organic matter comes from below-ground root inputs, indicating that plants such as grasses with more root biomass may be the best cover crops for building soil organic matter.

## COVER CROPS BUILD SOIL ORGANIC MATTER

Cover crops are grown during the period when an agricultural field would otherwise be bare fallow. Cover crops increase organic inputs to soil and plant diversity over time. After finding that roots contribute more to SOM than shoots, we wanted to know whether different plant types, with different ratios of root and shoot inputs, might show different contributions to SOM pools. We expected that grass-type cover crops, such as rye, would build more SOM because they have more root inputs than other types such as legumes which are used for their unique ability to associate with nitrogen fixing bacteria. We performed a meta-analysis comparing soil carbon in agricultural systems with and without the use of a cover crop (research results in preparation). We found that all cover crops build SOM, but nitrogen-fixing legumes were the most effective at building SOM in agricultural fields and that cover crops were most effective in systems with low levels of nitrogen fertilization. Cover crops can be one of several sustainable agricultural practices used to regenerate soil carbon pools.

## CONCLUSION

The magnitude of the response of soil carbon warming represents a critical uncertainty in global climate predictions. Warming soil has the potential to drastically accelerate anthropogenic climate change. Yet, land management practices such as cover crops have the potential to offset some of the greenhouse gases emitted by warming soils. A greater understanding of the mechanisms controlling soil carbon dynamics should enhance our ability to predict or prioritize management practices that will mitigate climate change and increase food production.

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