Soil Carbon Storage

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Soil carbon storage is a vital ecosystem service, resulting from interactions of ecological processes. Human activities affecting these processes can lead to carbon loss or improved storage.

Organic matter is a key component of soil that affects its physical, chemical, and biological properties, contributing greatly to its proper functioning on which human societies depend. Benefits of soil organic matter (SOM) include improvement of soil quality through increased retention of water and nutrients, resulting in greater productivity of plants in natural environments and agricultural settings. SOM improves soil structure and reduces erosion, leading to improved water quality in groundwater and surface waters, and ultimately to increased food security and decreased negative impacts to ecosystems. Since the beginnings of recorded history, societies have understood that human activities can deplete soil productivity and the ability to produce food (McNeill and Winiwarter 2004). Only in recent history has the understanding of soil productivity been tied to SOM levels, with the depletion of SOM stocks often leading to large-scale impacts on whole ecosystems as well as the entire planet. For example, destruction of rainforests that hold a significant amount of the carbon stored in terrestrial ecosystems contributes significantly to rising atmospheric carbon dioxide (CO_2) levels linked to climate change, while reductions in SOM levels from soil disturbance from mining can impact infiltration of rainfall and the storage of soil moisture important for flood mitigation. Soil disturbance also leads to increased erosion and nutrient leaching from soils, which have led to eutrophication and resultant algal blooms within inland aquatic and coastal ecosystems, ultimately resulting in dead zones in the ocean (Fig. 1). Restoration of organic matter levels in soil requires an understanding of the ecological processes important for SOM storage. Proper restoration techniques can help restore terrestrial ecosystem functions.

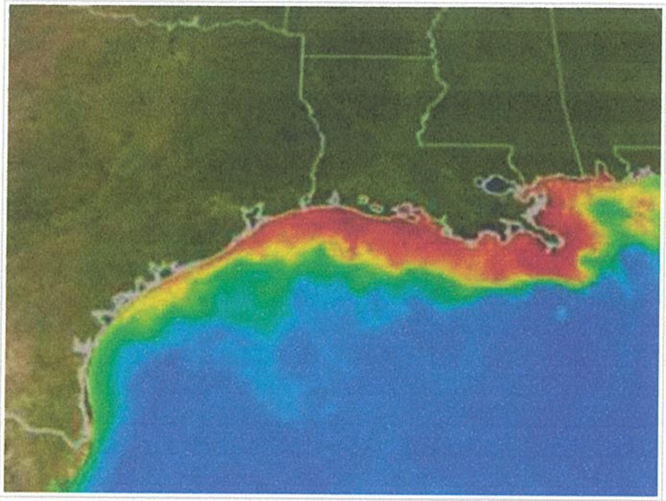


Figure 1: Summer algal conditions along the US Gulf Coast. Red indicates high concentrations of algae due to nutrients flowing into the Gulf of Mexico, primarily from the Mississippi River basin. © 2012 **Nature Education** Photo courtesy of NASA/Goddard Space Flight Center Scientific Visualization Studio. All rights reserved.

Fundamentals of Soil Organic Carbon

Soil organic matter is composed of soil microbes including bacteria and fungi, decaying material from once-living organisms such as plant and animal tissues, fecal material, and products formed from their decomposition. SOM is a heterogeneous mixture of materials that range in stage of decomposition from fresh plant residues to highly decomposed material known as humus. SOM is made of organic compounds that are highly enriched in carbon. Soil organic carbon (SOC) levels are directly related to the amount of organic matter contained in soil and SOC is often how organic matter is measured in soils.

SOC levels result from the interactions of several ecosystem processes, of which photosynthesis, respiration, and decomposition are key. Photosynthesis is the fixation of atmospheric CO_2 into plant biomass. SOC input rates are primarily determined by the root biomass of a plant, but also include litter deposited from plant shoots. Soil C results both directly from growth and death of plant roots, as well as indirectly from the transfer of carbon-enriched compounds from roots to soil microbes. For example, many plants form symbiotic associations between their roots and specialized fungi in the soil known as mycorrhizae; the roots provide the fungi energy in the form of carbon while the fungi provide the plant with often-limiting nutrients such as phosphorus. Decomposition of biomass by soil microbes results in carbon loss as CO_2 from the soil due to microbial respiration, while a small proportion of the original carbon is retained in the soil through the formation of humus, a product that often gives carbon-rich soils their characteristic dark color (Fig. 2). These various forms of SOC differ in their recalcitrance, or resistance to decomposition. Humus is highly recalcitrant, and this resistance to decomposition leads to a long residence time in soil. Plant debris is less recalcitrant, resulting in a much shorter residence time in soil. Other ecosystem processes that can lead to carbon loss include soil erosion and leaching of dissolved carbon into groundwater. When carbon inputs and outputs are in balance with one another, there is no net change in SOC levels. When carbon inputs from photosynthesis exceed C losses, SOC levels increase over time.

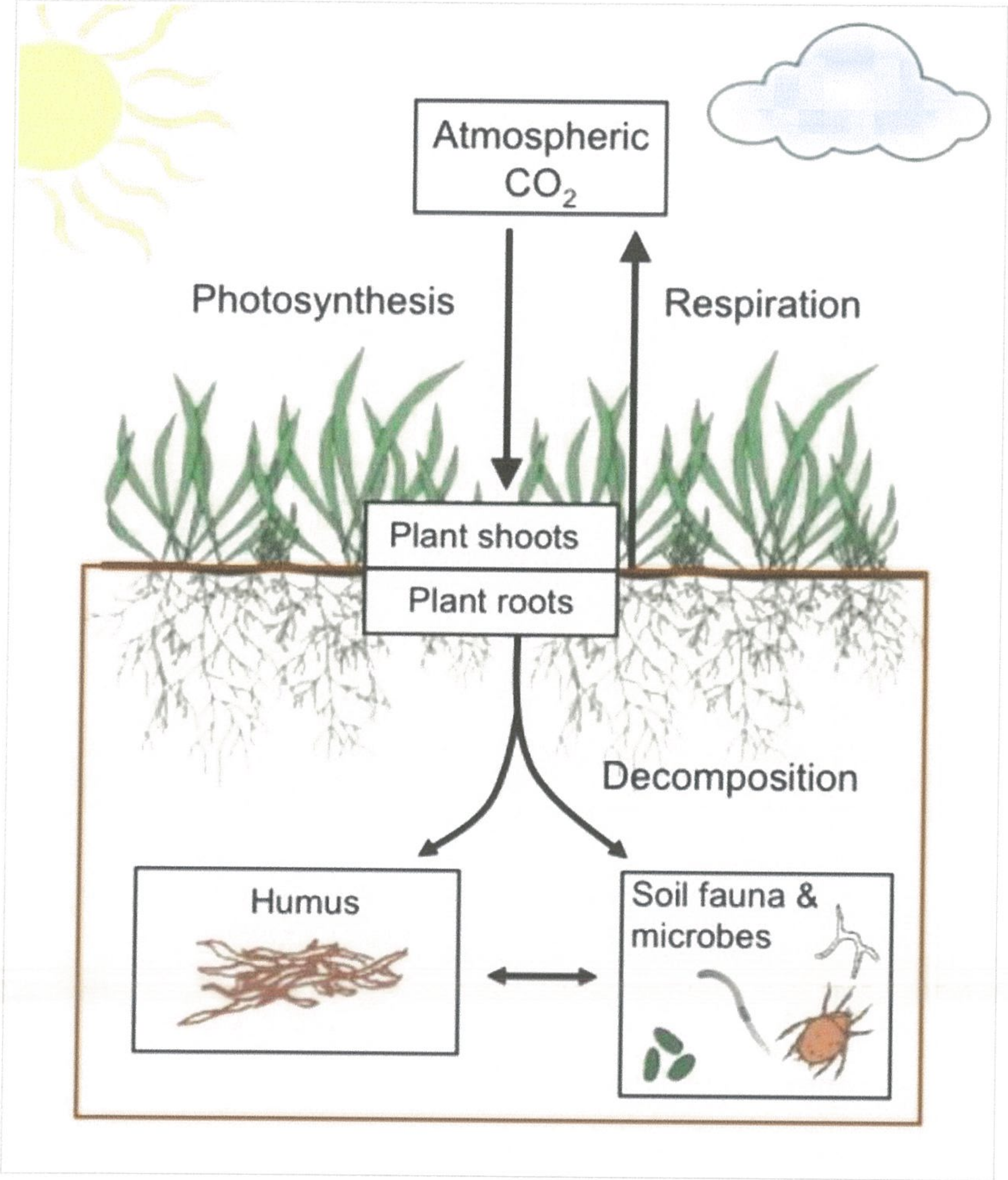


Figure 2: Carbon balance within the soil (brown box) is controlled by carbon inputs from photosynthesis and carbon losses by respiration.

Decomposition of roots and root products by soil fauna and microbes produces humus, a long-lived store of SOC.

Photosynthesis, decomposition, and respiration rates are determined partly by climatic factors, most importantly soil temperature and moisture levels. For example, in the cold wet climates of the northern latitudes, rates of photosynthesis exceed decomposition resulting in high levels of SOC (Fig. 3). Arid regions have low levels of SOC mostly due to low primary production, while the tropics often have intermediate SOC levels due to high rates of both primary productivity and decomposition from warm temperatures and abundant rainfall. Temperate ecosystems can have high primary productivity during summer when temperature and moisture levels are highest, with cool temperatures during the rest of the year slowing decomposition rates such that organic matter slowly builds up over time (Fig. 4). While climatic conditions largely generate global patterns of soil carbon, other factors that vary on smaller spatial scales interact with climate to determine SOC levels. For example, soil texture — the relative proportions of sand, silt, and clay particles that make up a particular soil — or the mineralogy of those soil particles can have a significant impact on soil carbon stocks. Additionally, the processes of erosion and deposition act to redistribute soil carbon according to the topography of the landscape, with low-lying areas such as floodplains often having increased SOC relative to upslope positions.

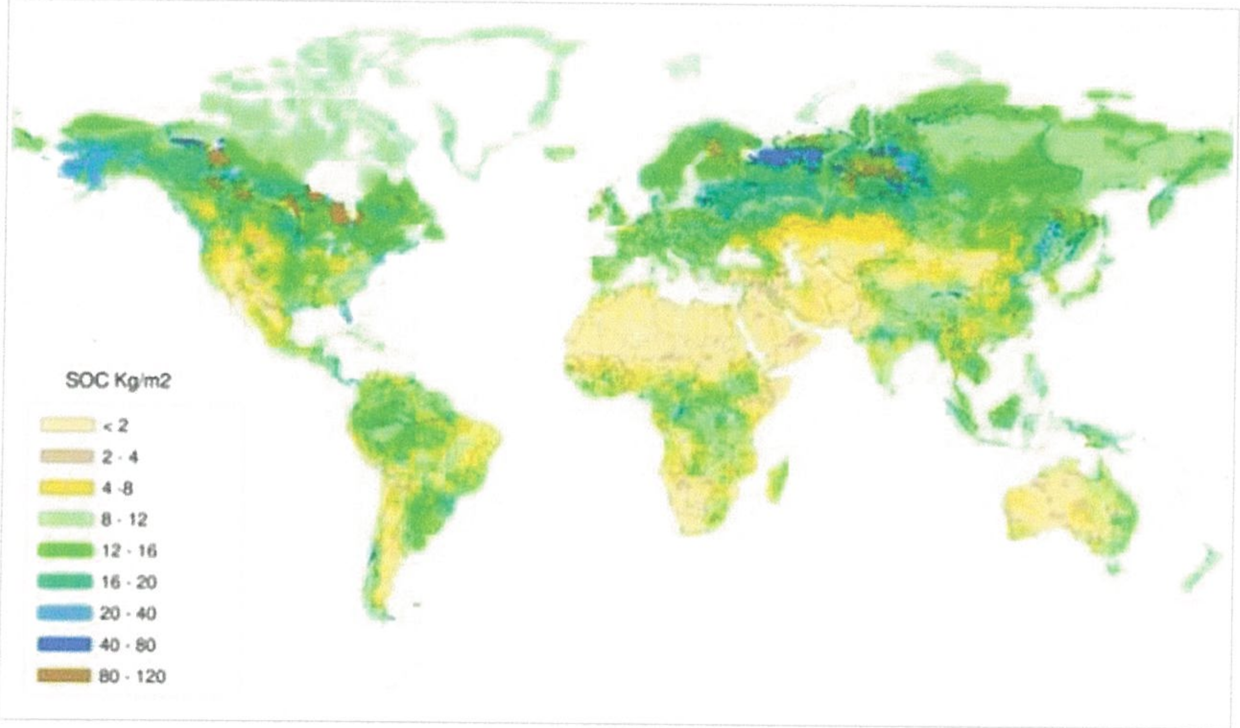


Figure 3: World map showing the quantity of SOC to 1 m depth.

Figure 4: Dark colored topsoil showing high levels of SOC due to abundant plant roots and their associated soil fauna and microbes in a cultivated soil in central Iowa.

Soil Carbon and the Global Carbon Cycle

The amount of C in soil represents a substantial portion of the carbon found in terrestrial ecosystems of the planet. Total C in terrestrial ecosystems is approximately 3170 gigatons (GT; 1 GT = 1 petagram = 1 billion metric tons). Of this amount, nearly 80% (2500 GT) is found in soil (Lal 2008). Soil carbon can be either organic (1550 GT) or inorganic carbon (950 GT). The latter consists of elemental carbon and carbonate materials such as calcite, dolomite, and gypsum (Lal 2004). The amount of carbon found in living plants and animals is comparatively small relative to that found in soil (560 GT). The soil carbon pool is approximately 3.1 times larger than the atmospheric pool of 800 GT (Oelkers & Cole 2008). Only the ocean has a larger carbon pool, at about 38,400 GT of C, mostly in inorganic forms (Houghton 2007).

Soil Carbon and Climate Change

There is a growing body of evidence supporting the hypothesis that the earth's climate is rapidly changing in response to continued inputs of CO_2 and other greenhouse gases (GHGs) to the atmosphere resulting from human activities (IPCC 2007). While a suite of GHGs exist (e.g., N_2O, CH_4), CO_2 has the largest effect on global climate as a result of enormous increases from the preindustrial era to today. Atmospheric CO_2 concentrations have risen from approximately 280 parts per million (ppm) prior to 1850, to 381.2 ppm in 2006 (WMO 2006), with a current annual increase of 0.88 ppm (3.5 GT C/yr) (IPCC 2007). Approximately two-thirds of the total increase in atmospheric CO_2 is a result of the burning of fossil fuels, with the remainder coming from

SOC loss due to land use change (Lal 2004), such as the clearing of forests and the cultivation of land for food production (Fig. 5).

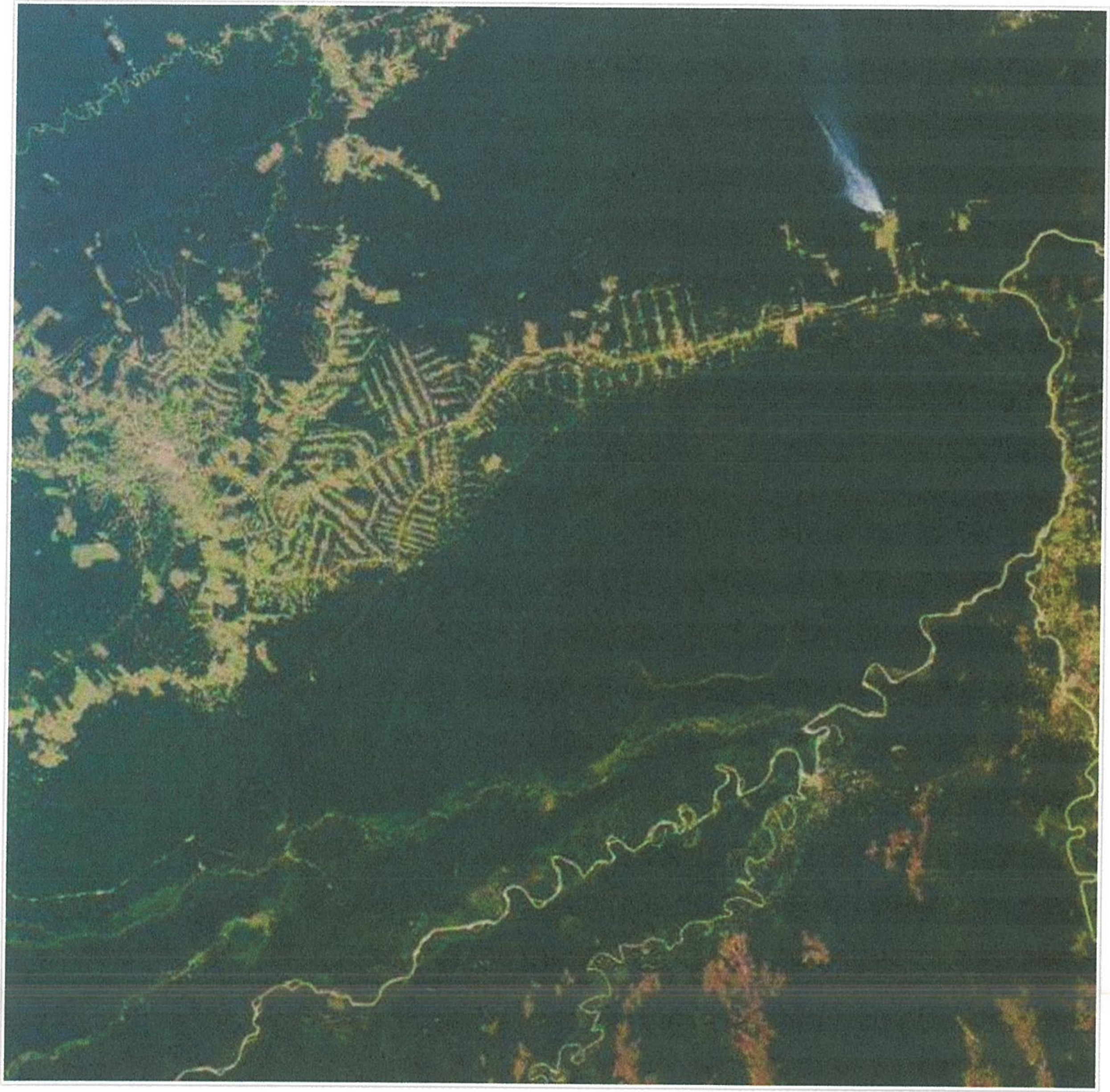


Figure 5: Deforestation around Rio Branco, Brazil.

Light colored areas are where rainforest vegetation has been cleared and burned (see smoke plume) for farming and cattle ranching.

While the carbon released to the atmosphere through deforestation includes carbon emitted from the decomposition of aboveground plant biomass, carbon levels in the soil are also rapidly depleted from the decomposition of SOM. The decomposition of SOM is due to the activity of the microbial decomposer community in the absence of continual rates of carbon input from the growth of forest vegetation, as well as increased soil temperatures that result from warming of the ground once the forest canopy has been removed. Although this soil carbon loss has contributed to increased CO_2 levels in the atmosphere, it also is an opportunity to store some of this carbon in soil from reforestation.

Despite the much larger size of the oceanic carbon pool relative to the soil carbon pool, the rate of exchange between the atmosphere and the soil is estimated to be higher than that between the atmosphere and the ocean. Current estimates are that carbon inputs from photosynthesis by terrestrial vegetation fixes more carbon than carbon loss through soil respiration, resulting in a soil storage rate of about 3 GT C/yr. Oceanic carbon flux rates suggest oceans store about 2 GT carbon/yr despite occupying a vastly larger proportion of the earth's surface. Although there is interest in increasing oceanic carbon storage rates through large-scale nutrient additions, there is skepticism towards this approach due to the unknown consequences on global nutrient cycles and marine ecosystems (Cullen & Boyd 2008). The goal of increased storage of carbon in soil has received much wider acceptance due to a better understanding of the processes involved in SOC storage, more direct control of these processes through human activities, and the other known ecosystem benefits to be obtained by increasing SOC, including benefits to water quality and increased food security.

Soil Carbon Sequestration

Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool. This process is primarily mediated by plants through photosynthesis, with carbon stored in the form of SOC. In arid and semi-arid climates, soil carbon sequestration can also occur from the conversion of CO_2 from air found in soil into inorganic forms such as secondary carbonates; however, the rate of inorganic carbon formation is comparatively low (Lal 2008).

Since the industrial revolution, the conversion of natural ecosystems to agricultural use has resulted in the depletion of SOC levels, releasing 50 to 100 GT of carbon from soil into the atmosphere (Lal 2009). This is the combined result of reductions in the amount of plant roots and residues returned to the soil, increased decomposition from soil tillage, and increased soil erosion (Lemus & Lal 2005). Depletion of SOC stocks has created a soil carbon deficit that represents an opportunity to store carbon in soil through a variety of land management approaches. However, various factors impact potential soil carbon change in the future, including climatic controls, historic land use patterns, current land management strategies, and topographic heterogeneity.

Continued increases in atmospheric CO_2 and global temperatures may have a variety of different consequences for soil carbon inputs via controls on photosynthetic rates and carbon losses through respiration and decomposition. Experimental work has shown that plants growing in elevated CO_2 concentrations fix more carbon through photosynthesis, producing greater biomass (Drake *et al.* 1997). However, carbon loss may also increase due to increased plant respiration from greater root biomass (Hungate *et al.* 1997), or from accelerated decomposition of SOM through increased microbial activity (Zak *et al.* 2000). Likewise, increased temperatures may impact the carbon balance by limiting the availability of water, and thus reducing rates of photosynthesis. Alternatively, when water is not limiting, increased temperatures might increase plant productivity, which will also impact the carbon balance (Maracchi *et al.* 2005). Increased temperatures may also lead to higher rates of SOM decomposition, which may in turn produce more CO_2, resulting in positive feedbacks on climate change (Pataki *et al.* 2003).

At the scale of a watershed or crop field, the carbon sequestration capacity of the soil may be influenced by local controls on ecosystem processes. Processes such as rainfall infiltration, soil erosion and deposition of sediment, and soil temperature can vary on local scales due to landscape heterogeneity — all of which affect carbon input and carbon loss rates (Fig. 6), resulting in differences in SOC contents along topographic gradients (Thompson and Kolka 2005). For example, slope position impacts soil moisture and nutrient levels, with subsequent impacts on the root growth of plants that may have consequences for soil carbon (Ehrenfeld *et al.* 1992). The combined effects of changes in carbon inputs and losses from land use, land management, and landscape-level effects on carbon input and loss rates result in variation in the carbon sequestration capacity across landscapes.

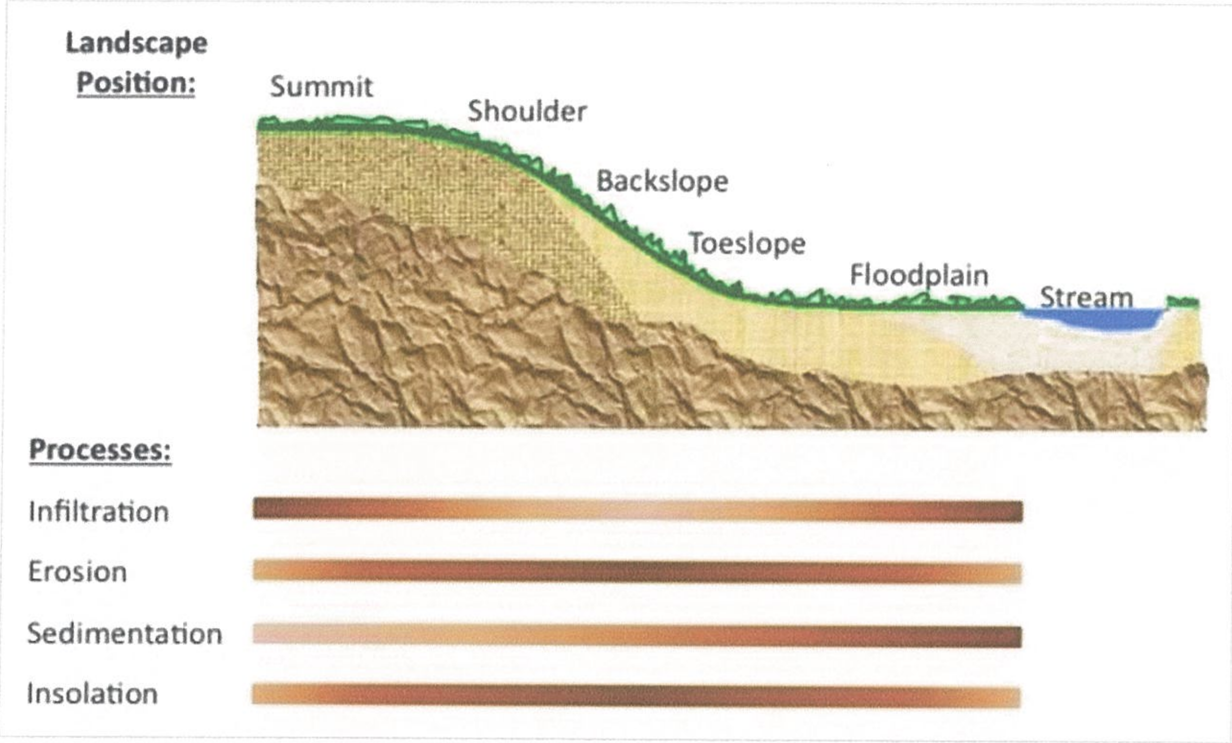
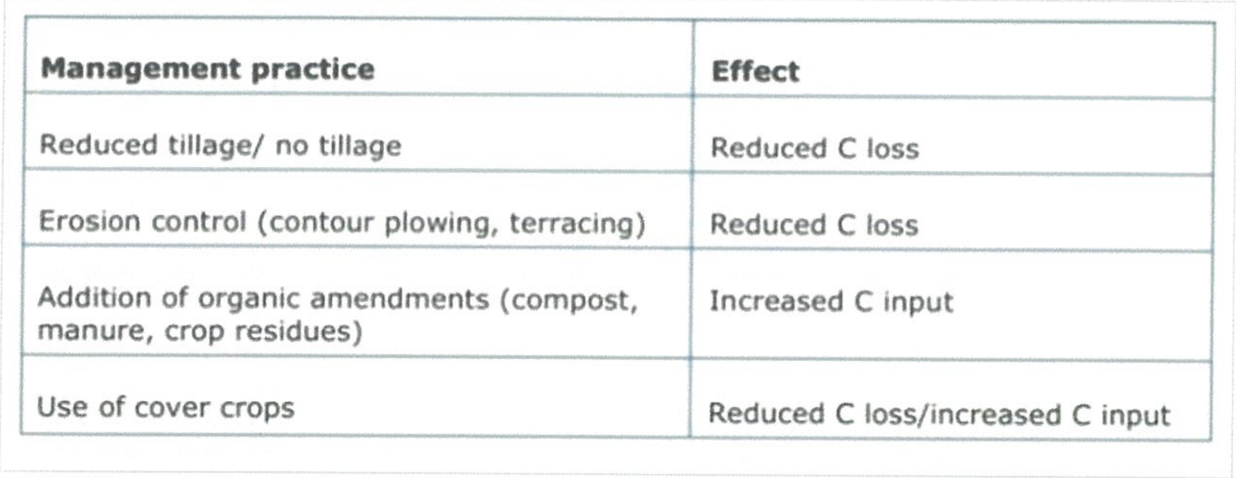


Figure 6: Landscape heterogeneity due to landscape position along a hill slope and possible effects on biophysical processes that effect carbon inputs and losses.

Darker areas on bars indicate higher rates.

Carbon sequestration potential may be determined by an understanding of both the historic SOC stocks under natural vegetation prior to conversion to other uses and the influences of those land uses on carbon loss. Land uses and management that reduce carbon inputs or increase losses compared to natural vegetation result in reductions in SOC over time, creating a soil carbon deficit relative to the levels of carbon that previously existed in the soil. This deficit represents an opportunity to store carbon from conversions in land use and management when those changes result in either increased inputs or decreased losses of carbon. For example, reforestation or grassland restoration on a former crop field can reduce the carbon deficit caused from years of agricultural production and sequester carbon through higher root productivity compared to crops. Likewise, the creation of wetlands and ponds can sequester large amounts of carbon because decomposition is greatly reduced in waterlogged soils from lack of oxygen; this can actually result in carbon gains that exceed the deficits resulting from past land use. Other management practices such as irrigation of pasture or rangelands may also increase carbon levels beyond historic SOC stocks if carbon inputs under new management greatly exceed levels under natural conditions. The effect of land management on SOC levels, especially the impacts of management in agricultural settings, is the subject of much current research (Table 1). These changes in soil carbon, however, typically take many decades to occur, making actual measurements of changes in SOC stocks difficult.



Management practice	Effect
Reduced tillage/ no tillage	Reduced C loss
Erosion control (contour plowing, terracing)	Reduced C loss
Addition of organic amendments (compost, manure, crop residues)	Increased C input
Use of cover crops	Reduced C loss/increased C input

Table 1: Possible management practices for increasing SOC levels through reduced carbon losses and increased carbon inputs in agricultural systems.

Conclusion

SOC is a vital component of soil with important effects on the functioning of terrestrial ecosystems. Storage of SOC results from interactions among the dynamic ecological processes of photosynthesis, decomposition, and soil respiration. Human activities over the course of the last 150 years have led to changes in these processes and consequently to the depletion of SOC and the exacerbation of global climate change. But these human activities also now provide an opportunity for sequestering carbon back into soil. Future warming and elevated CO_2, patterns of past land use, and land management strategies, along with the physical heterogeneity of landscapes are expected to produce complex patterns of SOC capacity in soil.

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