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SOIL CARBON SEQUESTRATION

LABORATORY OF CONSERVATION AND DYNAMICS OF VOLCANIC SOIL
UNIVERSIDAD DE LA FRONTERA
CHILE

WHY DOES SOIL ORGANIC MATTER WORRY US?

FRANCISCO MATUS

Laboratory of Conservation and Dynamics of Volcanic Soils, Department of Chemical Sciences and Natural Resources, Universidad de La Frontera, Avenida Francisco Salazar, P.O. Box 54-D, 01145 Temuco, Chile
(francisco.matus@ufrontera.cl)

Organic matter is a crucial component of soil that affects its physical, chemical, and biological properties, contributing significantly to various ecosystem services such as soil carbon (C) sequestration. In recent history, understanding the relationship between crop productivity and soil organic matter (SOM) levels becomes a significant issue due to global warming. The benefits of SOM include improving soil quality through increased nutrients and water retention, and soil structure resulting in reduced erosion and more significant nutrient fluxes to the plants in natural environments and agricultural soils. Besides, SOM promotes water quality, increasing food security, and lowering negative impacts on ecosystems (Photo 1).

Photo 1. A Mollisol soil profile from central Kanazas, US exposing roots to a depth of 2.5 m from (A) perennial wheat grass (*Thinopyrum intermedium*) and (B) wheat (*Triticum aestivum*) (photo: J. Richardson and J. Glover) obtained from Crews and Rumsey (2017)

Photo 2. Massive accumulation of algal biomass as a result of less oxygen in the seawater andcontribute to widescale mortality among less mobile aquatic organisms (Photo: ESA).

The soil can store between two to three times C than that existing in the atmosphere as carbon dioxides (CO_2). Thus, the destruction of rainforests that deplete a significant amount of the organic C stored in soil contributes significantly to rising atmospheric CO_2 levels associated with warming. Soil disturbance like plowing, burning crop residues, and other human practices enhance erosion and nutrient percolation beyond rooting depth (leaching), generating eutrophication (for example, algal blooms) within the lake and coastal ecosystems (Photo 2). Restoration of organic matter levels in soil requires many years and, therefore, an understanding of the SOM storage in ecological processes matter.

Inspired from Ontl, T. A. and Schulte, L. A. (2012) Soil Carbon Storage. Nature Education Knowledge 3(10):35.

WHAT IS SOM MADE OF?

The SOM is highly enriched in organic C, a heterogeneous mixture of materials that range in decomposition from fresh plant residues to significantly decomposed materials or humus (highly microbial processed organic compounds). Soil organic matter is formed from live and dead microbes, including bacteria and fungi, decaying materials, plant and animal tissues.

Soil organic matter levels are directly related to the amount of organic C in the soil often being 58% of the SOM. Its formation results from several factors and ecosystem processes. Photosynthesis is the absorption and fixation of atmospheric CO_2 into plant biomass from which respiration and decomposition are the essential processes of CO_2 emissions into the atmosphere. Consequently, the SOM inputs rates are primarily determined by the plant roots biomass, including the litterfall from forests from which soil microbes decompose C-enriched compounds associated withint soil aggregates and the mineral particles (Fig. 1).

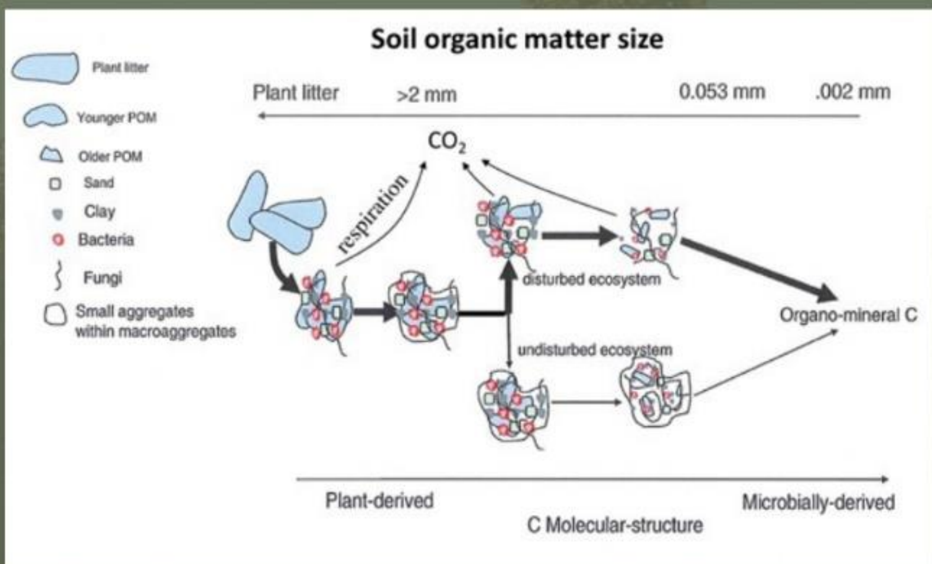


Fig. 1. Schematic overview of soil aggregate formation and breakdown processes and its effects on particulate organic matter structure and size (adapted from Crews and Rumsey, 2017).

WHY SOM IS DEPLETED?

Since the industrial revolution, the conversion of natural ecosystems to agricultural use has resulted in the depletion of SOC levels, more than 100 Gt of C emissions from the soil into the atmosphere. This is the combined effect of lowering in the plant roots and residues returned to the soil (for example due to burning), increased decomposition from soil tillage, and increased soil erosion. Decomposition of biomass by soil microbes results in C loss as CO_2 from the soil due to microbial respiration that causes SOM depletion. The specialized fungi associated with the roots, known as mycorrhizas, can explore new soil sites exposing SOM to further decomposition. Thus, fungi provide the plant with often-limiting nutrients such as phosphorus, while the plant provides the C to the fungi.

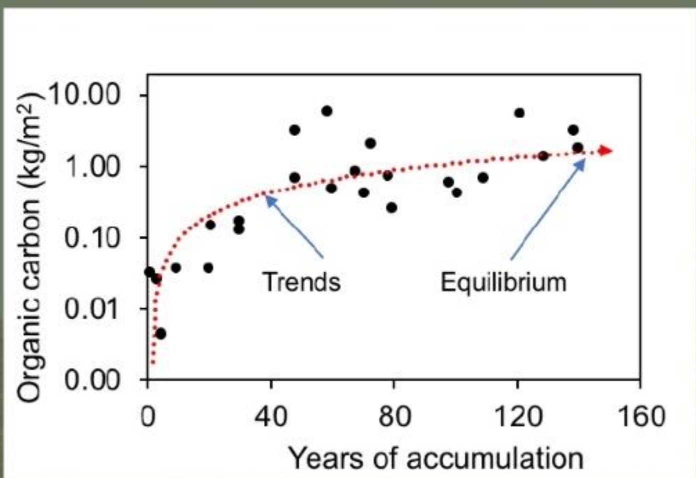


Fig. 2. Temporal evolution (over 140 years) of soil organic matter stocks after the glacier retreated a Morteratsch (after Matus and Egli, 2019).

If we start from a crop residue incorporation in the soil after harvest, a small proportion of the original C input is retained in the soil through humus formation. For example, in a temperate climate, one-third of the C added to the soil in crop residues remain in the SOM after one year of decomposition. Increasing or decreasing the SOM content depends on a net SOC balance (gain or loses) and decomposition speed. Humus is highly resistant (recalcitrant) to microbial consumption with a low decomposition rate or long-residence time in soil, while plant debris is less recalcitrant, resulting in a much shorter residence time decomposition. Other ecosystem processes that can lead to C loss include soil erosion and leaching of dissolved C into groundwater. However, when C inputs and outputs are in balance, there is no net change in SOM levels, called steady-state or equilibrium (Fig. 2). When C inputs from photosynthesis exceed C losses, SOC levels

WHAT ARE THE MOST CRITICAL FACTORS FOR SOM LEVEL?

The decomposition and respiration rates are determined partly by climatic conditions, such as soil temperature and soil moisture. Suppose the rates of photosynthesis exceed the decomposition of SOM. In that case, the soil will result in a high SOM level, for example, the slow decomposition rates in the cold, wet climates of the northern latitudes, or an intermediate SOM levels associated to the high primary productivity and decomposition rates in the tropics with warm temperatures and abundant rainfall.

Although climatic conditions affect a global SOM decomposition pattern, other factors interact with climate to determine SOM levels. For example, soil texture (the proportions of sand, silt, and clay particles and its mineralogy associated) can significantly impact SOM stocks depending on climates and the amount and type of mineral.

As above-mentioned, the soil organic carbon (SOC) is 58% of the SOM measured. It represents a considerable portion of the total C found in terrestrial ecosystems (plants and soils), approximately 3,170 gigatons (Gt; 1 Gt = 1 petagram = 1 billion metric tons). Of this amount, nearly 80% (2,500 Gt) is found in soil, either in organic (1,550 Gt) or inorganic C (950 Gt) forms (Fig. 3). The latter contains carbonate materials, for example, calcite, dolomite, and gypsum. The amount of C found in living plants and animals is comparatively little relative to that found in the soil (560 Gt). The soil C pool is approximately 3.1 times larger than the atmospheric pool of 720-800 Gt. Only the ocean has a higher C pool (38,400 Gt), mainly in inorganic forms. The CO_2 concentrations have risen from approximately 280 parts per million (ppm for short), equivalent to 0.028% of the air volume before 1850 (preindustrial time), to more than 410 ppm (0.041%) in 2019, with a current annual increase greater than 0.9 ppm (3.5 Gt C per year).

It is hard to imagine that such a small percentage of CO_2 in the atmosphere can produce such climate changes. One good reason is that CO_2 has increased more than any greenhouse gas in the last 800,000 years, driven by human activity. Approximately two-thirds of the total increase in atmospheric CO_2 results from the burning of fossil fuels, and the remainder is from SOC loss due to land-use change, for example, the clearing of forests and the cultivation of land for food production (Fig. 3). The decomposition of SOM is due to the microbial decomposer community, and in the absence of continual rates of C input due to burning vegetation, the SOM level decrease enhanced by raised soil temperatures. So, soil organic carbon depleted soil can be restored ideally to the same original level by soil C sequestration and strategies managements.

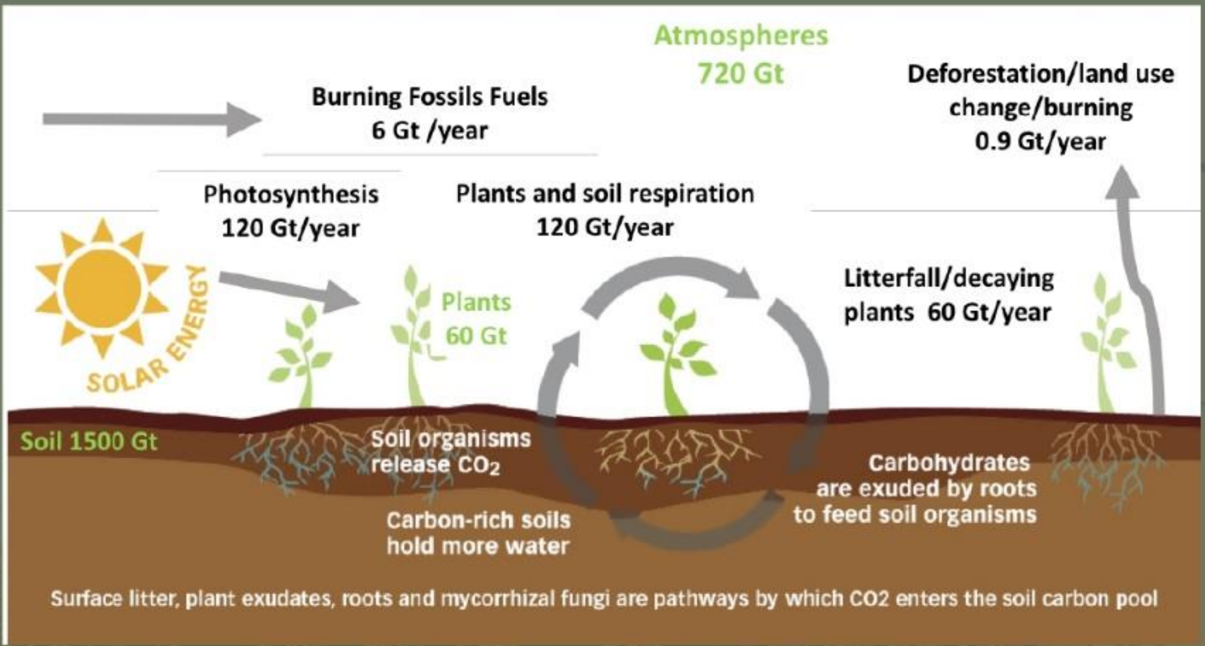


Fig. 3. Global carbon circulation adapted from https://resource.cecsb.org/rethink-food/carbon- farming. 1 Gt = 1 billion metric tons of organic carbon (C). Black letters stand for fluxes per year. Green letters stand for the accumulated pool of organic C in soil, plant, or C as CO_2 in the atmosphere. Burning fossil fuels come mainly from industries (for example, cements companies and city transports).

WHAT IS SOIL CARBON SEQUESTRATION?

The CO_2 removed from the atmosphere and stored in the soil is what is called soil C sequestration. Although plants mainly facilitate this process through photosynthesis to place a large amount of above-ground and below-ground biomass into the soil, in arid and semi-arid climates with fewer plants, C sequestration can also occur by the transformation of CO_2 in the air pore volume of soil to inorganic forms, such as secondary carbonates, but at a comparatively low rate of formation. Understanding that the oceans globally accumulate more C than terrestrial pools, the motivation to increase C storage in soil has received much wider recognition due to a better understanding of the processes than the knowledge to increase the C storage in the oceans.

The current estimated of soil C storage rate of terrestrial vegetation fluxes (photosynthesis minus respiration per year) is 1.5 times higher (3 Gt per year) than the ocean calculated storage rate. These differences and more direct knowledge of soil C dynamics and control through human activities and other indirect ecosystem services such as water quality and increased food security have influenced to consider the soils as nature-based solutions subject for global warming mitigation. Depletion of SOC stocks creates a C deficit that can be partially recovered through various land use management strategies. There is a strong need for additional research on establishing the threshold or critical limit of SOM level for diverse soils and management systems. Experiments shows that plants growing in elevated CO_2 concentrations fix more C through photosynthesis, producing greater biomass, but at the same time, the plant respiration increases from greater root biomass and accelerated decomposition of SOM. As a result, the SOM level increase or remains more or less the same or even decrease. Alternatively, increased temperatures may impact the C balance by limiting water availability, thus reducing photosynthesis rates (Fig. 4). However, under the scenario of not limiting water, increased temperatures might increase plant productivity, impacting the C balance.

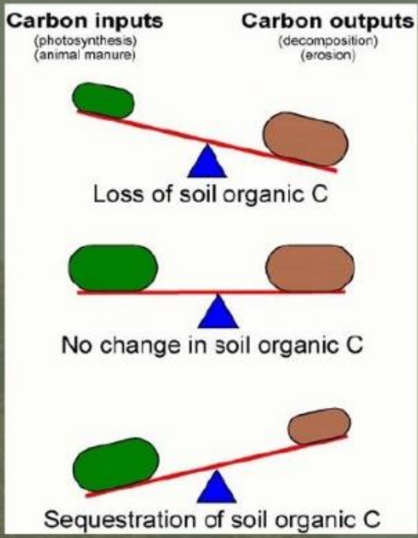
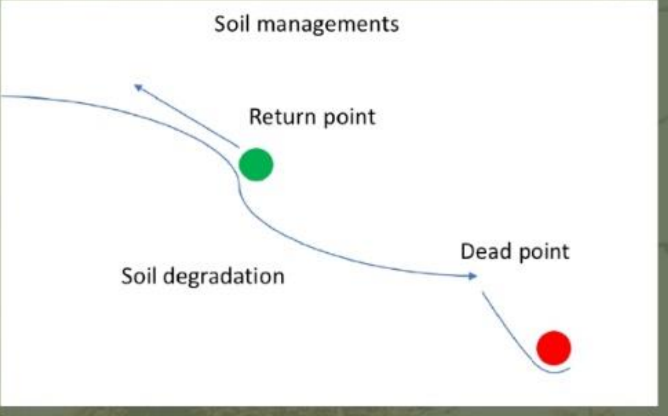


Fig. 4. Soil organic carbon balance between carbon input (carbon fixed by photosynthesis in plant biomass and carbon output (carbon decomposed by soil microbes and soil fauna). Soil carbon sequestration increase if it is stabilized in the long-term (Causarano et al., 2005).

HOW DO WE GUARANTEE THE C SEQUESTRATION IN THE SOIL?

At the scale of a watershed or crop field, the soils C sequestration capacity may be influenced by local controls on ecosystem processes such as rainfall infiltration, soil erosion and deposition of sediment. Soil temperature can contrast on local scales due to landscape characteristics and agricultural management all which affect the C gain and C losses. The combined effects of C inputs and C losses in different climates and soils types result in variation in the sequestration capacity across landscapes and agricultural fields. Carbon sequestration potentially may be determined by knowing both the historic SOC stocks under natural vegetation before conversion to other uses and the influences land-use managements that reduce the inputs or increases losses compared to natural vegetation over time. By estimating the difference in soil C deficit relative to previous SOC levels, we can calculate soil C sequestration in degraded ecosystems that can reach a return point beyond which it is difficult to restore the original level (Fig. 5).

Fig. 5. Soil degradation can reach a green dot beyond which is not possibility to restore the ecosystems reaching the red dot).



Our lab developed a technique for determining the soil deficit, the amount of SOC necessary to reach a threshold value (upper C level) in various soils and management systems. If we know the soil texture, particularly the amount of C in the clay and silt, we can estimate that per each gram of C in this fraction we can sequester 1.23 g of C in the whole soil. For example, reforestation or grassland re-establishment in degraded soils can reduce the C deficit caused by agricultural activities sequestering C through higher root productivity than previous condition. This calculations does not include wetlands and ponds that can sequester large amounts of C because decomposition is significantly reduced in waterlogged soils due to lack of oxygen resulting in SOC exceeding the average of well drained soils.

CONCLUDING REMARKS

The organic matter and its associated carbon are indispensable components of the soil with essential functions on terrestrial ecosystems. Storage of SOC results from interactions among the dynamic ecological processes of photosynthesis, decomposition, and soil respiration. Over the last 160 years, human activities have led to a depletion of SOC and the exacerbation of global warming. However, there are opportunities to revert SOC losses sequestering C back from the atmosphere to the soil, although land management strategies and the physical heterogeneity of landscapes impose various challenges.

RECOMMENDED READING

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