

Carbon Preservation and Sequestration in Agricultural Soils

Ivić, Lara

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Master's studies:

Agroecology- Microbial Biotechnology in Agriculture

**CARBON PRESERVATION AND SEQUESTRATION IN
AGRICULTURAL SOILS**

DIPLOMSKI RAD

Lara Ivić

Zagreb, November, 2022.

**SVEUČILIŠTE U ZAGREBU
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Agroekologija- Mikrobna biotehnologija u poljoprivredi

**OČUVANJE I SEKVESTRACIJA UGLJIKA U
POLJOPRIVREDNIM TLIMA**

DIPLOMSKI RAD

Lara Ivić

Mentor:

Prof.dr.sc. Ivica Kisić

Zagreb, studeni, 2022.

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Carbon Preservation and Sequestration in Agricultural Soils

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Table of contents

1. Introduction	1
1.1. The aim of the paper	2
2. Literature review	3
2.1. History of Climate Change	3
2.2. The Keeling Curve and Changes in Carbon Concentration	5
2.3. The Global Carbon Cycle	9
2.4. Soil Organic Matter (SOM) and Soil Organic Carbon (SOC)	11
2.5. Land Usage and Disruption of Soil Quality	14
2.6. Variations in Topsoil Organic Carbon across Europe	16
2.7. Soil Carbon Sequestration	17
2.8. Mechanisms of Carbon Sequestration through Carbon Stabilization	20
2.8.1. Soil Aggregation and C Storage	21
2.8.2. Physical Protection	22
2.8.3. Chemical Stabilization	23
2.8.4. Biochemical Stabilization	23
2.9. Agroforestry for Biomass Production and Carbon Sequestration	24
2.10. Agricultural Systems that could sequester carbon	28
2.10.1. Conventional No-Till and Conservation Tillage	28
2.10.2. Organic No-Till	29
2.10.3. Cover Crops and Crops Rotations	30
2.10.4. Rotational Grazing	31
2.10.5. Perennial Cropping Systems	32
3. Conclusion	33
4. Bibliography	34
Biography	43

Sažetak

Diplomskog rada studenta/ice **Lara Ivić**, naslova

Očuvanje i sekvestracija ugljika u poljoprivrednim tlima

Sekvestracija ugljika je proces koji se odnosi na prenošenje atmosferskog ugljičnog dioksida u tlo, smanjujući njegovu koncentraciju u atmosferi. Poljoprivredne metode koje povećavaju količine organskog ugljika u tlu mogu pomoći u ublažavanju klimatskih promjena. Pretvaranje prirodnih šuma u oranice, monokulturna poljoprivreda i obrada tla uzrokuju poremećaj kvalitete tla i smanjuju njegovu sposobnost skladištenja ugljika. Sekvestracija ugljika ovisi o vremenu razgradnje organske tvari tla te fizikalnoj i kemijskoj zaštiti od mikroorganizama. Organski ugljik u tlu stabilizira se mehanizmima fizičke zaštite, kemijske i biokemijske stabilizacije. Agrošumarstvo nudi veliki potencijal za sekvestraciju ugljika jer drveće omogućuje njegovu stabilizaciju u dubljim slojevima tla. Konzervacijske poljoprivredne prakse koje obnavljaju organski ugljik u tlu uključuju smanjenu obradu tla, no-till (gospodarenje bez obrade), pokrovne usjeve, plodorede, rotacijsku ispašu i sustave višegodišnjih usjeva.

Ključne riječi: Sekvestracija ugljika, klimatske promjene, stabilizacija ugljika, agrošumarstvo

Summary

Of the master's thesis – student **Lara Ivić**, entitled

Carbon Preservation and Sequestration in Agricultural Soils

Carbon sequestration is a process of capturing atmospheric carbon dioxide in the soil, reducing its concentration in the atmosphere. Therefore, agricultural methods for improving soil organic carbon can help mitigate climate change. Converting natural forests into croplands, monoculture farming, and tillage are causing the disruption of soil quality and reducing its ability to store carbon. Carbon sequestration depends on the turnover time of soil organic matter and physical and chemical protection against microorganisms. Organic carbon in soils is stabilized through the mechanisms of physical protection, chemical, and biochemical stabilization. Agroforestry offers great potential for carbon sequestration, as trees enable carbon stabilization in deeper layers of the soil. Conservational agricultural practices which can rebuild soil organic carbon include reduced tillage, no-till, cover crops, crop rotations, rotational grazing and perennial cropping systems.

Keywords: Carbon sequestration, climate change, carbon stabilization, agroforestry

1. Introduction

Soil is a key compartment for climate regulation as a source of greenhouse gases (GHGs) emissions and as a sink of carbon. Soil is involved in the biogeochemical cycles of carbon (C) and nitrogen (N), and thus is a key compartment for climate regulation either by emitting greenhouse or by sequestering carbon (Bispo et al., 2017).

Human activities, particularly the use of fossil fuels like coal, oil, and gas, have resulted in a significant increase in the concentration of carbon dioxide (CO₂) in the atmosphere. This increase in atmospheric CO₂ over the last 250 years, from about 280 to more than 380 parts per million (ppm), is causing measurable global warming. Sea-level rise; increased frequency and intensity of wildfires, floods, droughts, and tropical storms; changes in the amount, timing, and distribution of rain, snow, and runoff; and disturbance of coastal marine and other ecosystems are all potential negative consequences. Rising atmospheric CO₂ levels increase CO₂ absorption by seawater, causing the ocean to become more acidic, and potentially disrupting marine plankton and coral reefs. Technically and economically feasible strategies are needed to mitigate the consequences of increased atmospheric CO₂ (Sundquist et al., 2000). Agriculture is one of the largest anthropogenic sources of GHG emissions yet few authorities take account of this fact in their proposals and programs for low C development (Norse, 2012).

Land management has a significant impact on soil organic carbon (SOC) stocks with a number of measures clearly leading to carbon emissions. Depletion of soil C has been documented to result in decreased productivity, poor soil physical and chemical properties, and negative secondary environmental impacts (Jose and Bardhan, 2012). Carbon sequestration is a process of capturing and storing atmospheric carbon dioxide in the soil. It is a method of reducing the amount of carbon dioxide in the atmosphere (USGS, n.d.). Microbes play a major role in this process and thus affect the climate. They transform the state of carbon, by sequestering carbon from and releasing carbon into the atmosphere, oceans, and biosphere (ASM, 2020). Carbon capturing in the soils presents an important strategy for mitigating the risks of global warming.

Preventing the Earth's atmosphere from warming any further is taking a huge collective effort by humanity. Consequently, the interest in the mentioned process is increasing globally. It is crucial to examine the ways of carbon sequestration and try to incorporate them into the soil management practice. This research paper elaborates on carbon sequestration and analyzes problems that connect agronomy and global warming.

1.1. The aim of the paper

The aim of this paper is to study the literature related to changes in the amount of carbon in agricultural soils and the atmosphere due to anthropogenic influence and suggest agricultural practices of its sequestration. As the concentrations of atmospheric carbon are rising, causing climate change, studying the ways of carbon capture in agricultural soils is crucial.

2. Literature review

2.1. History of Climate Change

The link between CO₂ and the Earth's temperature had been made already in 18th century. It was the French scientist Joseph Fourier (1768-1830) who first realised that certain atmospheric gases shrouded the planet like a bell jar, transparent to sunlight, but absorbing to infrared rays. It means the atmosphere is heated from above and below: first, by sunlight as it shines through and second by the infrared the Earth emits as it cools overnight (Sample, 2005).

The father of climate change, Svante Arrhenius (1859-1927), recognized over 100 years ago that atmospheric CO₂ plays a critical role in regulating Earth's temperature. Arrhenius challenged himself to calculate how much water and CO₂ in the atmosphere warmed the planet. From others' work, he knew that CO₂ was only part of the process. While CO₂ and other gases trapped infrared radiation and so heated the atmosphere, warmer air holds more water vapor, itself the most potent contributor to the greenhouse effect. So, if atmospheric CO₂ levels increased, water vapor would ensure the warming effect was seriously magnified. What followed was a year doing what Arrhenius described as "tedious calculations". His starting point was a set of readings taken by US astronomer Samuel Langley, who had tried to work out how much heat the Earth received from the full moon. Arrhenius combined the data with global temperature figures to calculate how much of the incoming radiation was absorbed by CO₂ and water vapor and thus heated the atmosphere. (Sample, 2005).

After the calculations, Arrhenius had some useful results that he published in 1896 (*On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground*). According to Arrhenius (1896), if CO₂ levels were halved the Earth's surface temperature would fall by 4-5 °C. He also concluded that human activity, in the form of the widespread burning of coal, was increasing atmospheric CO₂ above the natural levels. He thought it would take millennia to see a 50% rise in CO₂. Modern measurements show a 30% rise during the 20th century alone (Sample, 2005).

The existence of an increasing greenhouse effect was hotly debated until postwar funding became available in the 1950s and researchers began to collect firm data. In 1956, physicist Gilbert Plass confirmed that adding CO₂ to the atmosphere increased the amount of infrared radiation absorbed, and that industrialization would raise the Earth's temperature by slightly more than 1 degree Celsius per century. Plass and other scientists in the United States began warning government officials by the end of the 1950s that greenhouse warming could become a serious problem in the future (Sample, 2005).

Attempts to measure atmospheric CO₂ concentrations revealed wide and difficult-to-interpret variations. Researchers needed precise, accurate, and continuous measurements of atmospheric CO₂ concentrations by the 1960s. In the 1960s, researchers at the Scripps Institution of Oceanography in San Diego took on the testing challenge of taking a large number of atmospheric CO₂ measurements. The goal was to establish a baseline against which future readings would be compared in a decade or so (Sample, 2005).

Charles Keeling (1928-2005) began studying atmospheric carbon dioxide in 1956 by taking air samples and measuring the amount of CO₂ they contained. Over time he noticed a pattern. The air samples taken at night contained a higher concentration of CO₂ compared to samples taken during the day. He drew on his understanding of photosynthesis and plant respiration to explain this observation: plants take in CO₂ during the day to photosynthesize—or make food for themselves—but at night, they release CO₂. Keeling discovered a larger seasonal pattern while studying his measurements over a few years. He discovered that CO₂ levels are highest in the spring when decomposing plant matter emits CO₂, and lowest in the autumn, when plants stop taking in CO₂ for photosynthesis. (National Geographic Society, 2022).

Keeling was able to establish a permanent residence at the Mauna Loa Observatory in Hawaii to continue his research. At Mauna Loa, he discovered global atmospheric CO₂ levels were rising nearly every year. By analyzing the CO₂ in his samples, Keeling was able to attribute this rise to the use of fossil fuels. Since its creation, the Keeling Curve (shown in Figure 2.2.1 has served as a visual representation of Keeling's data, which scientists have continued to collect since his death in 2005 (National Geographic Society, 2022).

2.2. The Keeling Curve and Changes in Carbon Concentration

The carbon dioxide data on Mauna Loa constitute the longest record of direct measurements of CO₂ in the atmosphere. They were started by C. David Keeling of the Scripps Institution of Oceanography in March of 1958 at a facility of the National Oceanic and Atmospheric Administration (Keeling, 1976). NOAA (National Oceanic and Atmospheric Administration) started its own CO₂ measurements in May of 1974, and they have run in parallel with those made by Scripps since then (Thoning et al., 1989).

Soon after Scripps Institution of Oceanography geochemist Charles David Keeling launched his atmospheric CO₂ measurement series at Mauna Loa Observatory in 1958, researchers began to measure CO₂ levels at many sites around the world. As they added field stations to their CO₂ measurements, they found that at different latitudes, the seasonal cycles of CO₂ follow predictable patterns. At all sites, there is an accelerating upward trend in CO₂ levels driven mostly by fossil fuel burning. The main difference between the sites is the amount of seasonal fluctuation in CO₂ levels observed each year. In general, researchers found strong seasonal CO₂ fluctuations throughout the Northern Hemisphere and weaker fluctuations near the equator and in the Southern Hemisphere (Monroe, 2013).

For example, The station at Barrow, Alaska (71° N latitude), experiences enormous swings in seasonal CO₂. In fact, at this site, the daily 400 part-per-million (ppm) benchmark was passed for brief periods starting in 2006. At the other end of the spectrum, there is almost no seasonal variation at the South Pole (90° S latitude) and other sites in the Southern Hemisphere. Plants' photosynthetic activity causes these latitudinal differences in fluctuation. Plants consume CO₂ from the atmosphere as they begin to photosynthesize in the spring and summer, eventually using it as a carbon source for growth and reproduction. This results in the annual decrease in CO₂ levels, which begins in May. When winter arrives, plants conserve energy by reducing photosynthesis. Without photosynthesis, the dominant process is the total ecosystem's CO₂ exhalation, which includes bacteria, plants, and animals. (Monroe, 2013).

The Keeling Curve, presented in Figure 2.2.1, represents the concentration of carbon dioxide (CO₂) in Earth's atmosphere since 1958 (National Geographic Society, 2022). It is one of the most recognized successful examples of a long-term study, giving it academic value. But beyond this, it is the connection between modern CO₂ concentrations and those of the past (Mulhern, 2021).

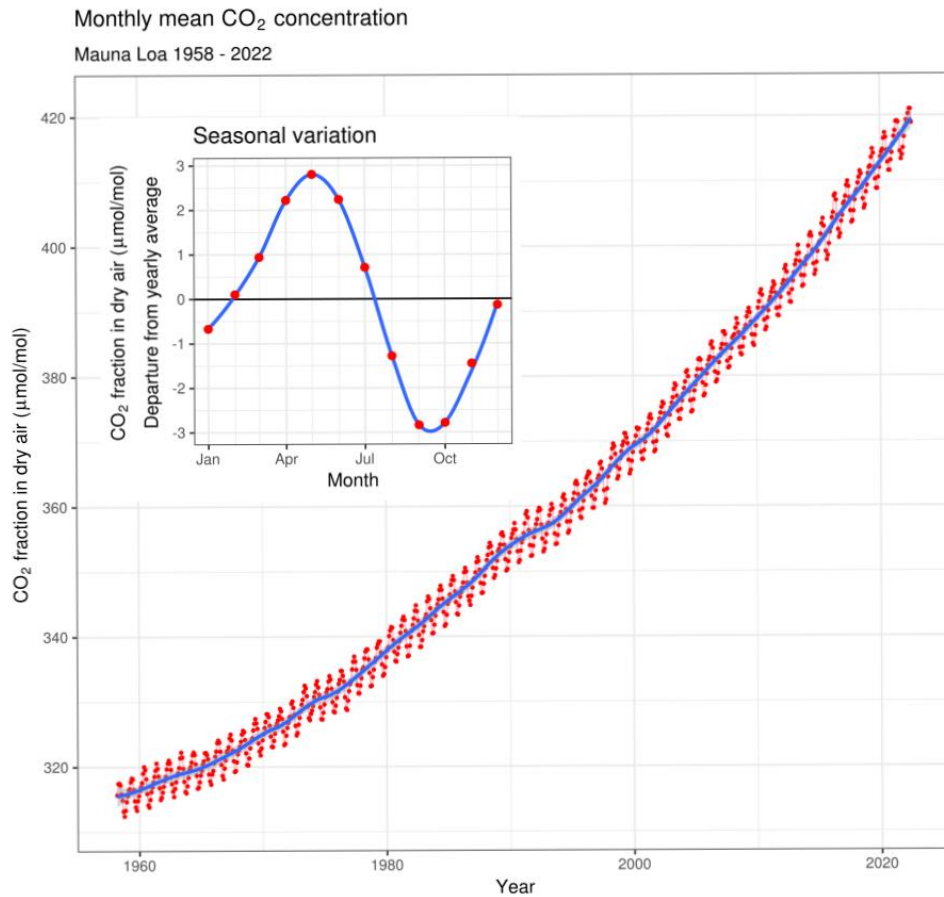


Figure 2.2.1. The Keeling Curve.

Source: Dr. Pieter Tans, NOAA/ESRL - <https://gml.noaa.gov/ccgg/trends> and Dr. Ralph Keeling, Scripps Institution of Oceanography - <https://scrippsco2.ucsd.edu/> - accessed 20.08.2022

Since many more forests are concentrated in the Northern Hemisphere, more carbon dioxide is removed from the atmosphere during Northern Hemisphere summer than during Southern Hemisphere summer. This annual cycle is shown in the inset Figure 2.2.1 by taking the average concentration for each month across all measured years (NOAA, 2022).

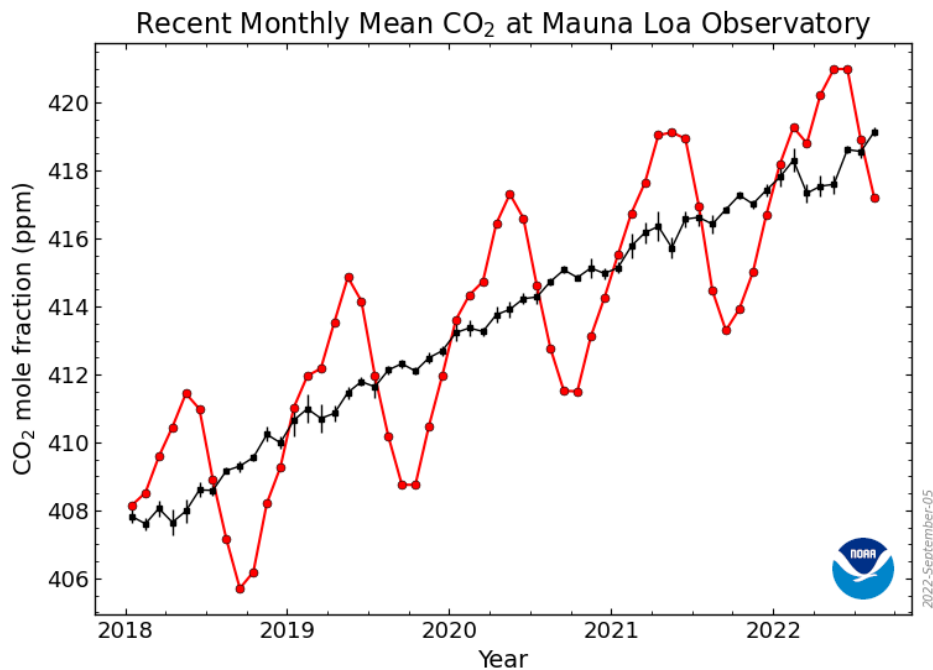


Figure 2.2.2. The last five complete years plus the current year of the Mauna Loa CO₂
Source: NOAA, Global Monitoring Laboratory- <https://gml.noaa.gov/ccgg/trends/> -accessed
05.09.2022

The last five complete years of the Mauna Loa CO₂ record plus the current year are shown in the Figure 2.2.2. The red lines and symbols represent the monthly mean values, centered on the middle of each month. The black lines and symbols represent the same, after correction for the average seasonal cycle. The latter is determined as a moving average of seven adjacent seasonal cycles centered on the month to be corrected (NOAA, 2022).

The vertical bars on the black lines of the graph in the figure show the uncertainty of each monthly mean based on the observed variability of CO₂ in different weather systems as they go past the top of Mauna Loa. This is manifest in the deviations of daily means from a smooth curve that follows the seasonal cycle (Thoning, 1989).

Data are reported as a dry air mole fraction defined as the number of molecules of carbon dioxide divided by the number of all molecules in air, including CO₂ itself, after water vapor has been removed. The mole fraction is expressed as parts per million (ppm) (NOAA, 2022).

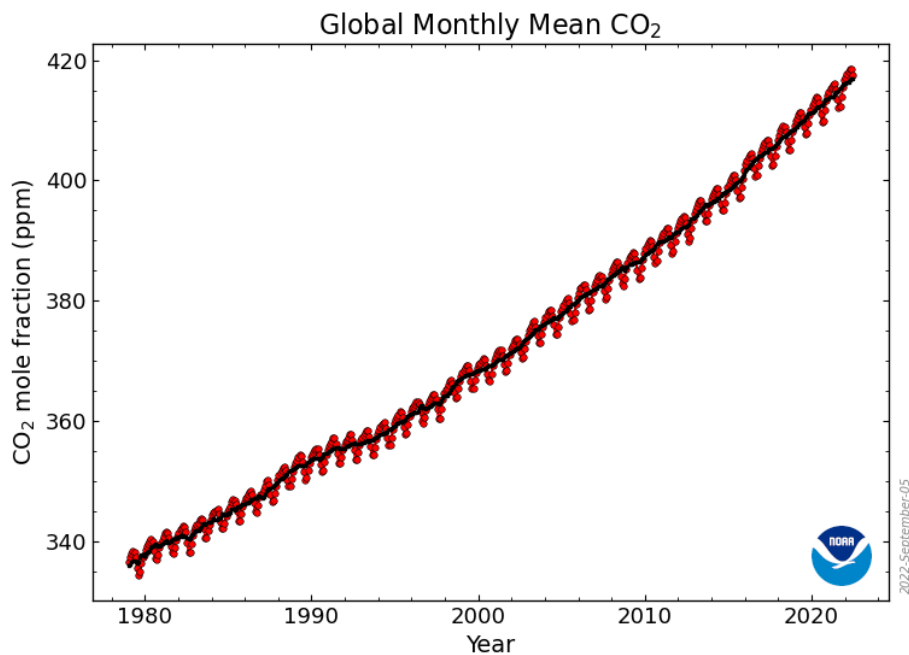


Figure 2.2.3. The monthly mean carbon dioxide globally averaged over marine surface sites.
Source: NOAA, Global Monitoring Laboratory <https://gml.noaa.gov/ccgg/trends/global.html> - accessed 05.09.2022.

Figure 2.2.3. displays monthly mean carbon dioxide globally averaged over marine surface sites from the year 1980. The Global Monitoring Division of NOAA/Earth System Research Laboratory has measured carbon dioxide and other greenhouse gases for several decades at a globally distributed network of air sampling sites (Conway, 1994).

A global average is constructed by first fitting a smoothed curve as a function of time to each site, and then the smoothed value for each site is plotted as a function of latitude for 48 equal time steps per year. A global average is calculated from the latitude plot at each time step (Masarie and Tans 1995). Based on analysis from NOAA's Global Monitoring Lab (2022), the last global monthly mean CO₂ measured in June 2022 was 417.42 ppm. In comparison to June 2021, when the measurements were 415.20 ppm.

The annual rate of increase in atmospheric carbon dioxide over the past 60 years is about 100 times faster than previous natural increases, such as those that occurred at the end of the last ice age 11,000-17,000 years ago. Carbon cycle experts estimate that natural “sinks”—processes that remove carbon from the atmosphere—on land and in the ocean absorbed the equivalent of about half of the carbon dioxide we emitted each year in the 2011-2020 decade. Because we put more carbon dioxide into the atmosphere than natural processes can remove, the amount of carbon dioxide in the atmosphere increases every year (Lindsey, 2022).

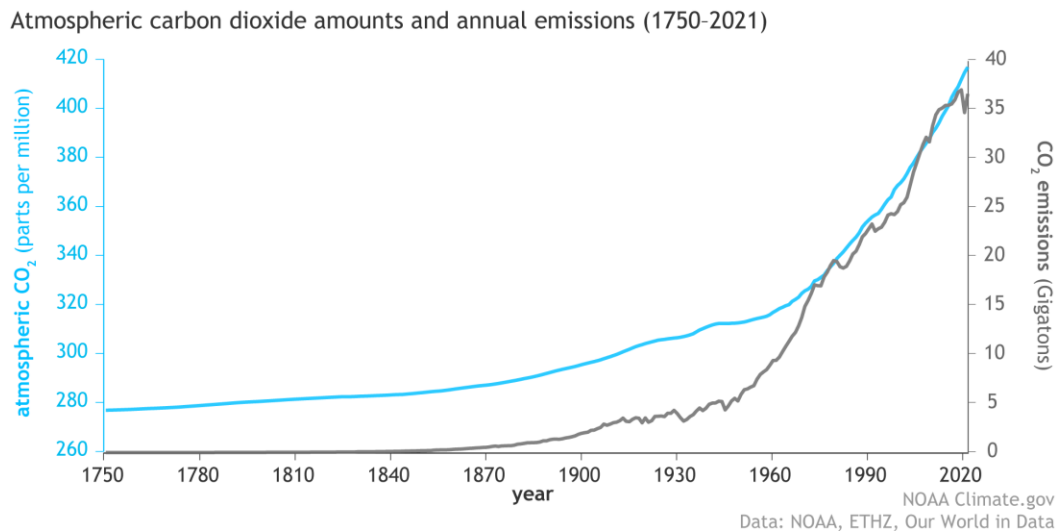


Figure 2.2.4. Atmospheric carbon dioxide amounts and annual emissions (1750- 2021). Gray line represents human emissions and blue line the amount of carbon dioxide in the atmosphere.

Source : NOAA, Global Monitoring Laboratory - <https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide> - accessed 20.10.2022.

Analyzing the graph from Figure 2.2.4., it can be concluded that the amount of carbon dioxide in the atmosphere has increased along with human emissions. The change started with the Industrial revolution. Emissions rose slowly to about 5 billion tons per year in the mid-20th century before skyrocketing to more than 35 billion tons per year by the end of the century (Lindsey, 2022).

2.3. The Global Carbon Cycle

Living things are made of elements, the most important of which are: carbon, oxygen, hydrogen, nitrogen, calcium and phosphorous. Carbon joins with other elements to form compounds necessary for life, e.g. sugars, starches, proteins, and fats. All these forms of a carbon account for approximately half of the total dry mass of all living things. Carbon is present in the Earth's atmosphere, soils, oceans, and crust (The Univeristy of Hampshire, 2008).

When viewing the Earth as a system, these components can be referred to as carbon pools (sometimes also called stocks or reservoirs) because they act as storage houses for large amounts of carbon. The main reservoirs of carbon are the ocean (the largest one), geologic reserves of fossil fuels, the terrestrial surface (mainly plants and soil) and the atmosphere (The Pennsylvania State University, 2020). Any movement of carbon between these reservoirs is called a flux. In any integrated system, fluxes connect reservoirs together to create cycles and feedbacks (The University of New Hampshire, 2008). An example of the cycle is shown in Figure 2.3.1

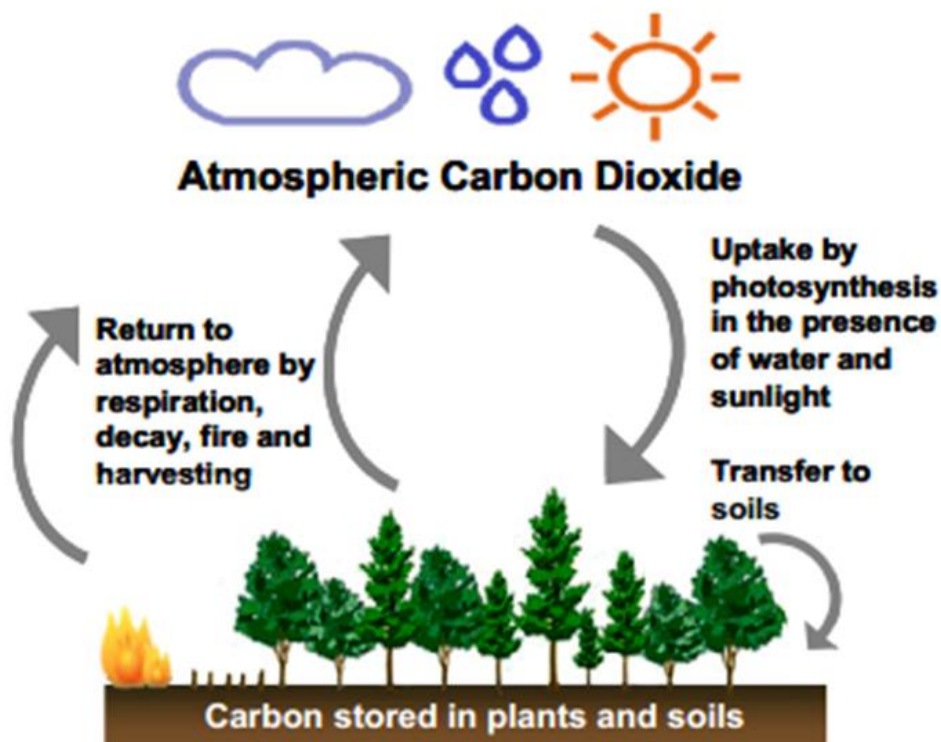


Figure 2.3.1. Sub-cycle within the global carbon cycle. Carbon continuously moves between the atmosphere, plants and soils through photosynthesis, plant and microbe respiration, harvesting, fire, and decomposition.

Source: University of New Hampshire - <http://globecarboncycle.unh.edu/CarbonCycleBackground.pdf> - accessed 25.06.2022

Photosynthesis uses carbon in the atmosphere to create new plant material. This process transfers large amounts of carbon from one pool (the atmosphere) to another on a global scale (plants). These plants die and decay over time, are harvested by humans, or are burned for energy or in wildfires. All of these processes are fluxes that can move carbon between ecosystem pools and eventually release it back into the atmosphere. Individual cycles like this are linked to others involving oceans, rocks, etc. on a variety of spatial and temporal scales to form an integrated global carbon cycle. Plants remove carbon from the atmosphere via photosynthesis and return it via respiration on the shortest time scales, seconds to minutes. Carbon from dead plant material can be incorporated into soils over longer time scales, where it may remain for years, decades, or centuries before being broken down by soil microbes and released back into the atmosphere. On a larger time scale, organic matter buried in deep sediments (and thus protected from decay) gradually transforms into deposits of coal, oil, and natural gas, the fossil fuels we use today. When these substances are burned under anthropogenic use, carbon that has been stored in the atmosphere for millions of years is released in the form of carbon dioxide (The University of New Hampshire, 2008).

The carbon cycle has a large effect on the function and well-being of our planet. Globally, the carbon cycle plays a key role in regulating the Earth's climate by controlling the concentration of carbon dioxide in the atmosphere. Carbon dioxide (CO₂) contributes to the greenhouse effect, in which heat generated from sunlight at the Earth's surface is trapped by certain gasses and prevented from escaping through the atmosphere (Green et al., 2004).

The greenhouse effect itself is a perfectly natural phenomenon and, without it, the Earth would be a much colder place. But as is often the case, too much of a good thing can have negative consequences, and an unnatural buildup of greenhouse gasses can lead to a planet that gets unnaturally hot. In order to understand how carbon is cycled and how atmospheric CO₂ will change in the future, scientists must carefully study the places in which carbon is stored (pools), how long it resides there, and the processes that transfer it from one pool to another (fluxes) (The University of New Hampshire, 2008).

Pools of C in rocks are inert and change over the millions of years of time while pools of C in the terrestrial biosphere, atmosphere, and oceans constitute active pools that are vulnerable to anthropogenic activities. The exchange of C among these pools over a short and long period of time is known as the Global Carbon Cycle (GCC) (Chatterje et al., 2020).

The soil C pool, comprising about 2,500 Gt, is one of the largest C pools and is larger than the atmospheric pool (760 Gt) (Lal, 2004). The extent of soil C is dependent on a delicate balance between litter and rhizodeposition and the release of C due to decomposition and mineralization. Several other factors such as quality of C input, climate, and soil physical and chemical properties further determine the rate of decomposition and thus stabilization of soil organic C in a particular ecosystem. Since modernization of agriculture in the 19th century, soil carbon pool has gradually depleted because of several factors such as deforestation, intensive cropping and biomass removal, soil erosion, and unsustainable agricultural practice (Jose and Bardhan, 2012).

2.4. Soil Organic Matter (SOM) and Soil Organic Carbon (SOC)

Soil plays a crucial role in food security, climate change mitigation, and other essential ecosystem services. Hence, efficient management and adapted policies are required for the maintenance and improvement of soil quality (Stoate et al., 2009). Among others, Karlen et al. (1997) defined soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". In order to measure the preservation and improvement of soil quality, quantifiable meaningful

parameters for soil quality assessment have to be monitored by suitable and efficient Soil Monitoring Networks (SMN) (Arrouays et al., 2008).

Soil organic matter (SOM) has been recognized as one of the most important attributes in terms of “soil quality”. Soil organic matter represents all organic components in the soil including decayed plant and animal tissues, their partially decomposed products, and the soil biomass (Baldock et al., 2000).

Soil organic matter plays several roles in agro-ecosystems such as: the regulation of CO₂ fluxes between the soil and the atmosphere, mineral reserve and soil fertility, soil structure and hydrological behavior, soil stability and its resistance against erosion and compaction, and biodiversity of soils (Trigalet et al., 2017). It has beneficial effects on soil biological, physical and chemical properties, which influence the productive capacity of agricultural soils. Yet, the loss of SOM resulting from conversion of native vegetation to farmland has been confirmed and is one of the best-documented ecosystem consequences of our agricultural activities (Paul et al., 1997).

Soil organic matter (SOM) is a key soil component that performs a variety of functions and defines the physical and chemical properties of soil. The retention of nutrient elements such as potassium, the pH buffer function, and the supply of air and water because of particle aggregation has long been recognized as the role of SOM (Stevenson, 1994). Moreover, SOM plays an important role in influencing soil structure, microbial activity, and carbon (C) storage (Bronick and Lal, 2005).

Soil organic carbon (SOC) includes plant, animal and microbial residues in all stages of decomposition. Many organic compounds in the soil are intimately associated with inorganic soil particles. The turnover rate of the different soil organic carbon compounds varies due to the complex interactions between biological, chemical, and physical processes in soil (Post and Kwon, 2000). Soil organic carbon (SOC), the principal component of SOM (*ca.* 58%, depending on edaphic conditions), is often used as one of the major indicators of soil quality (Pribyl, 2010). SOC is the largest terrestrial reservoir in the biosphere, accounting for 1500–1770 Pg, as compared to C stocks of vegetation (450–650 Pg) (IPCC, 2013).

Soil carbon stocks consist of soil organic carbon (SOC) and soil inorganic carbon (SIC). Soils contain carbon in both organic and inorganic forms, i.e., oxidized carbon and non-oxidized carbon. The sum of the two forms of carbon is named total carbon (Chatterje et al., 2020).

Although there may be a continuum of degradation and turnover time for soil organic carbon compounds, physical fractionation techniques are frequently used to define and delineate different relatively discrete soil organic carbon pools. While containing a variety of organic compounds, physically defined fractions integrate the functional and structural properties of soil organic carbon (Christensen, 2001).

Soil organic matter is composed of four major pools – plant residues, particulate organic carbon, humus carbon and recalcitrant organic carbon. These pools differ in their chemical composition, stage of decomposition, and role in soil function and health (Figure 1). Management can alter not only total organic carbon stocks, but also the proportion of carbon present in these different pools. Knowing how carbon pools change in response to management can provide valuable information on probable soil functioning and health (Soil Quality, 2022).

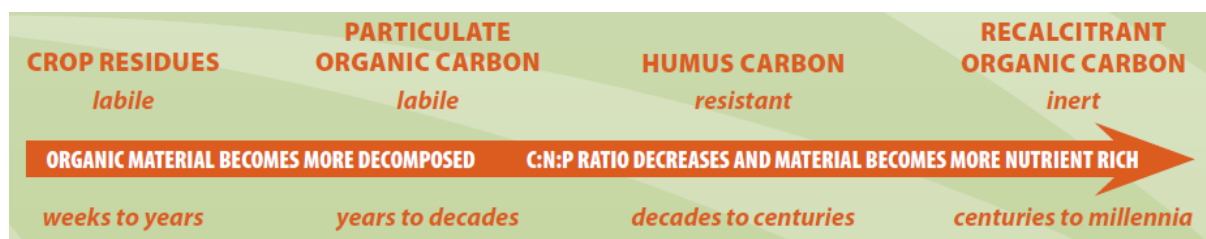


Figure 2.4.1 Organic carbon is made up of four different pools that decompose at different rates (adapted from Bell and Lawrence, 2009).

Each of the different carbon pools decomposes, or turns over, at a different rate and is involved in different soil processes as shown in Figure 2.4.1.

Plant residues are shoot and root residues found on the soil surface and in the soil. They are broken down relatively quickly (weeks to years) and provide an important source of energy for soil microorganisms (Soil Quality, 2022).

Particulate organic carbon is defined as pieces of plant debris 0.053–2 mm in size. Particulate organic carbon also decomposes relatively quickly (years to decades) and provides an important source of energy for soil microorganisms. It also plays an important role in maintaining soil structure and providing soil nutrients. Plant residues and particulate organic carbon are often referred to as ‘labile carbon’ because they cycle in the soil relatively quickly (Soil Quality, 2022).

Humus is composed of decomposed material with a particle size of less than 0.053 mm and is typically found attached to soil minerals. Because this type of carbon is more resistant to decomposition by soil microorganisms, it turns over more slowly (over decades to centuries). It is essential for all key soil functions, but it is especially important for nutrient provision. (Soil Quality, 2022). Although humus C represents 60% to 80% of SOC, its dynamics still remain poorly understood after nearly a century of study, due to the multiplicity of factors that affect stabilization of humic matter. Industrial agricultural practices hasten the decline of soil humus content and, as a result, the reduction of soil fertility, biodiversity, and structural stability (Fontaine et al., 2007), while also increasing greenhouse gas (GHG) emissions from soil (Smith et al., 2014).

Recalcitrant organic carbon is organic material resistant to decomposition. Organic carbon that is recalcitrant can take hundreds to thousands of years to decompose and is largely inaccessible to microorganisms. Recalcitrant organic carbon is abundant in highly weathered soils and soils with a history of burning (Soil Quality, 2022).

To understand how SOC is lost or stabilized in soil (explained later in Chapter 2.8), SOC stocks in the soil can be classified into different functional pools depending on their varying residence time viz. labile and non-labile pools. Because it is easily affected by changes in environmental conditions, the labile pool (active pool) is the most sensitive pool available in a relatively small proportion. With any changes in land use practices, they decompose quickly and easily (Haynes, 2005).

The non-labile pool (passive pool) is a more stable and recalcitrant fraction of SOC that forms organic-mineral complexes with soil minerals and decomposes slowly due to microbial activity (Weisenberg et al., 2010). Therefore, labile SOC pools serve as a better indicator of soil quality to assess variations caused by land use changes, while the non-labile SOC pools adds to the total organic carbon stocks (Chan et al., 2001).

Organic matter is a food and energy source for soil microorganisms (nematodes, bacteria, fungi, etc.). Complex carbon-based molecules in crop residues and manure, such as cellulose, lignin, fat, and protein, are broken down into smaller components by these microbes. As a result, plants gain access to nutrients, and carbon dioxide is released as a byproduct. Aerobic bacteria are responsible for the fastest organic matter decomposition (Youngquist, 2022).

The large potential of the soil organic carbon (SOC) pool to sequester CO₂ from the atmosphere could greatly ameliorate the effect of future climate change. However, the quantity of carbon stored in terrestrial soils largely depends upon the magnitude of SOC mineralization. SOC mineralization constitutes an important part of the carbon cycle, and is driven by many biophysical variables, such as temperature and moisture (Zhang et al., 2018).

2.5. Land Usage and Disruption of Soil Quality

Land use can be define as “The set of anthropogenic activities and arrangements (e.g., cultivation, grazing, timber extraction) in a piece of land for economic and social welfare” (IPCC, 2000).

Land use/land cover change is one of the key factors which affect the soil organic carbon pool remarkably. The reason for this being the rate of input (e.g. plant litter) and rate of output (e.g. SOC mineralization) of soil organic matter (SOM) as a result of alterations in plant community and land management practice (Dawson and Smith, 2007). Tropical forests can act

either as a carbon sink or source which contributes significantly in the modification of atmospheric C concentration (Wei et al., 2013). The conversion of tropical forests into other land uses such as plantations and croplands through anthropogenic activities may act as a carbon source leading to alterations of soil properties and processes (Fan et al., 2016).

When natural forests are converted to croplands, the soil structure gets disrupted enhancing the mineralization of organic matter by microbes subsequently leading to SOC loss (Golchin and Asgari, 2008). The decrease in soil organic matter with increase in agricultural activities has been reported in numerous studies conducted worldwide (Golchin et al., 1995). Land use changes contribute 6–39% of increase in CO₂ emissions with profound impacts on SOC estimated at 1.5 Pg C yr⁻¹ (IPCC, 2007).

Tillage introduces oxygen into the soil, stimulating microbial activity. This burst of microbial activity leads to increased rates of organic matter metabolism in the soil and subsequent loss of soil carbon as carbon dioxide. Therefore, tillage is a primary factor in the loss of soil carbon and declining soil health (Youngquist, 2022).

Indiscriminate ploughing, residue removal, negative soil organic carbon (SOC) or nutrients budgets, and extractive farming can trigger the decline of SOM and therefore soil quality. Degradation of the soil structure leads to crust formation and compaction that increase runoff accelerating erosion. Loss of nutrients, SOC and water from ecosystems occurs and is followed by a decrease in agricultural efficiency, a loss of soil resilience, and the reduction of ecosystem services (Lal, 2015).

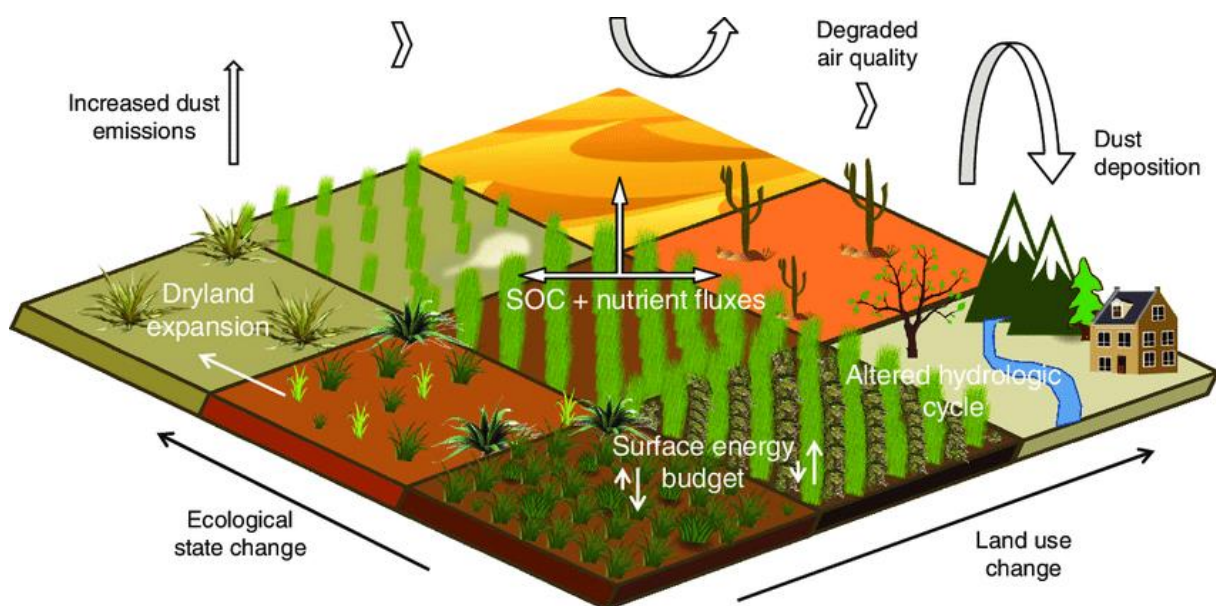


Figure 2.5.1. Illustration of interactions between anthropogenic land use and land cover change (LULCC) and dust cycle (adapted from Webb and Pierre, 2018).

Agriculture and livestock grazing are two examples of human land use activities that can cause soil surface disturbance as well as changes in vegetation species composition, structure, and spatial patterns. These changes in land cover can make landscapes more vulnerable to wind erosion. Wind erosion and dust emissions have a negative impact on human health, soil organic carbon (SOC) and nutrient cycles, the energy budget, the hydrologic cycle, and climate. Wind-driven soil loss and nutrient decline, as well as dust-climate feedback, affect agricultural production as well as the rates of ecological change and dryland expansion (Webb and Pierre, 2018).

2.6. Variations in Topsoil Organic Carbon across Europe

Around 45 % of the mineral soils in Europe have low or very low organic carbon content (0–2 %) and 45 % have a medium content (2–6 %) (Louwagie et al., 2009). Figure 2.6.1. shows that low levels are particularly evident in southern Europe where 74 % of the land is covered by soils that have less than 2 % of organic carbon in the topsoil (0–30 cm) (Zdruli et al., 2004). However, areas of low organic carbon can be found almost everywhere, including in some parts of more northern countries such as Belgium, France, Germany, Norway and the United Kingdom. More than 50 % of EU soil organic carbon stocks are to be found in peatlands (Schils et al., 2008)

In general, most soils across Europe are likely to be accumulating carbon. Except under drainage conditions, grassland soils accumulate carbon, although there is a high uncertainty as to the rate. Croplands generally act as a carbon source, although existing estimates are varied. Forest soils generally accumulate carbon (estimates range from 17 to 39 million tonnes per year) (EEA, 2021). Furthermore, the major SOC stores in the EU are peatlands. Thus, their preservation is an effective mechanism to preserve SOC stock (Jones et al., 2013). The levels of soil organic carbon are primarily determined by the balance between net primary production (NPP) from plants and the rate of decomposition of organic matter. Although climate change is expected to have a long-term effect on soil carbon, short-term changes are more likely to be driven by land management practices and land-use change, which can obscure the evidence of climate change's impact on soil carbon stocks. The effects of climate change on soil are complicated and lack rigorous data (EEA, 2022).

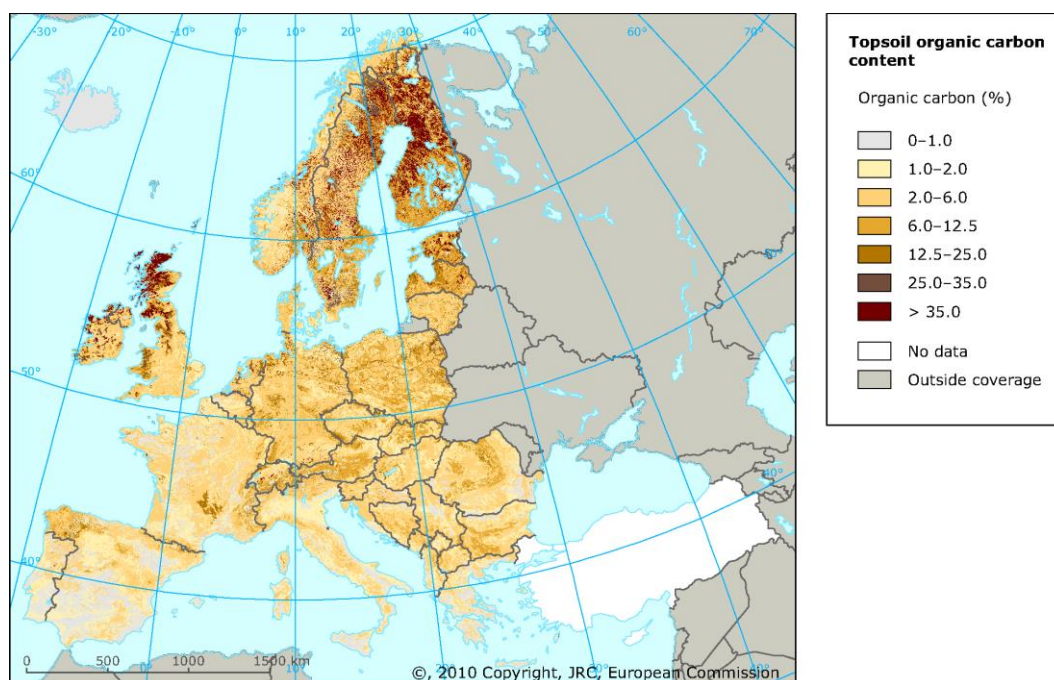


Figure 2.6.1. Variations in topsoil organic carbon content across Europe.

Source : European Soil Database

http://eusoils.jrc.ec.europa.eu/ESDB_Archive/octop/octop_data.html - accessed 20.08.2022

The map in the Figure 2.6.1 shows the percentage of organic carbon content in the surface horizon of soils in Europe. The darker regions correspond to soils with high values of organic carbon. The darkest colours, especially in Estonia, Fennoscandinavia, Ireland and the United Kingdom, denote peatlands (EEA, 2021).

Soil carbon stocks in the EU-27 are around 75 billion tonnes of carbon; around 50 % of which is located in Ireland, Finland, Sweden and the United Kingdom (because of the large area of peatlands in these countries). The largest emissions of CO₂ from soils are due to conversion (drainage) of organic soils, and amount to 20 to 40 tonnes of CO₂ per hectare per year. The most effective option to manage soil carbon in order to mitigate climate change is to preserve existing stocks in soils, and especially the large stocks in peat and other soils with a high content of organic carbon. Soils under grassland and forests are a carbon sink (estimated up to 80 million tonnes of carbon per year) whereas soils under arable land are a smaller carbon source (estimated from 10 to 40 million tonnes of carbon per year (EEA,2022)

2.7. Soil Carbon Sequestration

The Paris Agreement at the 21st Conference of Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) established a plan for reducing global warming below 2°C and limiting the temperature increase to 1.5°C by reducing GHG emissions to promote climate resilience through diverse pathways without compromising food

production. To achieve this long-term temperature goal, nations aim to reach global peaking of greenhouse gas emissions as soon as possible in order to achieve climate neutrality by mid-century (UN, 2015).

Under the current scenario, GHG emissions by anthropogenic activities could increase 55 Gt CO₂ equivalents in 2030 (Fawcett et al., 2015). To achieve the objective of COP21, anthropogenic emissions need to hit the highest point within the next 10 years and subsequently decline in trends towards net GHG (greenhouse gasses) removal by the end of the century. The “4 per 1000” initiative was launched as a part of the Lima-Paris Action Agenda promotes SOC sequestration to improve food security and mitigate climate change (Chatterje et al., 2020).

According to this initiative, anthropogenic GHG emissions should be counterbalanced by an annual increase of 0.4% in the top 40 cm of global soil carbon stocks. Moreover, agricultural activities and land-use change may enhance GHGs emissions like 25% of the CO₂, 50% of the CH₄, and 70% of the N₂O that perhaps compensate by SOC sequestration (Hutchinson et al., 2007). To achieve this goal, improved management practices should be adopted for C sequestration in agricultural, forest and wetland land as well as rehabilitation of degraded soils.

With the collaboration of scientists, educators, farmers, and policymakers, diverse institutions in more than 170 countries initiated a highly ambitious goal to implement suitable practices for increasing SOC stocks. In addition to that, 103 countries have set mitigation and adaptation targets related to agricultural practices, and about 129 countries developed goals related to forests and degraded land (Richards et al., 2016).

Chatterje et al. (2020) defined soil C sequestration as „a process of transfer of atmospheric CO₂ into SOM as C held in recalcitrant forms is less susceptible to losses by decomposition“. The above-mentioned research stated that SOC sequestration involves three basic steps:

1. Removal of CO₂ from the atmosphere via plant photosynthesis.
2. Transfer of carbon from CO₂ to plant biomass.
3. Transfer of carbon from plant biomass (crop residues) to the soil where it is stored in the form of SOC, i.e., labile pool with the highest turnover rate.

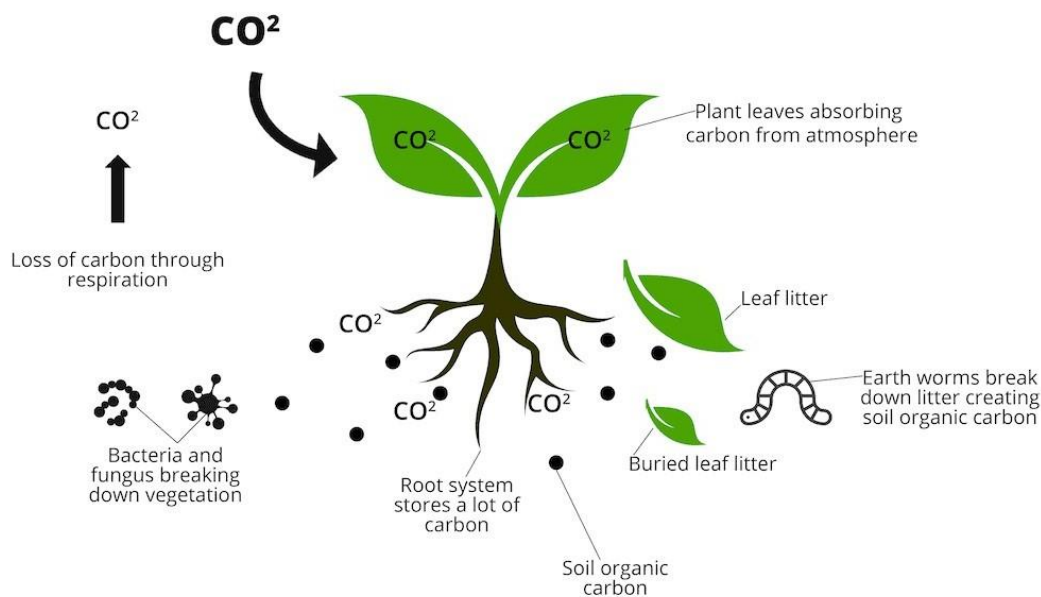


Figure 2.7.1. Infographic of photosynthesis.

The process of carbon sequestration is largely facilitated by plants through photosynthesis. During the process plants absorb CO_2 from the atmosphere and use it to make organic compounds which are vital for the plant growth. Once the plant dies, soil organisms such as bacteria, fungus and earth worms etc, breakdown the decomposing plant material transforming it into SOC.

Source : <https://www.greenelement.co.uk/blog/soil-carbon-sequestration/> - accessed 25.10.2022.

SOC sequestration should be done in such a way that captured atmospheric CO_2 can retain C in the slow SOC pool. But, it is a fact that the stable pool has little potential for carbon sequestration due to its resistance to change by management practices (Kane, 2015).

In the short term, it is important to manage the easily decomposable SOM by enhancing the cropping intensity that has a major impact on microorganisms, and humic complex production, which ultimately sequesters C. For the medium and long term, C sequestration can be achieved through the placing of recalcitrant C to the deeper layer which is resistant to rapid mineralization. The SOC sequestration is affected by many factors including C input, crop rotation, tillage management, climate condition, fertilization, and soil texture (Chatterje et al., 2020).

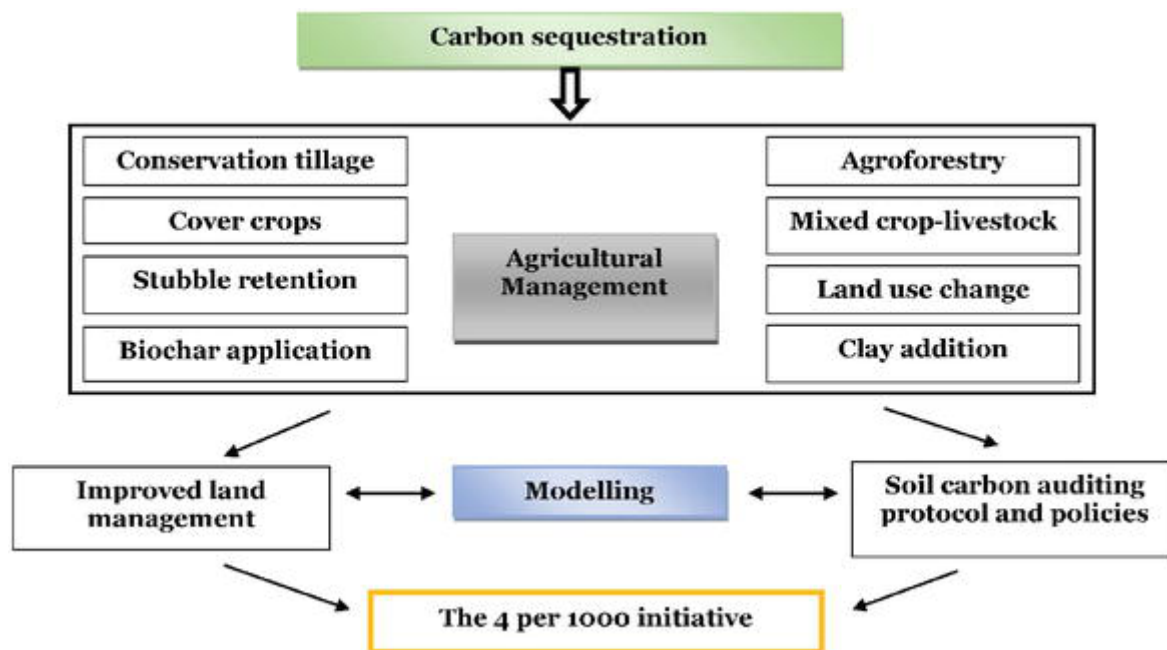


Figure 2.7.2. Impact of improved management practices on SOC dynamics (adapted from Singh et al, 2018).

According to Chatterje et al. (2020) carbon sequestration in soil can be done by following four major processes:

1. Decreasing the level of soil disturbance to enhance the physical protection of soil carbon in aggregates.
2. Increasing the agricultural inputs (e.g., organics) to soils.
3. Improving soil microbial diversity and abundance.
4. Maintaining continuous living plant cover on soils year-round.

Successful carbon sequestration is achieved when C storage through soil conservation practices exceeds their losses by converting atmospheric CO₂ into biomass through photosynthesis, and incorporation of biomass into the soil for humus enrichment (Smith et al., 2014). Carbon sequestration is possible through a number of processes which occur naturally in plants and soils. Soil contains circa three times more carbon than the amount stored in living plants (Lal, 2008).

2.8. Mechanisms of Carbon Sequestration through Carbon Stabilization

Carbon sequestration depends on turnover time and physical and chemical protection against microorganisms which is further influenced by the quality and physical location of SOC fractions in the soil system. The organic C in the soil is mainly stabilized through the following mechanisms: physical protection, chemical protection and biochemical protection (Chatterje et al., 2020). In order to understand the metioned principles, the knowledge about the soil aggregation is needed.

2.8.1. Soil Aggregation and C Storage

Soil is a heterogeneous, dynamic and biologically active porous medium (Totsche, 2017). Edwards and Bramner (1964), in their research of stability of the soils against ultrasonic excitation, concluded that soils are built of macroaggregates ($> 250 \mu\text{m}$) and microaggregates ($< 250 \mu\text{m}$), with macroaggregates being the consequence of weakly associated microaggregates. Soil aggregation involves the binding together of several soil particles into secondary units (Unger and McCalla, 1980).

Soil aggregates harbor a vast range of physico-chemical niches, which provide the space for the growth and the movement of soil microorganisms and communities. These respond to and act on the architecture of the soil, so allowing the development of a high level of biological diversity, which spreads and forms changing distribution patterns reflecting the interaction between microorganisms and the soil (Young and Crawford, 2004). Further, changes in aggregate architecture have major implications for many soil functions, *e.g.*, water storage and transport, biological activity and habitat, and the storage and biogeochemical cycling of carbon, nitrogen and other elements (Totsche, 2017).

Soil aggregation can help protect organic matter from biodegradation. Aggregates that are more stable can physically protect organic molecules, and hinder O_2 diffusion via micropores and consequent aerobic biodegradation (Bertini and Azevedo, 2022). Pores in soils consider micropores, which exhibit pore size up to 2nm, mesopores up to 2-50nm and macropores are greater than 50nm, respectively (Azman and Sulaiman, 2022).

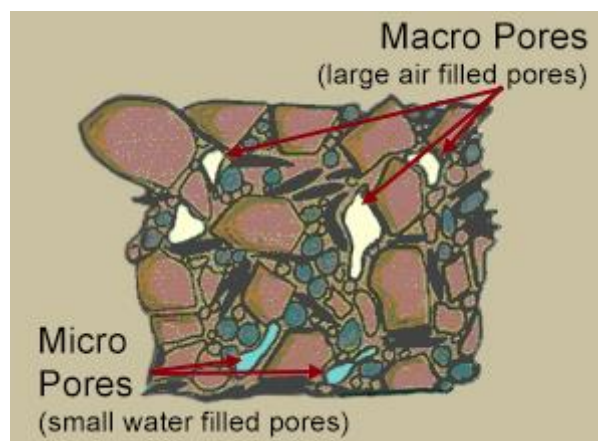


Figure 2.8.1.1. Micropores and macropores in the soil.

Source : https://www.dept.psu.edu/agsciences/agsci/elearning/0course-samples/turf_434_sample/Ln_1/L1_7.htm -accessed 15.10.2022.

In addition to organic matter, microbes also play an essential role in soil aggregation. As shown in Figure (2.8.1.2). This process is primarily driven by fungi and actinobacteria hyphae that

enmesh soil particles, and secondarily, by the gluey substances produced by fungi and bacteria. These substances may be humus and protein that are rich in surface charges capable of fixing colonies to the solid surfaces of soil particles. As a side effect, these substances work like cementing agents (Redmile-Gordon et al., 2020). The charges in the cell walls of hyphae and unicellular microbes can also join particles (Bertini and Azevedo, 2022).

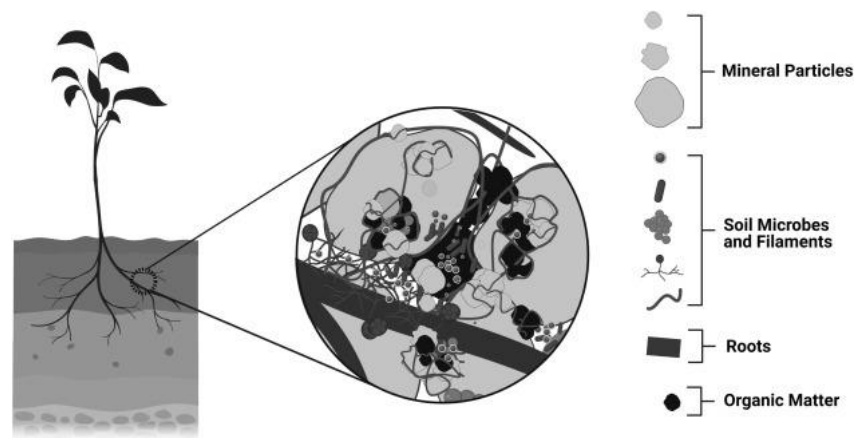


Figure 2.8.1.2. Organic and mineral particles within an aggregate.

Microbes play an essential role in soil aggregation, which helps protect organic matter from biodegradation. Fungi and actinobacteria hyphae enmesh soil particles, and secondarily, the gluey substances produced by microbes work like cementing agents. Besides, the cell walls of microbes can also join particles (adapted from Bertini and Azevedo, 2022).

Among fungi, mycorrhiza, a symbiotic association between a green plant roots and a fungus (Chen et al, 2021), contributes the most to total hyphae length in the soil. Therefore vegetated and unplowed soils also play an important role in maintaining soil aggregation by preserving mycorrhiza association, hyphae filaments, soil aggregates, and organic matter. Therefore, in the context of the carbon cycle, soil conservation benefits the soil microbes that contribute to the soil's capacity to store carbon (Bertini and Azevedo, 2022).

2.8.2. Physical Protection

Carbon sequestration in soils through physical protection is mainly done by mentioned aggregation, mentioned in the previous chapter . Aggregates are formed by clumps of soil particles adhered by clay, fine roots, and glue-like substances generated by microbes decomposing organic matter, such as glomalin produced by arbuscular mycorrhizal fungi (Wilson et al., 2009).

As these aggregates form, small particles of C, like partially decayed plant residues, are captured in the center of the aggregates which are physically protected from microbial attack

as they cannot penetrate the center of these stable aggregates where oxygen and water are low, thereby discouraging microbial metabolism (Six et al., 2000). Roots, fungal hyphae and less degraded organic materials stabilize macroaggregates. Their oxidation of C is dependent on management practices (Tisdall and Oades, 1982).

On the contrary, highly decomposed organic components stabilize more C in microaggregates, facilitated by its high surface area and polyvalent cation bridging (Balesdent et al., 2000). The turnover time of C is higher in microaggregates, circa 412 years than C in macroaggregates, circa 140 years (Jastrow et al., 1996). The reason behind this is that microaggregates have a higher level of physical protection of organic matter across the aggregate-size classes, depending upon the amount and type of clay in the soil (Hassink, 1997). The above mentioned stable aggregate can protect SOC for a very long but can be degraded by tillage exposing soil carbon to microbial attack (Grandy et al., 2006).

2.8.3. Chemical Stabilization

Aside from the physical protection of SOC through aggregate formation, C compounds are also chemically protected from decomposition. Chemical stabilization of SOM is controlled by the quantity and type of amorphous minerals, clay minerals, exchangeable cations, and the chemical composition of SOM. The surfaces of clay particles are strongly negatively charged. The soil microbial population generates several by-products with strong positive charges which create strong bonds with negatively charged clay particles, effectively protecting the molecules from microbial attack (Six et al., 2000).

The protection of soil organic matter is enhanced by silt and clay content due to the sorptive capacity provided by the larger surface area of minerals which additionally depends on clay mineralogy (Hassink, 1997).

Several studies show that 2:1 clay minerals generally have a better ability to stabilize SOM than 1:1 clays of which vermiculite and smectite are more efficient for the sorption of SOM due to higher specific surface areas compared to illite (Steffens, 2009). On the other hand, amorphous iron (Fe) and aluminum (Al) oxides present in acid soils have higher potential to stabilize SOM than clay minerals (Wiseman and Puttman, 2005). Carbon stabilization in saline soils is done through a higher concentration of exchangeable Ca which boosts the bridging of organic ions with clay minerals (Setia et al., 2013).

2.8.4. Biochemical Stabilization

„Biochemical stabilization of SOM is the function of structural bond strengths, the regular degree of occurrence of structural units and the degree of aromaticity which are related to the inherent chemical composition of residues“ (Chatterje, 2020). Because of their strong

aliphatic character non-hydrolyzable forms of C, such as lipids, waxes, insoluble polyesters, and microbial-synthesized macromolecules, are more amenable to biodegradation. Lignin, being an aromatic compound is more resistant to decomposition (Krull, 2003). Thus, aliphatic and aromatic C compounds present in soil constitute stable or passive pools.

2.9. Agroforestry for Biomass Production and Carbon Sequestration

C inputs from various sources like trees, shrubs, and vegetation in the form of litterfall, roots, and rhizodeposition contribute towards enhancing SOC stocks, primarily within woody components. As a result, SOC stocks can be increased by conducting agroforestry near agricultural fields (Lorenz and Lal, 2014).

Alternative agricultural practices where biomass crops are cultivated can impact CO₂ levels not only by sequestering C, but also by replacing fossil fuel with the biomass produced. Agroforestry, like many other land use systems, offers great potential for sequestering C and producing biomass for biofuels (Jose and Bardhan, 2012). According to Figure 2.9.1 agroforestry has the largest capacity for carbon sequestration among all other different sources.

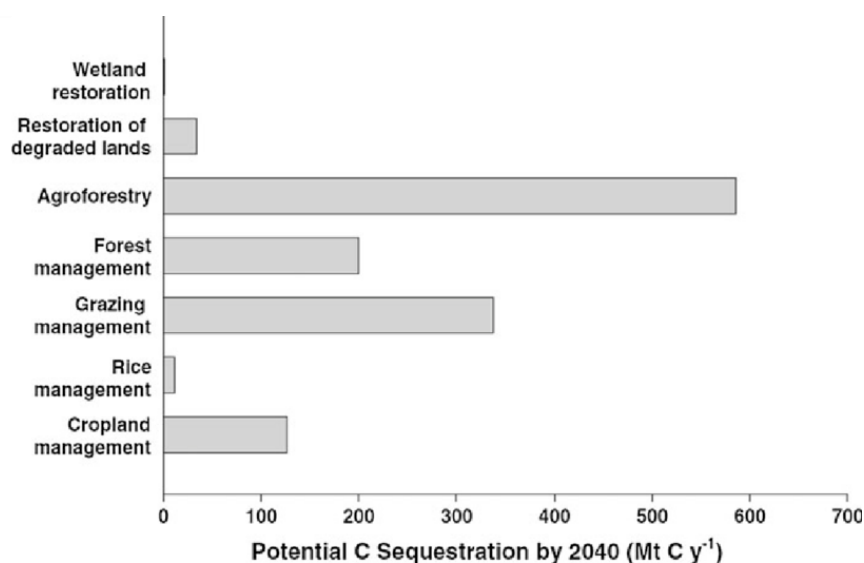


Figure 2.9.1. Carbon sequestration potential of different land use systems by 2040 (adapted from IPCC, 2000).

Agroforestry offers the greatest potential because of the large extent of area (630×10^6 ha) available worldwide for agroforestry adoption. It has been well documented that conversion of degraded agricultural soils into agroforestry systems can rebuild soil productivity (Jose and Bardhan, 2012). The available estimates of C stored in agroforestry range from 0.29 to 15.21 Mg C/ha/year above ground, and 30–300 Mg C/ha up to 1 m depth in the soil (Nair et al., 2010).

Agroforestry with two main segments of agroforestry systems: belowground and aboveground is effective in increasing carbon sequestration in agricultural lands where the aboveground component is described as stem and leaves of herbaceous plants and trees, and the belowground component consists of roots and microorganisms associated with roots (Watson et al., 2000). Although, carbon is more stabilized in the belowground segments due to interactions between soil particles with root biomass and a slow decomposition rate is observed over above-ground biomass (Rasse et al., 2005). While most studies report aboveground C sequestration, belowground C and soil C are often not reported from agroforestry systems (Jose and Bardhan, 2012).

The incorporation of trees or shrubs on farms or pastures can increase the amount of C sequestered compared to a monoculture field of crop plants or pastures (Sharrow and Ismail 2004). It has been well documented that the conversion of degraded agricultural soils into agroforestry systems can rebuild soil productivity (Jose and Bardhan, 2012).

Agroforestry systems have a higher potential to sequester atmospheric CO₂ than the croplands, pastures, or natural grasslands, i.e., treeless land uses they replace, but effects on SOC vary greatly depending on biophysical and socioeconomic characteristics of the system parameters (Nair and Nair, 2014). The incorporation of trees, in particular, improves soil properties and can result in greater net C sequestration (Young, 1997).

Trees have extensive root systems which can grow deep into the mineral soil. The root-derived C inputs are critical sources for the SOC pool in deeper soil horizons (Kell, 2012). Specifically, root-derived C is more likely to be stabilized in the soil by physicochemical interactions with soil particles than shoot-derived C (Rasse et al., 2005). For example, the relative root contribution of European beech (*Fagus sylvatica* L.) to SOC was 1.55 times than that of shoots (Scheu and Schauermann, 1994). Similarly, in croplands, total root-derived C contributed between 1.5 times to more than 3 times more C to SOC than shoot-derived C. Thus, agroforestry systems store more C in deeper soil layers near trees than away from trees (Nair et al., 2010).

Another reason for the promotion of SOC sequestration in agroforestry systems is that tree roots have the potential to recover nutrients from below the crop rooting zone. The resulting enhanced tree and crop plant growth by subsequent increase in nitrogen (N) nutrition may result in an increase in SOC sequestration (Noordwijk et al., 1996). Mixed plantings with N-fixing trees may cause higher biomass production and, thus, SOC sequestration and pools particularly in deeper soil horizons as N may promote humification rather than decay (Gärdenäs et al., 2011). Nitrogen-fixing trees (especially Gliricida) together with maize increased yield by 42% over non-fertilized fields and similar to fields receiving 92 kg N ha⁻¹ in a field study conducted in Malawi and Zambia (Sileshi et al., 2012).

Changes in microbial decomposer community composition under N-fixing trees may result in greater retention of relatively stable SOC (Resh et al., 2002). N-fixing trees in mixtures with non-N-fixing trees may develop deeper root profiles due to niche partitioning. Mixed tree plantings in agroforestry systems may enhance SOC sequestration as increases in tree species diversity may potentially result in increasing in fine root productivity (Meinen et al., 2009).

Among the positive effects of trees on SOC sequestration are that trees modify the quality and quantity of belowground litter C inputs and modify microclimatic conditions such as soil moisture and temperature regimes (Laganière et al., 2010). Root litter usually decomposes more slowly than leaf litter of the same species (Cusack et al., 2009). Furthermore, hydraulic lift of soil water by roots of a single tree may enhance soil water uptake by neighboring trees and other plants in the agroforestry system which may affect SOC sequestration due to an increase in productivity and accelerated decomposition (Liste and White, 2008).

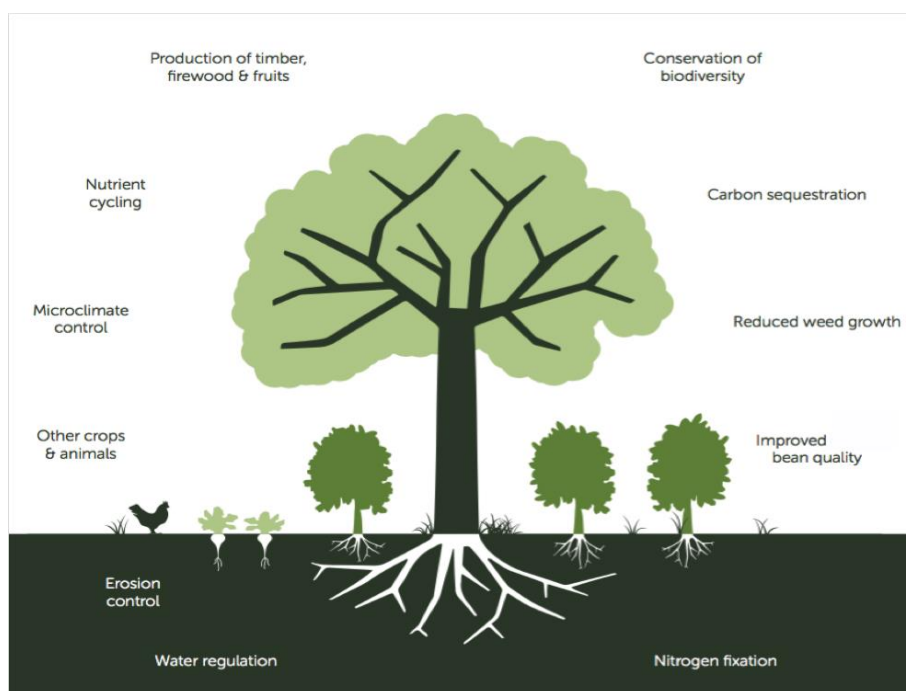


Figure 2.9.2. Benefits of Agroforestry.

Source : <https://stories.mightyearth.org/voice-network-agroforestry-in-cocoa/index.html> - accessed 20.10.2022.

Further, in surface soil horizons of intensively managed agricultural landscapes, trees potentially reduce SOC losses by reducing soil erosion (Lal, 2005). The changes in soil microbial communities and activities and biodiversity under trees may also enhance SOC sequestration. For example, the addition of a single tree species to moorland resulted in changes in belowground soil microbial communities and in nutrient cycling (Mitchell et al., 2010).

However, field studies on the mechanisms and processes associated with C dynamics and storage in tree-based systems such as agroforestry systems are scanty (Lorenz and Lal, 2014).

As demonstrated in Figure 2.9.2., the integration of trees into agricultural systems can create positive interactions like enhanced productivity, nutrient cycling, soil fertility, microclimate control etc. On the other hand, there are also some possible negative interactions. For example, understory species may be negatively affected by the tree presence, and trees and crops may compete for water (Burgess et al., 2004). The competitive relationship of tree and understory depends on edapho-climatic conditions (Mosquera-Losada et al., 2010).

Allelopathic and disease vectors are other possible negative interactions in agroforestry systems. Allelochemicals are present in many types of plants and are released into the soil by a variety of mechanisms. Mulching with plant residues may result in the liberation of allelochemicals into the soil. Allelochemicals affect germination, growth, development, distribution, and reproduction of a number of plant species (Malik, 2002).

According to Nair and Nair (2014), tropical and temperate agroforestry practices can be grouped under the subgroups :

1. **tree intercropping**
2. **multistrata systems**
3. **silvopasture**
4. **agroforestry tree woodlots**
5. **protective systems**

Tree intercropping is an agricultural technique where trees are grown together with other crops on the same land. Some intercropping systems use nitrogen-fixing trees such as evergreens to support crop production or use as protective systems against erosion, flooding, or wind damage (Earth Overshoot Day, 2022).

Multistrata systems is an agricultural system that mimics the forests. Furthermore, it is a perennial cropping system that features layers of carbon-sequestering vegetation. One or more layers of crops grow in the shade of taller trees. The structure and function resemble those of natural forests, in some cases simplified. The layers of trees and crops sequester substantial carbon while producing food. They also provide ecosystem services, such as habitat, erosion control, and water quality (Project Drawdown, n.d.).

Silvopasture is a form of land use where tree, forage, and livestock components occupy the same plot of land, which make a niple system for raising livestock They form a varied class of production practices, including elements of alley cropping, windbreaks and shelterbelts, scattered trees in pastures, and intensive management and rotational grazing. Silvopasture combines forest management, forage management, and livestock husbandry (Walter, 2011).

Woodlots are an agroforestry technology which aims at improving fuelwood supply and poles to rural communities, income generation and alleviating environmental degradation. A woodlot refers to planting of trees in sole stands on farm to provide wood for fuel and construction poles (Otsyina et al. 1999). Woodlots have been promoted in rural areas of Africa. **Protective systems** are based on physical protection of critical resources such as crops, soil and livestock. Windbreaks, shelterbelts and riparian buffers are an example of protective systems (Chatterje et al.,2020).

Agroforestry systems that utilize tree crops and are designed to mimic forested systems while still producing food could be readily implemented but are largely under-utilized and understudied (Kane, 2015).

2.10. Agricultural Systems that could sequester carbon

According to Lal (2015), improved management practices can help rebuild SOM levels, reduce CO₂ emissions, and improve soil quality. Improvements in tillage management and cropping systems, management to increase vegetation cover, and efficient use of production inputs, such as nutrients and water, can all help to restore SOM (Follett, 2001). Increasing soil carbon can have a significant impact on soil quality and agroecosystem productivity in addition to reducing carbon emissions. Soil carbon is essential for maintaining soil structure, improving water retention, fostering healthy soil microbial communities, and providing crop fertility (Kane, 2015).

Conservation agriculture aims to achieve acceptable profits, sustained production levels and at the same time conserve the environment. The principles that are followed are: minimum or no mechanical disturbance, permanent soil cover, diversified crop rotations and improving soil fertility by integrated nutrient management (INM) to transform biomass carbon into soil organic matter for healthy crop management (Lal, 2015). Some of the agricultural systems that can sequester carbon are explained in the following content.

2.10.1. Conventional No-Till and Conservation Tillage

Among the most widely studied agricultural management strategies that can increase soil carbon are no-till systems. No-till is a system used on over a third of US crop acres that generally relies on specialized planting equipment, chemical herbicides, and genetically modified seed to reduce or eliminate the need for tillage equipment. Since soils in these systems remain undisturbed, soil aggregates remain intact, physically protecting carbon (Kane, 2015).

Studies have demonstrated that no-till can increase soil carbon rapidly, especially at the soil surface (West and Post, 2002). Several more detailed studies have found that this increase in carbon is also linked to better aggregation (Six et al., 2000).

However, in order to maintain gains in soil carbon, it is important to continuously manage soils with no-till. Grandy and Robertson (2006) found that tilling a previously untilled soil quickly reversed nearly all the previously recorded gains by disrupting aggregates and exposing carbon molecules to microbial attack.

Conservation tillage utilizes tillage implements less aggressive than the classic moldboard plow and requires fewer tillage passes per season such that more residues are left on the surface and disruption of soil aggregates is reduced. This method also typically employs chemical herbicides and genetically modified seed to control weed growth. (Kane, 2015). Conservation tillage can also increase soil carbon by increasing soil aggregation and physically protecting carbon, but the rate of carbon sequestration is typically lower than with no-till. (Halvorson et al., 2002).

The carbon accrued in these systems is largely due to physical protection, so maintaining the same tillage regimen is important to ensuring that carbon remains sequestered. What raises questions is that many producer do not actually utilize no-till or conservation tillage every season, but prefer to periodically till their soils with more aggressive implements to prevent problems such as compaction and to combat weeds (Grandy et al., 2006).

Furthermore, extensive reliance on herbicides and fertilizers can have a severe influence on water quality, and persistent glyphosate usage has resulted in a number of glyphosate-resistant weeds that frequently require tillage to control (Duke and Powles, 2008). The possible lack of soil carbon permanence in many conservation tillage or no-till regimes, along with the issues highlighted by their substantial reliance on herbicides, calls into doubt the viability of this technique for long-term carbon sequestration (Kane, 2015).

2.10.2. Organic No-Till

Because organic agricultural methods are not permitted to use pesticides or chemical fertilizers and instead rely on cultivation to control weeds, decreasing tillage in these systems is significantly more difficult than in conventional systems. Conservation tillage implements that plow to a limited depth and do not invert soil like a traditional moldboard plow can reduce disturbance, but the requirement to make numerous passes with cultivating equipment to suppress weeds can outweigh the gains and lead to carbon losses (Kane, 2015).

Researches at the Rodale Institute have been experimenting with an organic no-till system. The system relies on an implement called a roller-crimper that is used to roll over a standing cover crop in spring, flattening and crimping plants so that they die, creating a mulch on the soil surface that will continue to suppress weeds throughout the growing season. (Rodale Institute, 2015). Most organic systems using cover crops will mow the cover crop to terminate it then till it into the soil, a roller-crimper avoids these steps, protecting the soil from disturbance. Soil modeling projections estimate that the carbon sequestration rates and full cycle carbon budgets, including external carbon costs, of organic no-till systems could outperform more conventional tillage systems (Ryan et al., 2009).

Researchers testing these systems have had to deal with significant issues of weed pressure and regrowth of cover crops that affect crop productivity (Mirsky et al., 2012). Key to terminating the cover crop effectively is rolling it at the correct developmental stage. Organic no-till may also have an effect on soil nitrogen availability, as the massive amount of plant biomass required enables soil microbes to rapidly consume soil nitrogen, making it unavailable to plants (Parr et al., 2014).

Organic no-till is still being researched and used on a small scale, and farmers and scientists are actively exploring for solutions to these problems. This technique could lead to considerable carbon sequestration and numerous additional co-benefits if reliable procedures are established (Kane, 2015).

2.10.3. Cover Crops and Crops Rotations

While conservation tillage and no-till rely on protecting soil from tillage disturbance, other methods simply compensate for the carbon loss caused by tillage by increasing plant carbon inputs. The use of periodic green fallows, winter cover crops, and crop rotations that utilize semi-perennial crops, such as alfalfa, were practices long used in agriculture that fell out of use as synthetic fertilizers and pesticides became more widely used. Such practices have demonstrated advantages for weed control and soil fertility, and there is some evidence that they can also result in carbon sequestration (Kane, 2015).

In a long-term cropping systems experiment conducted at the Kellogg Biological Station of Michigan State University, researchers discovered that an organic management system with increased rotational diversity and extensive use of winter cover crops led to a significant increase in soil carbon over a 12-year period, despite extensive tillage for weed control (Syswerda et al., 2011). Such results might be explained by a net positive difference in carbon inputs versus carbon respired as CO₂, as well as improved soil biological function. Researchers found that more diverse crop rotations consistently have higher soil carbon and soil microbial

biomass than less diverse systems, especially when cover crops were included in the rotation (McDaniel et al., 2014).

Tiemann et al. (2015) demonstrated further that rotational diversity has significant effects on soil carbon accumulation by enhancing the capacity of soil microbial communities to process plant residues rapidly and protect them in aggregates. Incorporating a variety of crops into a rotation also increases the soil's diversity of carbon compounds, some of which may be more resistant to decomposition.

The initial chemistry of the plant residues and the microbial community have a strong influence on which carbon compounds are present in the soil. The inclusion of a diversity of crops, as a result, might ensure that a diversity of carbon compounds is present in the soil, improving soil carbon sequestration potential (Wickings et al., 2012). Technically, increasing cropping system diversity is a relatively simple strategy to implement, as it primarily requires growers to plant cover crops or maintain a more consistent rotation of grain crops. This strategy may be met with resistance due to the dominance of monocultures in global agriculture, the concomitant decline in markets for alternative crops, and the perceived risk associated with growing multiple crops. Nonetheless, diverse crop rotations can match the productivity of monocultures while also enhancing environmental services and reducing input requirements (Davis et al., 2012).

2.10.4. Rotational Grazing

Herds of grazing animals can maximize annual pasture biomass production and redistribute carbon throughout pastures in the form of manure, resulting in rapid increases in soil carbon when properly managed. Methods such as Management Intensive Grazing emphasize moving cattle to new pastures frequently, maintaining high stocking densities, and preventing overgrazing so that pasture plants maintain a high biomass continuously. In addition, this style of production typically does not necessitate tillage, which means that soil aggregates are not disrupted and their carbon remains physically protected (Kane, 2015).

The addition of compost amendments to rangelands may increase the effectiveness of rotational grazing. Studies conducted by the Marin Carbon Project in collaboration with soil scientists from the University of California, Berkeley demonstrated that very thin applications of compost to managed grazing grasslands led to substantial increases in plant biomass and a net increase in carbon sequestration (Ryals et al., 2014). These results suggest that even small additions of composted organic matter can significantly increase the carbon sequestration capacity and productivity of degraded rangelands.

In the majority of studies, conversion of croplands to grasslands and improvements in grassland management led to greater carbon sequestration, as determined by a meta-analysis

of existing research on the effect of grassland management on soil carbon accumulation (Conant et al., 2001). Researchers in the southeastern United States discovered that converting formerly row-cropped land to management-intensive grazing rapidly increased soil carbon to an apparent saturation point (Machmuller et al., 2015).

In addition, they estimated that the methane emissions of cattle resulting from enteric fermentation were neutralized during the initial phase of rapid carbon accumulation. More extensive research on the full carbon cycle of grazing operations, including fine-scale measurement of methane emissions from cows themselves, will be required to accurately evaluate the effectiveness of this method for soil carbon sequestration, but preliminary results are encouraging.

2.10.5. Perennial Cropping Systems

The vast majority of cropping systems are dominated by annual plants that rely on cycles of tillage and seed sowing for adequate productivity. In contrast, perennial plants that can endure multiple seasons require less disturbance. Perennial cropping systems have been proposed as systems that could effectively protect soil carbon, and because perennial plants frequently rely on more extensive root systems to ensure longevity, they likely produce more belowground biomass (Cox et al., 2006).

3. Conclusion

The changes in the atmospheric CO₂, which have been noticed already in the 19th century, are causing Earth's climate change. Soil is a significant and long-term reservoir of organic carbon and thus has an important role in regulating the climate. Land management has a notable impact on carbon dioxide fluxes. The conversion of land from natural vegetation to croplands leads to decrease in soil organic matter, which is one of the best-documented ecosystem consequences of agricultural activities. Primarily, oxidation of carbon during tillage is causing soil carbon to be released back in to the atmosphere.

Improved agricultural management practices can rebuild soil organic matter levels and at the same time help mitigate climate change. Based on scientific literature, several agricultural systems which follow the principle of conservation agriculture, have been shown to sequester carbon in soils. Apart from sequestering a very significant portion of atmospheric carbon, they also have other co-benefits including improved soil aggregation, water retention and soil fertility.

Trees have the highest potential for carbon sequestration as they store carbon in the deeper profiles of the soil. Therefore, the conversion of degraded agricultural soils into agroforestry systems is a great method for environmental protection. Apart from carbon storage, agroforestry is a source of biomass for biofuel production.

These important outcomes of improved agricultural practices should serve as motivation for increased action and attention from policymakers, farmers and scientists. Remaining forests and other natural habitats should be completely preserved while innovative strategies for carbon storage should be implemented on existing croplands.

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Biography

Lara Ivić was born in 1997 in Zagreb, Croatia. She grew up in her home town, attended the elementary school of Vladimir Nazor followed by XVIII language gymnasium. In the year 2015 she enrolled in the Faculty of Agriculture at the University of Zagreb, studying agroecology. She finished her undergraduate studies in 2019 and continued her education at the graduate program in microbial biotechnology in agriculture. In the academic year 2020/2021 she participated in Erasmus+ student exchange in Italy, at the University of Catania. During the summer of 2021 she did an internship through Erasmus+ program at the same University in Italy. Internship included practical work in laboratory. Currently, she is finishing her master studies in Zagreb. After graduation she is travelling to Verona (Italy) to gain more practical experience by working at the Department of Biotechnology at the University of Verona.